Contemporary Food Engineering Series

Advances in Sustainable Meat Technology

Engineering, Quality, and Safety

Edited by
Slim Smaoui, Angelos Vakalopoulos
and Theodoros Varzakas

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Advances in Sustainable Meat Technology

This book explores the intersection of innovation and bioprocess technology in meat products and by-products, offering a comprehensive guide to the latest technological advancements that are transforming the landscape of meat technology.

It begins with an insightful overview of the chemistry, microbiology, structure, and composition of meat. From there, it delves into a wide range of emerging technologies, including state-of-the-art machinery, data analytics for postharvest quality management, and engineering approaches for the safety and preservation of meat. The second part of the book focuses on recent developments in meat products and by-products, highlighting cutting-edge innovations in the field.

Advances in Sustainable Meat Technology: Engineering, Quality, and Safety also addresses the growing importance of circular economy principles and the sustainability impact of meat waste. It discusses sustainable supply chain practices, adaptation strategies, and new technologies such as cultured meat.

Contemporary Food Engineering

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Preface

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It begins with an insightful overview of the chemistry, microbiology, structure, and composition of meat. From there, it delves into a wide range of emerging technologies, including state-of-the-art machinery, data analytics for postharvest quality management, and engineering approaches for the safety and preservation of meat. The second part of the book focuses on recent developments in meat products and by-products, highlighting cutting-edge innovations in the field.

The book also addresses the growing importance of circular economy principles and the sustainability impact of meat waste. It discusses sustainable supply chain practices, adaptation strategies, and new technologies such as cultured meat.

In addition, the science of meat preservation and processing, along with consumer concerns, is thoroughly explored. The scope of the book extends beyond the processing of meat and by-products to include sustainable safety practices. It examines how innovative technologies are contributing to more sustainable meat production methods, addressing environmental challenges while meeting the growing demand for ethically sourced and environment-friendly meat and by-products.

The book features case studies of various meat products, offering readers practical insights into the implementation of these technologies. It caters to a diverse audience, including professionals in the meat processing industry, researchers, policymakers, and anyone interested in the future of meat technology.

Readers will gain a deep understanding of how these technologies enhanced the safety and quality of meat and meat products. This book would contribute to increase the added-value of meat and meat products and by-products and solve waste management problems. This would also highly contribute to the development of these co-products producers maintaining the sustainability of their products.

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About the Editors

Slim Smaoui (H-Index 34) is currently working as Associate Professor at the Centre of Biotechnology of Sfax (CBS-Tunisia). According to August 2024 and 2025, data-update for "Updated science-wide author databases of standardized citation indicators" published by John P.A. Ioannidis (Stanford University) and Elsevier, Dr. Smaoui is in the top 2% scientists worldwide. Dr. Smaoui's research interests are centered on the development of new healthier meat products; use of agro-food industries by-products as potential sources to obtain valuable and bioactive compounds, and incorporation of bioactive compounds and development of functional foods. Dr. Smaoui is the author or co-author of several papers (Scopus indexed) published in international peer-reviewed journals in food science. Dr. Smaoui has published over 250 articles and reviews, 35 book chapters, 8 books (as editor), and 10 national patents. Dr. Smaoui also belongs to the Editorial Boards of several reputed international journals, besides being the guest editor and an active reviewer of several ISI-indexed journals.

Angelos Vakalopoulos is a veterinarian with over 40 years of experience in the public sector. He holds a master's degree in public health with specialization in epidemiology and veterinary public health. He served at the Department of Zoonoses, Directorate of Animal Health, Directorate General of Veterinary Medicine, Ministry of Rural Development and Food and since 2003, he serves at the Hellenic Food Safety Authority, Ministry of Rural Development & Food, Directorate of Food Safety, Department of Food of Animal Origin, and lately as Head of the Department of Internal Audits, Quality & Efficiency.

He was appointed as national expert in the EU Task Force for the control and eradication of bovine tuberculosis and member of scientific and technical committees for the monitoring and surveillance of zoonoses and for the hygiene and safety of food of animal origin. He has worked on animal health and safety of food of animal origin in national and EU research programs, written more than 10 research papers, and presented several papers at national and international veterinary and food congresses. He is also a lecturer in food safety training seminars for the competent food control authorities' personnel, has edited guides on food hygiene, quality, and safety management systems, and represented Hellenic Food Safety Authority as speaker on several food conferences.

Theodoros Varzakas serves as Full Professor in the Department of Food Science and Technology, University of the Peloponnese, Greece, since 2019, specializing in issues of food technology, food processing/engineering, and food quality and safety. Varzakas is Section Editor in Chief of *Journal Foods in Food Security and Sustainability* (2020–). He has also served as Ex-Editor in Chief of *Current Research in Nutrition and Food Science* (2015–2019); Series Editor for contemporary Food Engineering, CRC Press; reviewer and member of the editorial board in many international journals such as *International Journal of Food Science & Technology*, *Journal of Food Engineering*, *Waste Management*, *Critical Reviews in Food Science and Nutrition*, *Italian Journal of Food Science*, *Journal of Food Processing and Preservation*, *Journal of Culinary Science and Technology*, *Journal of Agricultural and Food Chemistry*, *Journal of Food Quality*, *Foods*, *Microorganisms*, and *Current Research in Food Science*. He has written more than 200 research papers and chapters in books and has presented more than 160 papers and posters at national and international conferences. He has written and edited 14 books in Greek, and 16 in English on sweeteners, biosensors, food engineering, food processing, published by CRC. He has participated in many European and national research programs as coordinator or scientific member. According to http://scholar.google.gr/citations?user=12zr6IYAAAAJ&hl=el, his h-index is 48 and has to his credit approximately 8,600 citations.

According to September 2021, 2022, October 2023, and August 2024 data as well as September 2025-update for "Updated science-wide author databases of standardized citation indicators", Varzakas is in the top 2% scientists worldwide.

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Theodoros Varzakas would like to dedicate this book to God and his family.

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1

Introduction

Slim Smaoui, Angelos Vakalopoulos, and Theodoros Varzakas

An industrial transformation has taken place for meat for centuries now as a vital component of the food sector. The first meat assembly line in 1870 was introduced by the Cincinnati Meat Works, starting the mechanization of meat processing (Barbut, 2020).

However, public concern about meat safety and quality has occurred with the emergence of pathogens such as *Escherichia coli* and *Listeria* (Altekruse, Cohen and Swerdlow, 1997; Hulebak and Schlosser, 2002).

EU's adoption of the Hazard Analysis and Critical Control Points (HACCP) framework in the 1990s has helped toward the direction of prevention and traceability to avoid food crisis (Ehiri, Morris and McEwen, 1995).

Automation had been widely adopted in primary processing steps such as slaughtering, defeathering, and segmentation during the twentieth century. These advancements have improved hygiene through improved cold chain logistics and safety standards (Welch and Mitchell, 2000).

A new round of transformation in the meat industry, characterized by the rapid adoption of intelligent and digital solutions (Tao *et al*., 2019), has taken place in recent years, with the integration of information technology, computer science, and advanced engineering along with disruptive technologies such as artificial intelligence (AI), the Internet of Things (IoT), digital twins (DT), and robotics (Wang *et al*., 2021; Zhang *et al*., 2025). Moreover, nonthermal processing techniques such as high-pressure processing (HPP) and pulsed electric field (PEF) are emerging as alternatives to traditional thermal processing, with advantages in improvement of protein functionality, efficient inactivation of microorganisms, and extension of product shelf life (Zhang *et al*., 2019).

X-ray and ultrasound are multimodal sensing technologies that can achieve millimeter-level cutting precision (Barbut, 2020) with machine vision three-dimensional modeling systems guiding robotic arms to achieve high-precision cutting. Hyperspectral imaging technology enables the real-time, nondestructive detection of pork quality characteristics such as pale color, soft texture, and exudation (Zhang *et al*., 2017) by exploiting spectral information within the 400–500 nm range.

Sun *et al*. (2025) explored all these technologies along with the potential of alternative meat production technologies (cell-cultured meat and 3D bioprinting) to disrupt traditional models. They reported significant improvement of production efficiency, product quality, and safety by application scenarios such as central kitchen efficiency improvements (e.g., food companies leveraging the "S2B2C" model to apply AI agents, supply chain management, and intelligent control systems, resulting in a 26.98% increase in overall profits), end-to-end temperature control in cold chain logistics (multi-array sensors for real-time monitoring of meat spoilage), intelligent freshness recognition of products (based on deep learning or sensors), and 3D-printed customized nutritional meat products.

This book explores the intersection of innovation and bioprocess technology in meat products and by-products, offering a comprehensive guide to the latest technological advancements that are transforming the landscape of meat technology.

It begins with an insightful overview of the chemistry, microbiology, structure, and composition of meat. From there, it delves into a wide range of emerging technologies, including state-of-the-art machinery, data analytics for postharvest quality management, and engineering approaches for the safety and

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preservation of meat. The second part of the book focuses on recent developments in meat products and by-products, highlighting cutting-edge innovations in the field.

The book also addresses the growing importance of circular economy principles and the sustainability impact of meat waste. It discusses sustainable supply chain practices, adaptation strategies, and new technologies such as cultured meat.

In addition, the science of meat preservation and processing, along with consumer concerns, is thoroughly explored. The scope of the book extends beyond the processing of meat and by-products to include sustainable safety practices. It examines how innovative technologies are contributing to more sustainable meat production methods, addressing environmental challenges while meeting the growing demand for ethically sourced and environment-friendly meat and by-products.

Throughout, the book features case studies of various meat products, offering readers practical insights into the implementation of these technologies. It caters to a diverse audience, including professionals in the meat processing industry, researchers, policymakers, and anyone interested in the future of meat technology.

Advances in Food Engineering and Quality & Safety Aspects in Meat Technology: From Stable to Fork offers a comprehensive array of features aimed at providing readers with valuable insights and tangible benefits as follows.

1.1 In-Depth Exploration of Emerging Technologies

Benefit: Offers an in-depth analysis of the latest technological advancements in the meat industry, providing readers with a comprehensive understanding of how these innovations are transforming meat processing practices and shaping the future of the sector.

1.2 Quality and Safety Assurance

Benefit: Explores how cutting-edge technologies are instrumental in upholding the highest standards of quality and safety throughout the meat production process. This section highlights the role of innovative systems in improving traceability, hygiene, and product consistency, ultimately fostering trust and confidence among industry professionals, regulatory bodies, and consumers alike. It also delves into how these advancements not only safeguard public health but also support the meat industry's efforts to meet evolving consumer expectations for ethically produced, safe, and high-quality products.

1.3 Sustainability and Ethical Considerations

Benefit: Tackles the rising demand for sustainable and ethically sourced meat and meat products, highlighting how innovative technologies play a key role in promoting environment-friendly and socially responsible practices throughout the industry.

1.4 Real-World Case Studies and Expert Interviews

Benefit: Provides practical insights through real-world examples and case studies, offering readers tangible evidence and a deeper understanding of how these technologies are applied in practice.

1.5 Appeal to a Diverse Audience

Benefit: Designed for professionals in the meat processing industry, researchers, policymakers, and anyone interested in the convergence of technology and food production, making it accessible to a diverse audience.

1.6 Future-Focused Perspective

Benefit: Offers a forward-thinking perspective on the meat processing industry, enabling readers to anticipate upcoming trends and advancements in technology, sustainability, and ethical practices.

1.7 Navigational Guide for Industry Transformation

Benefit: Acts as a comprehensive guide for readers to navigate the dynamic landscape of meat processing, engineering, safety, and quality, empowering them to embrace and apply innovative technologies for a more sustainable and efficient future.

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Part I

The Role of Animal Welfare in Sustainable Meat Industry

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2

Principles, Evaluation, and Livestock Management for Optimal Animal Welfare

Bytyqi Hysen and Kryeziu Alltane

2.1 Introduction

The growing global demand for meat protein is projected to increase by 3% (Vinci, 2025). Meeting this demand requires the intensification of animal production to increase their efficiency. But this has generated major concerns about animal welfare, as the intensification of animal production requires practices such as increased stocking density, high-yield genetic selection, and closed animal housing systems. These practices often limit the animals' freedom of space and behavior, increase the risks of stress and disease, and require the integration of welfare assessment protocols. So, Blokhuis *et al.* (2008) argue that the safety of our food chain can be directly affected by animal welfare. This is because stress, injury, and poor welfare together can lead to infectious diseases among animals, some of which can be passed on through food to the consumer. Furthermore, animals are sentient beings (European Union, 1997). Therefore, the current societal focus strongly supports the need for meat that is not only safe and of good nutritional value but also ethically produced. As reported by del Campo *et al.* (2025), animal welfare plays a crucial role in meat production and consumption. Also, data published by Tatemoto *et al.* (2020, p. 237) show that welfare has become established as one of various criteria used to decide on whether a system is sustainable, focusing on the acceptance by the society.

In livestock systems, welfare plays a crucial role that is not only morally just but also closely related to productive results. The literature lays down that suboptimal welfare has been found to correlate negatively with growth performance, reproduction performance, immune function, and carcass quality (Broom, 2011, p. 121; Hemsworth and Coleman, 2011; Tatemoto *et al.*, 2020). Transport and handling stress, for example, raises cortisol levels, which disrupt muscle glycogen metabolism and cause undesirable meat quality traits such as dark, firm, dry (DFD) or pale, soft, exudative (PSE) meat (Jassim, Salih and Ghadir, 2025; Terlouw, Bourguet and Deiss, 2016). Similar to this, long-term welfare issues like poor housing or an imbalanced diet caused more illnesses and deaths, which reduced economic returns and slowed the utilization of resources. These findings validate that welfare is naturally associated with system survival, validating its status as a priority issue for management of contemporary animal production.

Some management facets, including stockperson training and handling protocols, veterinary care, feeding regimens, and housing design, are included in animal welfare in the meat production industry. Each of these components must be carefully evaluated to balance the animals' behavioral and biological requirements with the requirements of production. The functions of veterinarians, nutritionists, and stockpersons have therefore been expanded to include the prevention of disease, enhancement of productivity, safeguarding psychological well-being, and allowing the expression of species-specific behavior (Buckham-Sporer, Early and Marti, 2023). Modern welfare assessment systems—such as the Five Domains model and Welfare Quality® protocols—have provided systematic approaches to measure and improve these parameters in a wide range of production systems (Botreau *et al.*, 2007; Mellor, Beausoleil and Littlewood, 2020).

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The connection between sustainability and animal welfare has gained more attention. When stress, illness, and inefficient output result in excess feed, water, and energy use without improved production, welfare negative impacts usually translate into environmental costs (Blokhuis *et al.*, 2013). For instance, increased inputs to compensate for animal losses in pig or broiler production systems result in a larger carbon footprint per unit of edible protein (O'Driscoll, Butler and Arnott, 2023). However, welfare-driven systems—better housing, lower stocking density, or precision livestock farming technology for early diagnosis of diseases—can achieve the highest productivity and efficiency of resource utilization with minimal environmental stress (Berckmans, 2017; Papakonstantinou *et al.*, 2024). This triple bottom-line objective of environmental conservation, economic sustainability, and ethical responsibility locates welfare as a potentiality, not a limitation, for sectoral sustainability in the long term.

Welfare is still on the food system agenda because of consumer attitude and demand. Alongside nutrition, safety, and taste, welfare is increasingly being considered a component of food quality (de Boer and Aiking, 2022; Harper, 2001). Welfare is increasingly a social license to operate expectation in most markets, particularly in the European Union (EU). Institutionalization also occurs in laws such as Council Directive 98/58/EC and Council Regulation (EC) No. 1/2005 on animal welfare during transport. The European Green Deal and, more recently once more, its Agricultural or Farm to Fork Strategy reaffirmed welfare as central to sustainable food systems (European Commission, 2020a). Along with regulation, voluntary certification schemes—organic certification, UK Red Tractor Assurance, and Animal Welfare Approved in the United States—have appeared, which have created consumer demand for traceability, transparency, and humanely produced animal-source foods (Hyland *et al.*, 2022; Miele *et al.*, 2011).

Globally, the integration of welfare in livestock policy and management is diverse, but there is a general trend toward growing recognition. In industrialized economies such as North America and Oceania, industry assurance schemes are expanding, but in developing countries, welfare is being debated increasingly in the context of trade competitiveness and export market access (Fraser, 2008, p. 2; von Keyserlingk and Hötzel, 2015, p. 180). For instance, foreign meat-exporting countries such as Australia and Brazil are increasingly being put under pressure by their importing markets to comply with higher welfare standards, in which case welfare performance is equivalent to market viability (Adekunle *et al.*, 2024). This global situation highlights that welfare is now not a specialist concern confined only to high-income consumers but a mainstream force for livestock sector growth in the twenty-first century.

Collectively, these changes indicate that animal welfare is at once a moral necessity and an efficient opportunity for contemporary livestock production systems. Welfare-led solutions have a fourfold advantage by coupling the ethical imperative with biological performance, sustainability, and consumer choice. Welfare is no constraint on efficiency; it is increasingly a basis for building robust, productive, and socially sustainable food systems. At present, knowledge and application of animal welfare principles in cattle farming are not only a matter of ethics but also competitiveness and sustainability in the global meat market.

2.1.1 Historical Evolution of Welfare Concepts

Over the past century, there has been a substantial development in animal welfare due to the interplay between societal expectations, ethical considerations, and scientific research. The largest percentage of participants in the debate of early ideas about farm animal care were utilitarian ethics. The concern in utilitarianism, however, was not so much whether animals had inherent rights, as it was whether they could be treated in a way that would benefit humans, supposing that obvious suffering was to be avoided. Here, welfare served primarily as a tool to increase productivity rather than as an end in and of itself (Rollin, 1995). These insights aligned well with the industrialization of farming following World War II, when animals were increasingly seen as production units to increase productivity and efficiency.

The watershed was the mid-1960s (Brambell, 1965). The classical report was one of the outrages over intensive husbandry of animals and defined principles subsequently formalized as law in the

"Five Freedoms": freedom from thirst and hunger; freedom from discomfort; freedom from pain, injury, or disease; freedom from fear and distress; and freedom to exhibit normal behavior. Although legislatively codified in 1979 by the UK Farm Animal Welfare Council (FAWC), the Five Freedoms were heavily grounded on the recommendations of the Brambell (1965). The first attempt at codifying a general ethical and practical approach to animal welfare, the Five Freedoms supplied scientists and policymakers with a common vocabulary in which to frame thinking about welfare within various production systems (FAWC, 1979; Webster, 2016).

The Five Freedoms, which were first a critique of industrial agriculture, gained enormous popularity and were adopted as the gold standard for social policies, assurance programs, and guidance worldwide. They were subsequently criticized in the longer term for having a focus on preventing undesirable states rather than promoting pleasant ones. By defining welfare in terms of the absence of suffering, the model could not capture the entire spectrum of animal flourishing and, for example, possible play, social contact, or environmental stimulation (Mellor and Beausoleil, 2015; Yeates and Main, 2008).

In order to overcome these limitations, scientists developed fresh conceptual models addressing positive welfare. Among those, the Five Domains model was particularly important. First created in the 1990s and later developed in the following decades, the model quantifies welfare in terms of four physical/functional domains—environment, nutrition, health, and behavior—and one mental domain encompassing the subjective feelings that arise out of these physical environments (Mellor, Beausoleil and Littlewood, 2020). Reducing pain and maximizing positive feelings like social engagement, agency, and comfort are part of this multidimensional perspective as well. By focusing welfare assessment on more general "quality of life" matters, it is a cultural move away from avoiding harm and toward positively promoting flourishing.

At the same time, the emergence of One Welfare as a philosophy during the 2010s expanded animal welfare focus from the individual animal to include human welfare and environmental conservation (Pinillos *et al*., 2016). This combined strategy appreciates that animal welfare is inextricably connected to public health, ecosystem functioning, and social justice—so it is one of the cornerstones of resilient food systems of the twenty-first century.

Scientific advance has also shaped the evolution of welfare concepts. Welfare discourse went beyond mere morality as welfare debates moved beyond ethical debate. Welfare science developed as a multidisciplinary field, including ethology, physiology, immunology, and veterinary medicine. For example, scientific studies of stress physiology revealed that chronic stressors such as crowding or abusive handling suppress immunocompetence and increase susceptibility to disease (Broom and Fraser, 2015). Welfare was expanded with more quantitative biological indicators—such as cortisol, heart rate variability (HRV), and immune markers—that were able to be used in welfare assessments on a more objective basis. Ethological research likewise highlighted the importance of needs for behavior, demonstrating that withholding access to natural behaviors such as rooting in pigs or dustbathing in birds is a root cause of serious deficits in welfare (Duncan, 2005, p. 488). Welfare science therefore now, as much as ever, is as concerned with finding animal biology as it is with answering public ethics.

Another essential driver of welfare change can be found in religious and cultural tradition of meat production. Animal welfare concern has been linked to ritual slaughter practices, such as kosher and *halal* practice, whose origins were rooted in core social values and moral obligation. Some other writers like Grandin and Regenstein (1994) pointed out that fitting present welfare needs into religious practice is a new and delicate issue, particularly within the context of more integrated world food systems. Whereas some believe preslaughter stunning offers the most humane method, others continue to place greater importance on the cultural rights of societies in maintaining traditional practices. This tension still shapes welfare policy, with the heterogeneity of opinion that shapes welfare governance across the world (Fuseini *et al*., 2017).

When taken as a whole, the development of animal welfare ideas demonstrates a distinct progression: from considering animals as mere industrial tools to setting minimal standards to avoid suffering to achieving positive welfare states and being consistent with sustainability and customer confidence. Figure 2.1 summarizes this history by listing significant turning points and conceptual models across time.

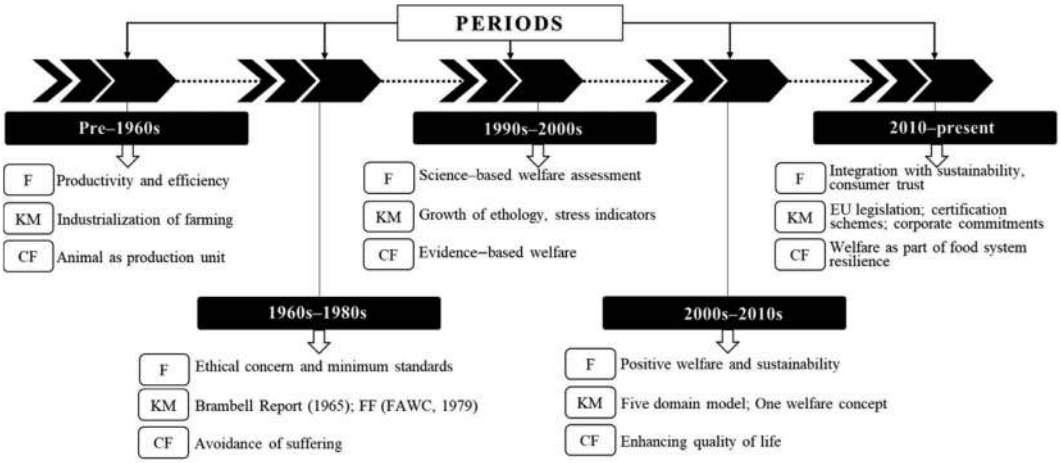

FIGURE 2.1 Evolution of animal welfare concepts and frameworks. *Abbreviations*: CF, Conceptual Framework; F, Focus; FF, Five Freedoms; K, Key Milestones.

2.2 Core Principles and Ethical Foundations

The animal welfare idea is of a complex nature and has both biological, psychological, behavioral, and ethical components. During the past five decades, science and ethics have influenced each other to formalize its basic principles. Animal welfare is no longer simply construed as a lack of suffering, but increasingly also as promotion of positive conditions and experiences improving quality of life and sustainable farm animal production.

At the heart of welfare assessment, there are two intellectual frameworks: The Five Freedoms and the Five Domains. The Five Freedoms were initially expressed in terms of the Brambell Report (1965) and, in their formal formulation, defined by the Farm Animal Welfare Council (FAWC, 1979), and remain a foundation of welfare science. They mandate that animals be in states where they are free of hunger and thirst, discomfort, pain, injury or disease, fear and distress, and freedom to demonstrate natural behavior. Such a system was groundbreaking since it gave clear, generic principles that applied to farming systems as well as cultures. To date, they form the cornerstone of welfare legislation, certification programs, and education schemes worldwide (Carenzi and Verga, 2009; Webster, 2016).

However, the Five Freedoms are now seen as necessary but not enough. They focus mainly on the elimination of adverse states and less on the active promotion of desired ones. To address this deficit, Mellor and Beausoleil (2015) created the Five Domains model that measures welfare on five combined dimensions: nutrition, environment, health, behavior, and mental state. In contrast to the negative emphasis of the Five Freedoms—freedom from ill—the Five Domains positively recognize the role that positive affective states, such as comfort, pleasure, and security, play in animal welfare. Mellor, Beausoleil and Littlewood (2020) more recently also used this model to include the contribution of human–animal interaction, illustrating the benefit of compassionate stockmanship and good management practice. By shifting the focus from survival only to flourishing, the Five Domains model has elevated the science and ethics of welfare evaluation to the next level.

At a biological level, measurable parameters like growth rate, immunological performance, metabolic condition, and reproductive performance may be utilized to assess well-being. These parameters are indicators of productivity as well as metrics of efficiency of resource utilization in addition to conveying the well-being of animals. Through research, it has been discovered that impaired welfare—measured as chronic stress or poor accommodation—affects immune function and increased susceptibility to disease (Broom and Fraser, 2015; Hemsworth and Coleman, 2011). On the contrary, animals reared under circumstances that commensurate with their biological needs have improved feed conversion ratios,

decreased mortality rate, and improved meat quality (Napolitano *et al*., 2020). In doing so, welfare not only becomes a moral imperative but also a key promoter of sustainable production.

Behavioral perspective provides additional information. Observations of natural behaviors, activity rate, and stereotypy absence (recurrent, unnatural behaviors such as pacing or bar-biting) are important welfare indicators. Ethological research emphasizes that thwarted animals with inadequate space to express normal behaviors experience less cognitive stimulation and poor psychological health (Fraser, 2008). Systems allowing expression of species-typical behavior—for example, access to pasture for ruminants or rooting materials for pigs—are strongly associated with positive welfare outcomes. Interestingly, these systems also align with consumer demand, in that market surveys suggest that the public welcomes apparent expressions of "natural living" in farm animals (Clark *et al*., 2017).

Animal welfare also has ethical and cultural roots. Social values, religious beliefs, and consumer preference all shape the assumptions livestock businesses must meet in order to have public trust and market share. In Muslim-majority and Jewish societies, for instance, *halal* and kosher forms of slaughter are constant sources of controversy about how to mediate religious practice and contemporary standards of welfare (Fuseini *et al*., 2017). Concurrently, the consumers from Europe demand transparency, traceability, and certification of welfare standards, leading to rapid growth of welfare-labeling schemes (Blokhuis *et al*., 2013). Here, welfare is as much about biological performance as social license to operate.

Another animal welfare pertains to sustainability. Modern food systems are no longer judged solely on productivity but also on how they preserve resources, reduce greenhouse gas emissions, and sustain food stocks in the long term. Poor welfare is the cause of inefficiencies such as reduced growth rates, veterinary costs, and loss of feed—all of which enhance environmental footprint of production (Blokhuis *et al*., 2010). Conversely, welfare-oriented systems maximizing health, behavior, and resilience maximize productivity while reducing wasteful consumption of resources. The One Welfare model also sheds light on this relationship by bringing out the interconnectedness of environmental sustainability, human well-being, and animal welfare (Pinillos *et al*., 2016). Livestock production is made not only morally imperative but also a cornerstone in climate-resilient agriculture and global food security by positioning welfare within sustainability agendas.

These, when considered as a whole, constitute the moral and scientific bases of sustainable livestock production: biological, behavioral, ethical, cultural, and sustainability. Feed efficiency and reduced mortality, for example, are biological traits that demonstrate the way in which welfare enhances productivity. Checks on behavior ensure that animals can exhibit natural behaviors, in accordance with rights-based ethical views. In order to enter global markets, welfare labeling initiatives are guided by cultural and ethical considerations that also promote consumer acceptance. Finally, sustainability indices associate quality of life with reduced emissions, better resource usage, and the long-term stability of the food system.

Animal welfare is therefore an interdisciplinary concept that integrates sustainability, ethics, and science rather than being a one-disciplinary concept. Concepts like the Five Freedoms and Five Domains are framework ideas, yet their translation into practice depends on good biological indicators, ethological information, ethical thought, and cultural sensitivity. Lastly, welfare is a science and ethical guide for directing the course of animal agriculture into directions that are respectful to animals, responsive to society's needs, and supportive of hardy, lasting systems of meat production (Table 2.1).

2.3 Welfare Evaluation and Assessment Methods

Effective animal welfare control in meat production systems relies on strict monitoring and evaluation systems that measure the biological condition of animals along with their experience. Since welfare is multidimensional in nature, a single measurement is not sufficient; instead, different physiological, behavioral, and production-oriented measures are generally employed to provide an integrated assessment (Broom, 2014). They are increasingly supplemented by standardized methods for welfare evaluation as well as by emerging information technologies, all of which collectively enable producers, regulators, and consumers to assess welfare in scientific and ethical terms. According to data published by Sejian *et al*. (2011) welfare indicators can be grouped under four categories: behavioral, physical, physiological, and production oriented. Their data also presented the general concept of animal welfare (Figure 2.2).

TABLE 2.1

Core Principles of Animal Welfare, Ethical Foundations, and Links to Sustainable Meat Production

Principle/ Framework	Key Components	Assessment Domain	Ethical Basis	Implications for Sustainable Meat Production
Five Freedoms (FAWC, 1979)	• Hunger/thirst • Discomfort • Pain/injury/disease • To express normal behavior • Fear/distress	Physical and behavioral indicators, resource availability	Utilitarian	Reduces stress and disease, improves growth, reproduction, and meat quality
Five Domains (Mellor and Beausoleil, 2015)	Nutrition, environment, health, behavior, and mental state	Physiological, behavioral, affective measures	Utilitarian/ positive welfare	Promotes positive affective states, enhances animal resilience, aligns with ethical and productivity goals
Biological perspective	Growth rates, reproduction, immune function, metabolic health	Physiological	Utilitarian	Optimizes feed efficiency, lowers mortality, reduces veterinary costs
Behavioral perspective	Natural behavior, activity patterns, stereotypies	Observational/ ethological	Rights-based/ utilitarian	Improves mental well-being, reduces abnormal behaviors, enhances welfare certification compliance
Ethical/cultural considerations	Societal norms, religious values, consumer expectations	Surveys, market research	Rights-based/ utilitarian	Influences consumer acceptance, supports market access, drives certification schemes
Sustainability integration	Resource use efficiency, reduced emissions, food security	Production metrics, environmental indicators	Utilitarian	Connects welfare with long-term system resilience, food security, and sustainable meat production

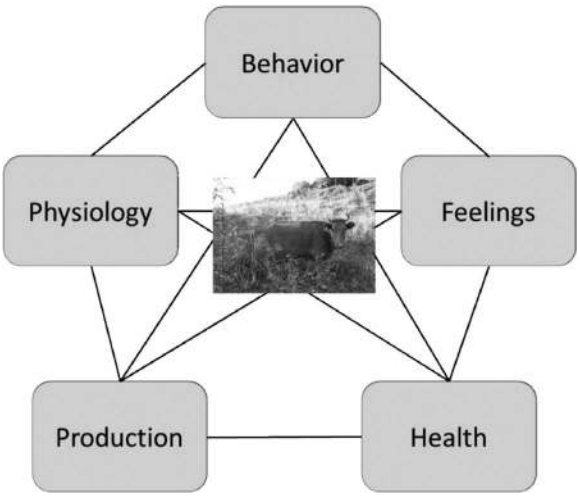

FIGURE 2.2 General concept of animal welfare.

In the modern production system, the best mechanism to assess animal welfare is the use of artificial intelligence (AI). Through their observations, the researchers (Neethirajan, 2024) demonstrate that application of AI in animal welfare assessment is a rapidly growing field, with promising results in both research and practical applications.

2.3.1 Physiological Indicators

Physiological tests have traditionally provided some of the most objective measures of animal welfare. Biomarkers such as cortisol levels, HRV, markers of immune function, and markers of metabolism are direct measures of an animal's health and state of stress. Higher cortisol, for example, has often been used as a surrogate for acute or chronic stress, while HRV reflects autonomic nervous system responses to environmental and handling stress (Mormède, Andanson and Aupérin, 2007). More recently added are immune biomarkers, including cytokine profiles or leukocyte function, which were included on the list as being useful for identifying stress-related immunosuppression leading to disease (Hemsworth *et al.*, 2015). Advances in proteomics and metabolomics technologies are progressively expanding the number of biomarkers of physiological health, allowing diagnosis of early maladaptation or subclinical disease states prior to these being evidenced by behavior or production (Chakraborty, Sharma and Kour, 2022).

2.3.2 Behavioral Indicators

While physiological measures reveal internal state, behavioral measures reveal how animals and other animals act in the world and therefore are paramount to ascertaining the mental and affective dimension of welfare. Incidence of abnormal behavior such as aggression, feather pecking, tail biting, or stereotypies and prevalence or absence of normal pattern activity such as grazing, lying down, or rumination are controlled by behavioral controls (Mason and Latham, 2004). They are most likely to be probable expressions of coping responses to environmental inadequacy and are closely associated with adverse welfare effects (Rushen, Butterworth and Swanson, 2011). Recent literature focuses not only on quantification of avoidance behavior but also on positive measures of welfare indices such as play, social interaction, and exploratory behavior, since they are predictive of good welfare states (Wemelsfelder *et al.*, 2009). The use of behavior indicators in welfare assessment marks this move away from the pain avoidance toward quality-of-life enhancement.

2.3.3 Production-Based Indicators

Because they connect well-being to quantifiable economic outcomes, production-based measurements are nevertheless significant even though they are indirect. Proxies for the effect of well-being on long-term production include growth rate, feed conversion ratio, reproductive performance, illness, and mortality (Broom, 2014). Producers and legislators are strongly motivated to combine welfare and productivity since poor welfare is often associated with decreased growth efficiency, increased veterinary expenses, and larger losses (von Keyserlingk and Weary, 2017). Importantly, even so, sole reliance on production measures is insufficient, for animals are capable of growing or reproducing regardless of compromised welfare. Thus, production data must be interpreted together with physiological and behavioral assessment to avoid confusing results.

2.3.4 Standardized Assessment Protocols

For the operationalization of welfare assessment under field conditions, a number of standardized protocols have been formulated. The most prominent among them are Welfare Quality protocols covering animal-based measures for poultry, cattle, and pigs and Animal Welfare Indicators (AWIN) protocols providing species-specific tools adapted to farm animals (Blokhuis *et al.*, 2013; Napolitano, Girolami and Braghieri, 2010). To provide comprehensive assessments, these systems integrate resource-based metrics (such as shelter and feed availability) with animal-based metrics

(such as physical condition, lesions, and behavior). As a global standard for regulation and commerce, the World Organization for Animal Health (OIE) has developed recommendations covering welfare in production, transportation, and slaughter (OIE, 2021). For regulatory enforcement and certification programs, these systems work together to support comparability and uniformity as well as compliance monitoring.

2.3.5 Technological Innovations in Welfare Monitoring

Over the last few years, dramatic improvements in precision livestock farming (PLF) technologies have redefined the extent of welfare monitoring. Applications such as GPS tracking and accelerometers enable constant measurement of movement and activity in animals, picking up on deviations that can signal lameness, injury, or illness (Morales-Vargas *et al*., 2025). Computer vision systems endowed with AI now facilitate automatic detection of behavior, monitoring of parameters such as deception time, aggression, feeding frequency, and social interaction at the group level (Berckmans, 2014). Infrared thermography is also a noninvasive method to quantify stress and detect early indicators of inflammation or fever (de Melo *et al*., 2022). Simultaneously, advances in noninvasive biomarker assessment—for example, cortisol in hair or saliva—reduce stress related to sampling while enabling longitudinal monitoring (Chakraborty, Sharma and Kour, 2022).

These technologies have many benefits when combined. They enable real-time, ongoing, and predictive welfare monitoring that signals health or welfare issues ahead of time, before they are expressed in the form of production loss or mortality (Caja, Castro-Costa and Knight, 2016). Digital systems also allow scalability, where big herds or flocks are handled effectively and yet give datasets that are used in precision interventions. Through greater uptake, they complement welfare science and traceability and transparency and strengthen further consumer trust in food of animal origin.

2.3.6 Toward Integrated Welfare Evaluation

Each of the welfare indicator classes—physiological, behavioral, and production—provides unique information, but collectively these classes provide the most complete and evidence-based welfare measures (Table 2.2). Standardized systems such as Welfare Quality and technical innovation in PLF are bridging materials between science, ethics, and operational management. Standard welfare assessment

TABLE 2.2

Overview of Welfare Indicators, Assessment Protocols, and Technologies

Category	Examples	Measurement Method	Applications/Benefits	References
Physiological indicators	Cortisol, immune markers, HRV	Blood, saliva, feces, sensors	Detect stress, pain, disease Early intervention	Mormède *et al*., 2007; Hemsworth *et al*., 2015
Behavioral indicators	Natural behavior, stereotypies, aggression	Direct observation, video recording, AI analysis	Assess mental state, social welfare, abnormal behaviors	Mason and Latham, 2004; Rushen, Butterworth and Swanson, 2011
Production-based indicators	Growth rate, reproduction, mortality	Farm records, weighing, scoring	Indirect welfare measure, economic impact, meat quality	Broom, 2014
Assessment protocols	Welfare Quality®, AWIN, OIE	Combined animal- and resource-based scoring	Standardized evaluation, compliance, benchmarking	Blokhuis *et al*., 2013
Technologies	Accelerometers, GPS, video-AI, infrared thermography	Sensors, automated systems, software	Continuous monitoring, predictive analytics, early detection	Berckmans, 2014; Morales-Vargas *et al*., 2025; Wemelsfelder *et al*., 2009

is no longer just about compliance; it has become over the past decade an efficiency-promoting tool for competitiveness, sustainability, and market opening, which underpins the triple leg of environmental responsibility, economic sustainability, and ethical accountability in livestock production in today's age.

2.4 Livestock Management Strategies for Optimal Welfare

Livestock production is the key to welfare outcomes in meat production systems, determining the daily lived experience of animals and their biological performance and ethical acceptability. Proper management is required, which requires multidimensional policy, such as housing and environment; feeding, breeding, and genetics; handling and stockmanship; and health and disease control. Every sector is related to the other, and only through their integration can producers acquire systems that are efficient, durable, and compliant with society's expectations for animal welfare.

2.4.1 Housing and Environment

Environmental conditions are the most obvious welfare factors for animals. Shelter influences comfort, incidence of injury, incidence of illness, and the ability of animals to use natural behavior. Space allocation, clean bedding, ventilation, and enrichment enhance welfare by reducing stress and encouraging lying, searching, or social patterns of behavior (Appleby *et al*., 2011, p. 15; van de Weerd and Day, 2009). Advantages of pasture animal systems are greater mobility and potential for exhibiting the natural behavior, even though the systems are faced with challenges such as parasitism, predation, and climate. Intensive systems, on the other hand, have environmental climate control and protection from environmental stressors but are susceptible to stocking density, air quality, and enrichment to avoid boredom, aggression, or respiratory disease (Tatemoto *et al*., 2020). Welfare-concerned housing design nowadays comprises adaptive systems that are a combination of the strength of pasture and controlled environments to address health and behavior requirements.

2.4.2 Nutrition and Feeding

Nutrition is also important to productivity and welfare outcomes. Diets must meet species-specific requirements for growth, reproduction, and immunity, and ensure equal access to feed to avoid competition and social stress (Mitchell *et al*., 2012). Feeding practices that do not meet these requirements will lead to metabolic disease, compromised immunity, and reduced reproductive success. Development of precision feeding technology allows for individual- or group-specific dieting, which minimizes competition at the point of feeding as well as under- or overfeeding risk (de Haas, Windig and Calus, 2011). In ruminants, nutrition strategies maximizing rumen health are particularly critical given that acidosis and bloat remain ongoing welfare concerns (Plaizier, Mesgaran and Derakhshani, 2018). In monogastric, nutrition management is irrevocably intertwined with welfare, as it impacts at once physiological stability and affective states linked to feeding satisfaction. Minimizing stereotypies and enhancing behavioral welfare is linked to feeding regimes such as foraging possibilities and fibrous elements (Mens, van Krimpen and Kwakkel, 2020).

2.4.3 Breeding and Genetics

Historically, productivity characteristics such as growth rate and feed efficiency dominated breeding plans at the expense of welfare-type characteristics. This single-minded focus has occasionally been at the expense of welfare problems such as lameness, metabolic disturbance, and immune impairment in highly selected lines (Rauw *et al*., 1998). Subsequent breeding philosophies place more importance on robustness and resilience in breeding goals, with attributes such as disease resistance, longevity, adaptability, and docility prioritized at the top (Bishop *et al*., 2010). Genomic selection is now a possibility for more precise determination of welfare-related traits using the inclusion of resilience within genetics-based breeding programs (Knol, Nielsen and Knap, 2016). Of interest in this context is the

addition of welfare traits to breeding schemes as an active strategy, preventing the need for remedial management under production later in life and aiding sustainability by restraining morbidity and mortality.

2.4.4 Handling and Stockmanship

Handling and human–animal interaction practices are pivotal in welfare formation. Poorly trained handlers or careless handling practice result in injury, stress, and fear responses that interfere with development and reproduction (Grandin, 2014a). On the other hand, low-stress handling practices with gentle movement, quietness, and reinforcement decrease fear and aggression and enhance compliance with management procedures (Hemsworth and Coleman, 2011). There is also some indication that habituated animals are easier to manage, reduce stress during procedures, and are even more effective in the long term (Rault *et al*., 2020). Attitudes and empathy of stockpeople toward animals are also important with connotations for the necessity of training programs which reconcile technical competence with welfare sensitivity (Wathes, Becker and Buggiotti, 2021). Thus, stockmanship is a moral process and also an instrumental technique with immediate welfare consequences.

2.4.5 Health and Disease Management

Disease and trauma rank among the most significant welfare concerns in farm animal production. Prevention is achieved through preventive medicine management, for example, control of parasites, vaccination schemes, and good biosecurity with restriction of introduction and transmission of disease agents (Gleeson *et al*., 2007). When disease or trauma does occur, early diagnosis and successful treatment, including pain control, should be provided to alleviate suffering (Mota-Rojas *et al*., 2021). Current research places a big emphasis on ethical imperative of including analgesia and anesthesia protocols in routine husbandry practices such as dehorning or castration, once done in nonalleviating way (Stock, 2015). Second, veterinary practice prevents welfare and production goals getting distorted, providing scientific advice on herd health approaches optimizing resilience with lowered antimicrobial application by preventive measures (EMA and EFSA, 2017).

2.4.6 Integrated Outcomes of Livestock Management

Collectively, these approaches to livestock handling illustrate how productivity and welfare are complementary. Housing and enrichment provide comfort and permit natural behavior and reduce morbidity due to stress. Nutrition control permits healthy growth and reproduction and prevents metabolic disease. Breeding for hardness reduces morbidity and improves adaptability. Stock handling and expert stockmanship reduce fear and aggression and promote safer, more peaceful animal conduct. Then, veterinary preventative health care decreases the incidence of illness and promotes speedy recovery if illness or injury does happen. In addition to improving production efficiency and use of resources and consumer confidence, all these management techniques together produce quantifiable welfare returns.

2.5 Transport and Slaughter: Critical Welfare Points

Transportation and slaughter are two of the most vulnerable junctures in the life history of intensively kept animals with major consequences for animal welfare and meat quality. Compared to housing conditions where the animals become accustomed to static positions, transport, lairage, loading, and slaughter subject them to a range of stressors cumulatively. These are physical stresses, including overcrowding and trauma; physiological loads, including heat stress and fatigue; and psychological loads, including fear, novelty, and loss of social stability (Terlouw, Picard and Deiss, 2021). Such stressors not only undermine moral principles but also economic efficiency by having negative effects on carcass quality, meat pH, and consumer acceptability (Broom and Fraser, 2015; Faucitano, Juliana and Lambooij, 2024) unless well managed (Figure 2.3).

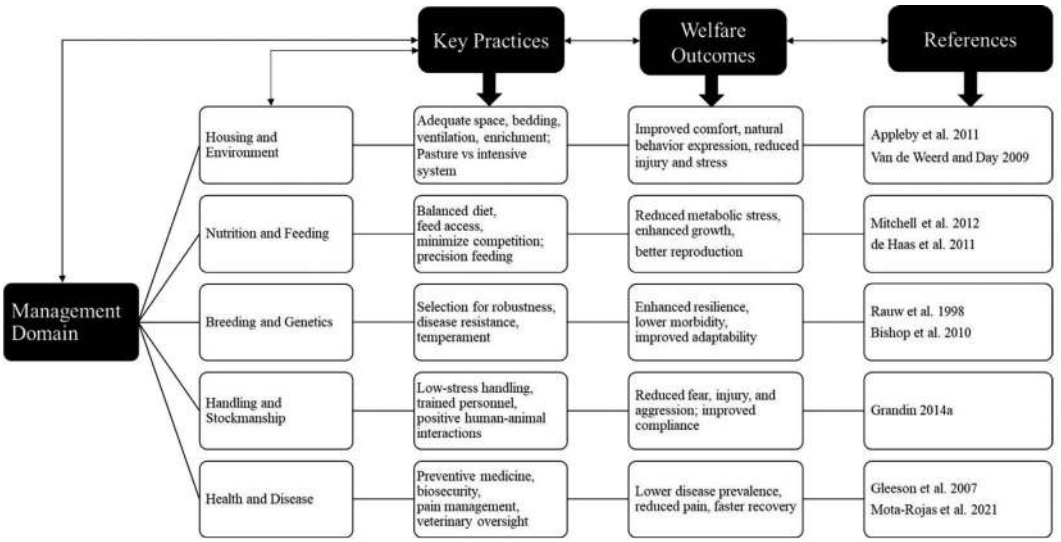

FIGURE 2.3 Key livestock management strategies and welfare outcomes.

2.5.1 Transport: Stress and Injury Risks

Welfare problems during transportation are primarily linked to handling at loading and unloading, vehicle design, stocking density, journey duration, and thermal environment. Loading and unloading both are categorized as extremely stressful procedures as they involve forced movement and close contact with humans. Steep gradients, inadequately designed ramps, slippery flooring, or rough handling practices can significantly contribute to fear and risk of injury in the form of bruising or fracture (Cockram, 2007; Schwartzkopf-Genswein *et al.*, 2012). Proper ramp gradients, non-slip flooring, and use of low-stress handling techniques by trained personnel are important mitigation strategies (Grandin, 2014a). Rest periods and transportation durations are also quite important. Fatigue, dehydration, and illness susceptibility are increased by prolonged transportation with little opportunity for feed, water, or rest (European Food Safety Authority [EFSA], 2011). In an effort to lessen suffering, Council Regulation (EC) No. 1/2005 sets duration limitations for travel and incorporates pauses. Similar guidelines are offered globally by the World Organization for Animal Health (OIE, 2021), which states that animals should be evaluated for transport suitability prior to being transported. Thermal stress is a major risk, particularly with climate change causing more extreme weather conditions (Tatemoto *et al.*, 2020). Overheating when it is hot or chilling when it is cold can lead to extreme welfare issues and even mortality during transport. Ventilation control, vehicle insulation, and constant observation of the climate need to be implemented in order to avert these risks. Emerging technologies like microclimate control systems and sensors mounted on board are being progressively applied in monitoring and controlling the environment (Li, Du and Long, 2019). Bruising, trampling, and transport stress are the consequences of overcrowding and inadequate vehicle design. The provision of adequate space allowances, nonslip floors, and bedding has the impact of reducing injury as well as improving welfare outcomes (Grandin, 2014a).

2.5.2 Slaughter: Stunning, Handling, and Facility Design

The slaughter stage is no less significant, and animals need to be made insensitive to pain before exsanguination. Choice and use of stunning methods—mechanical (captive bolt), electrical, or gas—are the focus points of preventing pain and distress. Ineffective stunning not only causes suffering, but also compromises compliance with animal welfare law (Terlouw, Porcher and Fernandez, 2005). Staff training, equipment calibration, and strict supervision are required to guarantee humane outcome from stunning (Grandin, 2015). Much more than an expertly displayed topic, plant layout affects welfare directly. Lairage space, when poorly managed, can be hotspots of aggression, overload, or prolonged stress before

slaughter. Ideal lairage treatment would involve minimized waiting times, ventilation, watering, and noise reduction (Terlouw, Arnould and Auperin, 2008). Curved chute, nonslip treatment of the floor surface, adequate lighting, and noise control systems enhance smooth animal movement and facilitate less fear (Grandin, 2010). But another crucial safety protocol is to examine operational and compliance procedures. Automatic monitoring of welfare, regular audits, and closed-circuit television (CCTV) cameras ensure accountability and transparency and incremental improvement in slaughter procedures (Velarde and Dalmau, 2018). Training employees is the answer too; seasoned handlers are far superior to new staff in reducing stress and unease in animals (Hemsworth *et al*., 2015).

2.5.3 Meat Quality and Consumer Confidence

Animal stress at transportation and slaughter has a direct impact on meat quality. High stress will lower glycogen content, leading to disease states such as dark, firm, and dry (DFD) beef or pale, soft, and exudative (PSE) pork (Faucitano, Juliana and Lambooij, 2024). Welfare-friendly practices thus do not only meet ethical demands but also serve the industry goals of product quality and consumer satisfaction. There has been increased public demand for transparency and traceability in meat production, and welfare guarantee has therefore become the basis of market access, especially in the EU and high-value export markets (Miele *et al*., 2011).

2.5.4 Critical Welfare Points and Mitigation Strategies

A brief overview of welfare issues, causes, and solutions for transport and slaughter is contained in Table 2.3. The table outlines the key stressors—for example, loading and unloading issues, heat issues, transport fatigue, and poor stunning—and demonstrates that they can be effectively countered by the implementation of evidence-based management practices such as improved facility design, technology, and trained personnel. Transport and slaughter are key stages in the production chain of animals where welfare may be most compromised. Best practices in the form of improved facility design, handler training, humane stunning practices, and technological innovation are essential for stress and suffering minimization. Contrary to popular belief, welfare management at these phases builds customer trust in the

TABLE 2.3

Critical Welfare Points, Challenges, and Mitigation Strategies during Transport and Slaughter

Stage	Welfare Challenge	Causes/Risk Factors	Mitigation Strategies	References
Transport	Loading/unloading stress	Poor ramp design, rough handling	Low-stress handling, well-designed ramps, handler training	Cockram, 2007; Grandin, 2014a
	Journey duration fatigue	Long transport times, inadequate rest	Limit journey duration, provide rest, water, and feed	EFSA, 2011; OIE, 2021
	Thermal stress	Extreme heat or cold, poor ventilation	Ventilation control, climate monitoring, microclimate adjustments	Cockram, 2007; EFSA, 2011; Tatemoto *et al*., 2020
	Injuries	Overcrowding, vehicle design, slippery floors	Adequate space allowance, nonslip flooring, proper bedding	Grandin, 2014a; Schwartzkopf-Genswein *et al*., 2012
Slaughter	Pain and fear	Ineffective stunning, rough handling	Proper stunning method selection, trained personnel	Grandin, 2010; Terlouw *et al*., 2005;
	Stress-induced meat quality defects	Handling stress, delays before stunning	Stress minimization, lairage design, monitoring systems	Terlouw *et al*., 2008; Faucitano *et al*., 2024
	Operational compliance	Inadequate training, lack of monitoring	Personnel training, CCTV, automated welfare monitoring	Grandin, 2010; Velarde and Dalmau, 2018

livestock industry and improves the quality of meat. By following international welfare standards such as Council Regulation (EC) No. 1/2005 and OIE principles, producers can increase production, uphold their social license to participate in a free global market, and meet their moral commitments.

2.6 Animal Welfare, Meat Quality, and Consumer Perception

Meat quality and animal well-being have been the primary objectives of livestock research since conditions pertaining to animal welfare directly affect the biochemical and physiological processes of the animals prior to their death. The metabolism of muscle is impacted by stressors like acute and chronic stress, which results in identifiable meat quality faults that impact the product's commercial value and customer acceptance in addition to its sensory qualities. One of the most straightforward effects of welfare compromise is that of acute preslaughter stress. Preslaughter stresses that occur with handling, loading, transport, and lairage cause animal stress leading to the rundown of muscle glycogen stores. The rundown disrupts normal postmortem glycolysis to create an abnormal pH decline in muscle tissue. This is frequent in pigs and poultry as PSE meat, whereas in beef it can lead to DFD meat (Warriss, 2010). Both defects adversely influence tenderness, juiciness, water-holding capacity, and shelf life, and lead to rejection at higher rates at food service and retail levels (Grandin, 2014a; Terlouw, Arnould and Auperin, 2008). Follow-up studies show the way of modern-day consumers, being more focused on freshness and appearance, are particularly vulnerable to such defects, extending economic risk beyond producers (Miranda-de la Lama *et al.*, 2019).

In addition to acute stress, meat quality is also impacted by chronic stressors brought on by inadequate housing, poor nutrition, overpopulation, or long-term unfavorable environmental conditions. Long-term stress alters the composition of muscle fibers, decreases intramuscular fat formation, and damages marbling, which lowers the acceptability of flavor and texture (Alfaro *et al.*, 2020). These are long-term cumulative impacts that cannot be lessened during processing. Low welfare during the growth and finishing stages has long-term effects on the quality of the carcass. Additionally, ongoing stress may make the animal more susceptible to illnesses, which may have an indirect impact on food safety and carcass cleanliness (Mancini and Antonioli, 2022; Terlouw, Porcher and Fernandez, 2005). The biological quality of meat is influenced by animal welfare, which also influences the market and consumers. The growing consumer interest in production ethics necessitated consideration of openness in both animal production and humane treatment. Food that comes from animals that are free-range, organic, or welfare-certified is thought to be better, safer, and healthier (Harper and Makatouni, 2002; Napolitano, Girolami and Braghieri, 2010).Customers in both developed and developing countries have also paid more for meat that has been welfare-certified because they are sure that the animals are being treated humanely and because it gives production systems guarantees (Font-i-Furnols and Guerrero, 2014). According to surveys, young consumers place higher priority on animal welfare obligations than on other issues. Most of them link these issues to sustainability, authenticity, and ethical responsibility in the food chain (Clark *et al.*, 2017; Lagerkvist *et al.*, 2023).

On the production side, welfare-friendly practice—in the form of low-stress handling, improved housing, and well-managed transport—has been demonstrated to generate measurable improvement in both meat quality and welfare (Figure 2.4). Grandin (2014b) has proven that humane handling is lowering physiological measures of stress such as cortisol and lactate, which subsequently lowers the risk of PSE and DFD meat. Similarly, institutionalized welfare programs such as those applied under the Welfare Quality testing system provide standardized methods of evaluating and enhancing livestock well-being, allowing for consistent gain-making for different systems of production (Welfare Quality, 2009). Besides the technical benefits, the practices create brand image and consumer confidence and allow producers to achieve market differentiation and sustainable competitiveness. Last but not least, there are two significant impacts of animal welfare: first, through physiological pathways that directly affect meat quality attributes, including softness, flavor, and shelf life; second, through consumer-oriented attitudes that are increasingly defining market success. Incorporating welfare standards into the production of meat guarantees not only humane treatment of the animals but also increased customer trust, product value, and satisfaction of the desire for sustainable and ethical food chains in society.

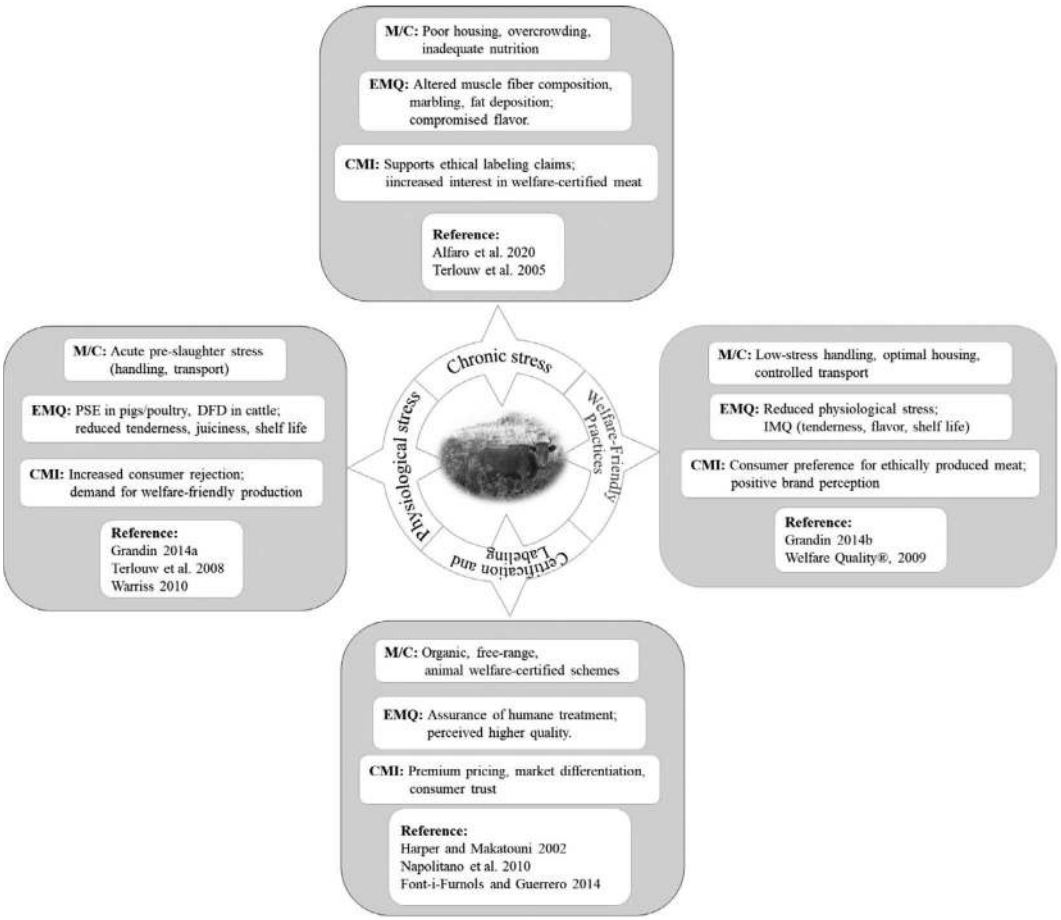

FIGURE 2.4 Impact of animal welfare on meat quality and consumer perception.

2.7 Global Challenges and Future Directions

Despite significant progress in the study, assessment, and regulation of animal welfare, there are still significant global disparities in the implementation, enforcement, and working adoption of welfare standards. These results in varying animal welfare results globally and are influenced by regional economic situations, societal attitudes, regulatory settings, and the availability of provisions. Regional inequalities remain one of the most graphic issues. The developed world such as the European Union, North America, and Oceania is fortunate to have the strength of robust welfare legislation, comprehensive enforcement regimes, and highly skilled consumption markets that actively encourage production methods. The EU, for instance, has enacted in great depth right throughout the welfare of animals in terms of rearing, transportation, and slaughter, often exceeding minimum ones set by the OIE (European Commission, 2020b). However, the majority of developing nations are faced with challenges of poor legal frameworks, weak capacity for enforcement, customary practices that may be in conflict with new welfare concepts, and inadequate resources hindering improvement in infrastructure (FAO, 2020). Such uneven distribution of welfare practices may deter international trade possibilities and put animal welfare in jeopardy. Harmonization of welfare standards, guided by the counsel of OIE advice and supported by global collaboration, is thus fundamental to ensuring consistent, high-standard animal welfare in global markets (OIE, 2021; Webster, 2016). Technological innovation is more and more considered to be a key welfare improvement driver in the future. Monitoring equipment, electronic sensors, automated scoring

apparatus, and precision livestock farming apparatus allow for permanent monitoring of animal behavior, physiology, and environment (Berckmans, 2017; Wolfert *et al.*, 2017). These technologies can detect stressors, onset of disease, or departure from optimal states of welfare at an early stage to allow proactive control and intervention. In the meantime, however, genomic selection and breeding strategies targeting resilience traits such as resistance to disease, temperament, and environmental stress tolerance present long-term solutions for OHV livestock production at high welfare and productivity levels (Bishop *et al.*, 2010). Technology linked with genetic selection consequently represents a paradigm shift from reactive welfare management toward proactive, resilience-based solutions.

Policy, education, and stakeholder engagement is the second significant welfare development area. Farmers' communities, vets, and industry leaders are pioneering welfare development within the farm, with consumers leading the way on market incentives through purchasing certified welfare-aware products. Policymakers can augment these initiatives with regulation, training programs, and economic incentives enabling compliance. Education and training initiatives, including stockperson and welfare auditor training initiatives, are important in empowering the stakeholders with the necessary knowledge and skills to respond to welfare effectively (Grandin, 2014b; Napolitano, Girolami and Braghieri, 2010). Familiarity with all partners in the supply chain over a period of time provides improvements in welfare to be effective, culturally acceptable, and economically beneficial.

Trade and harmonization issues add a further layer of international welfare governance concerns. Divergence of welfare levels is protectionism, which distorts world trade, and creates uncertainty among importers and exporters. Globalization of welfare standards, auditing process, and verification systems eliminate these uncertainties through the supply of uniformly acceptable clear standards of humane treatment (European Commission, 2020a, 2020b; OIE, 2021). Global standards also provide confidence to consumers worldwide by showing that practices which encourage welfare are not localized but an integral part of the global food system.

Overall, four interrelated elements impact the global agenda for animal welfare: trade harmonization, policy and education, technological change, and regional variations (Table 2.4). A multi-stakeholder strategy that incorporates consumer input, regulatory harmonization, capacity-building, and scientific advancement is required to address each of these concerns. Chances for the future are ongoing to advance with digital tracking and resilience breeding, increasing international cooperation, and improving education and certification programs so that welfare enhancement is commercially desirable and acceptable. Global livestock sectors may improve well-being while maintaining sustainability, productivity, and social license to operate if they work together.

TABLE 2.4

Global Challenges, Innovations, and Stakeholder Roles in Animal Welfare

Category	Challenges/Gaps	Innovations/Solutions	Stakeholder Roles	References
Regional disparities	Limited enforcement, cultural differences, resource constraints in developing nations	Adoption of OIE guidelines, harmonized protocols	Policymakers, industry, international organizations	FAO, 2020; OIE, 2021; Webster, 2016
Technological innovations	Need for real-time welfare monitoring	Digital sensors, automated scoring, precision livestock farming, genomic selection	Farmers, veterinarians, technology providers	Berckmans, 2017; Wolfert *et al.*, 2017; Bishop *et al.*, 2010
Policy and education	Knowledge gaps among producers, inconsistent training, market incentives	Welfare certification, training programs, consumer education	Policymakers, educators, farmers, consumers	Grandin, 2014b; Napolitano *et al.*, 2010
Trade and harmonization	Export/import compliance barriers	International welfare standards, audit and verification systems	Governments, exporters, importers	European Commission, 2020a, 2020b; OIE, 2021

2.8 Conclusions

It is now well acknowledged that the foundation of ethical, ecological, and productive livestock production is the fundamental idea of animal welfare. Contemporary ideas go far beyond avoidance of pain to recognition of positive states like expression, comfort, and well-being. Systemic methods of evaluation and management of well-being combining biological, behavior, and psychological factors are offered by frameworks like the Five Freedoms and the Five Domains. In addition to empirical quantification of physiological stress, behavior, and performance output, the models permit evidence-based welfare evaluation to ensure ethical treatment as well as maximum productivity. The best well-being is mostly dependent on efficient livestock management techniques, which include precise feeding, resilient breeding, competent handling, proactive disease treatment, and environmental and housing design. Every area is directly related to measurable performance, including meat quality, growth, reproduction, and immunological function. Welfare at critical points such as transport and slaughter requires careful attention to minimize stress, injury, and fear, with compliance and ongoing improvement aided by international standards and advanced monitoring technology. Moreover, animal welfare has a direct connection with meat quality and consumer attitude. While welfare certification promotes market distinction and customer trust, preslaughter stress reduction and improved living circumstances also boost tenderness, taste, and shelf life. Global difficulties still exist despite progress, especially where there are weak regulatory frameworks, cultural issues, and limited resources. Bridging such gaps call for technology advancements like automated monitoring, accuracy animal husbandry, and resistance breeding, coupled with stakeholder participation, policy harmonization, and capacity-building. Its increased applicability to environmental stewardship, food safety, and social license to operate is reaffirmed through integration in sustainability agendas. In conclusion, best animal welfare is a moral requirement and a spur to efficient, healthy, and sustainable beef cattle production systems. The future will witness sustained take-up of world standards, application of technology developments, and collaboration among all industries to make sure that welfare is ever consistently attained, monitored, and savored at all steps of beef production. By doing this, the beef sector can satisfy demands from society, enhance animal welfare, and offer quality, ethically sourced food simultaneously.

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3

Stress and Its Impact on Animal Health and Meat Quality

Fizza Jafar, Fizza Saleem, Fatima Irfan, and Bariqa Asif

3.1 Introduction

Livestock is exposed to a variety of environmental and physical stressors as a result of modern livestock production practices. Animal stressors include housing, handling, transport, and environmental extremes. All stressors act on neuroendocrine pathways (like hypothalamic–pituitary–adrenal [HPA] axis) to maintain homeostasis. However, excessive stress leads to reduction of immunity, growth, and overall health (Kumar *et al*., 2023; Mohan *et al*., 2025; Tatar, 2024). Prolonged exposure to stress, that is, extended transport time and extended storage at the collection facility, increases physiological indicators of stress (cortisol, lactate, and oxidative stress markers) before slaughter (Huanca-Marca *et al*., 2025; Wang *et al*., 2025). Heat stress also compounds these stress responses, resulting in a state of oxidative imbalance, mitochondrial dysfunction, and disturbances in hormone balance, which ultimately leads to decreased productivity and muscle integrity in livestock (Adegbeye *et al*., 2025; Bejaoui *et al*., 2023). Chronic exposure to suboptimal husbandry conditions increased levels of fatigue and inflammation, which negatively impacts the welfare and performance of the animal (Wang *et al*., 2025).

Animal welfare is recognized increasingly not only as an ethical issue but also as a factor that affects productivity and meat quality. Stress placed on animal affects biochemical makeup through changes to gut microbiota and will have long-term impact on how they recover from these stresses and demonstrates that animal welfare's impact goes beyond just the immediate physiology of animal (Lambooij, 2024; Roudbari *et al*., 2025). Interventions like giving antioxidant supplements and environmental enrichment, precision logistics, and better animal-handling protocols have been shown to reduce oxidative and heat stress in animals, improve their resilience, and provide consistent productive performance (Adegbeye *et al*., 2025; Lambooij, 2024). Therefore, management practices developed with focus on welfare are essential for both the alignment of ethical concerns with production efficiencies and consistency expected by consumers (Roudbari *et al*., 2025).

Stress before slaughter causes changes in muscle glycogen levels and can alter pH after animal died, as well as cause oxidative damage, which results in pale, soft, watery, or dark, firm, dry meat products (Kumar *et al*., 2024; Mohan *et al*., 2025; Wang *et al*., 2025). Studies at molecular level show change in stress-sensitive genes expression, as well as how proteins change and how oxidative processes occur, creating direct link between stress exposure and various meat characteristics, for example, tenderness, water-holding capacity (WHC), color and flavor of the meat (Bejaoui *et al*., 2023 Prates, 2025a, 2025b). By understanding these mechanisms, producers can better predict outcome of carcasses based on management and environmental conditions before slaughter and how carcass will appear in marketplace (for instance, through measurement of its quality characteristics) (Bejaoui *et al*., 2023; Kumar *et al*., 2024).

This work is novel due to its use of multidimensional framework that incorporates behavioral, biochemical, and molecular biomarkers along with management practices and consumer-focused outcomes into one comprehensive view, thus creating an unambiguous, direct relationship between mechanistic stress response(s) and practical management interventions. Rather than focusing on welfare, physiology,

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or meat quality aspects of livestock independently, this chapter expresses more complete view of stress response, allowing for development of mechanistic-to-practical basis for both scientific advances and improved sustainability for livestock production.

3.2 Types of Stress in Livestock

Stress in livestock is a very major concern in animal production systems as it directly affects animal welfare, health, productivity, and meat quality. Stress responses are activated when animals are unable to cope with physical, environmental, or psychological challenges. It is based on duration and cause. Stress in livestock can be broadly categorized into long-term preslaughter stress, short-term acute stress, environmental stressors, and psychological or social stress.

3.2.1 Long-Term Preslaughter Stress

Long-term preslaughter stress is a form of chronic stress which is experienced by animals and is over an extended period before slaughter. It commonly arises from prolonged transportation, long waiting times at lairage, feed and water deprivation, overcrowding, poor housing conditions, and repeated handling (Lawrie and Ledward, 2006; Warriss, 2010). These stressors lead to sustained activation of the hypothalamic–pituitary–adrenal axis, resulting in elevated cortisol levels over time. Chronic stress causes depletion of muscle glycogen reserves, which are essential for normal postmortem glycolysis. When glycogen levels are insufficient, lactic acid production after slaughter is reduced, leading to a higher ultimate pH of meat. This condition is associated with dark, firm, and dry (DFD) meat, particularly in cattle and sheep (Gregory and Grandin, 2007). In addition to meat quality defects, long-term stress weakens the immune system which increases susceptibility to infections, reduces growth performance, and negatively impacts reproductive efficiency (Moberg, 2000). Proper management practices, including adequate rest periods, humane transport, and good nutrition, are essential to minimize long-term preslaughter stress.

3.2.2 Short-Term Acute Stress

Short-term acute stress occurs immediately before slaughter and is caused by sudden or intense stressors. These include rough handling, use of electric prods, sudden loud noises, unfamiliar surroundings, and mixing with unknown animals during loading, unloading, or stunning (Grandin, 2014). Acute stress triggers a rapid physiological response characterized by the release of catecholamines such as adrenaline and noradrenaline, along with cortisol. This hormonal surge accelerates muscle metabolism and leads to a rapid decline in muscle pH after slaughter (Ferguson and Warner, 2008). In species such as pigs and poultry, acute preslaughter stress is strongly associated with pale, soft, and exudative (PSE) meat. PSE meat has poor WHC, undesirable texture, and reduced consumer acceptability (Offer, 1991). Implementing calm handling techniques, proper stunning methods, and trained personnel can significantly reduce acute stress responses.

3.2.3 Environmental Stressors: Temperature, Noise, and Handling

Environmental stressors are external physical factors that challenge the animal's ability to maintain physiological balance. Temperature extremes and heat stress are among the most significant environmental stressors affecting livestock (West, 2003). Heat stress leads to increased respiration rate, sweating or panting, reduced feed intake, dehydration, and altered metabolism. Prolonged exposure to high temperatures reduces growth rate, milk yield, fertility, and immune function (Renaudeau *et al*., 2012). Cold stress, although less common in intensive systems, also increases energy requirements and compromises animal health. Noise from machinery, transport vehicles, and slaughter facilities can elevate fear responses and stress hormone levels. Similarly, poor handling practices such as hitting, shouting, or overcrowding increase physical injury and psychological distress (Hemsworth and Coleman, 2010).

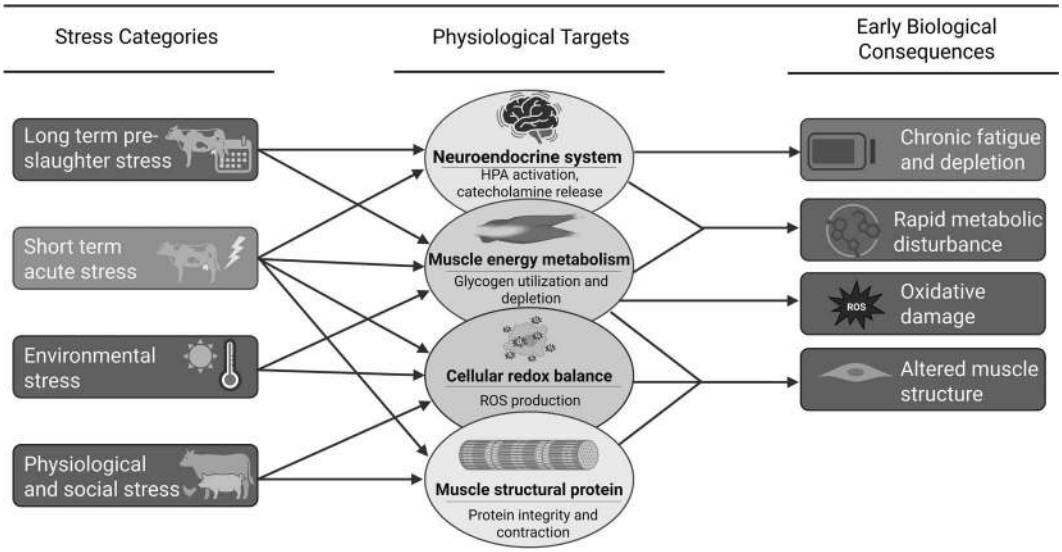

FIGURE 3.1 Classification of stress in livestock and its primary biological targets.

Environmental stress can be minimized through proper housing design, ventilation, temperature control, noise reduction, and adoption of low-stress animal-handling techniques. Figure 3.1 provides classification of stress in livestock and its primary biological targets.

3.2.4 Psychological Stress and Social Hierarchies

Psychological stress in livestock is closely associated with social interactions and hierarchical structures within animal groups. Many farm animals, including cattle, pigs, and poultry, establish social hierarchies that regulate access to feed, water, and resting areas (Fraser, 2008). Mixing animals from different social groups disrupts established hierarchies and leads to aggression, fighting, and competition. This results in injuries, increased fear, and elevated stress hormone levels, particularly in subordinate animals (Turner, 2011). Subordinate animals often experience chronic psychological stress due to repeated social defeat and restricted access to resources. This negatively affects growth performance, feed efficiency, and immune competence (Estevez, 2007). Maintaining stable social groups, providing adequate space, and minimizing regrouping are effective strategies to reduce psychological stress. Table 3.1 provides classification of preslaughter stressors in livestock and their primary biological effects.

3.3 Physiological Responses to Stress

Stressful environments cause physiological responses in animals through a variety of interconnected systems, including neuroendocrine, metabolic, cardiovascular, immune, and cellular systems. The stress response is initiated when an animal's homeostasis is disrupted by environmental, psychological, and physical stressors (Brown and Vosloo, 2017). The purpose of these responses during evolution was to ensure the animal's survival by creating a mechanism whereby energy resources are mobilized to meet the immediate physiological needs of the animal while providing for the maintenance of the animal's essential physiological processes at the expense of the animal's growth, immune system, and maintenance of their tissues (Prates, 2025a, 2025b).

When an animal senses danger, whether from being handled, moved, experiencing a new heat source, feeling social withdrawal, or being taken into another environment, a response is activated within the central nervous system which then sends a signal through both the autonomic nervous system and the hypothalamic–pituitary adrenal axis. The sympathetic–adrenomedullary (SAM) activation causes

TABLE 3.1

Classification of Preslaughter Stressors in Livestock and Their Primary Biological Effects

Type of Stress	Common Sources (Examples)	Duration	Primary Physiological Systems Affected	Typical Livestock Species	References
Transportation duration stress	Short (<3.5 h), medium (3.5–5 h), long (>5 h) transport times	Acute to subacute	Elevated cortisol (ng/mL), lactate, glucose changes HPA axis	Pigs	Huanca-Marca *et al.*, 2025
Handling and human interaction stress	Rough handling, untrained handlers, prodding, physical restraint	Acute	Elevated heart rate, blood glucose, catecholamines Sympathetic activation	Goats, cattle, pigs	Kumar *et al.*, 2024
Heat stress (environmental)	High ambient temperature (>27 °C in pigs), insufficient cooling	Chronic to acute	Increased corticosterone/ cortisol, oxidative stress, immune suppression Altered metabolism	Pigs, poultry, cattle	Prates, 2025
Lairage and holding stress	Long waits, overcrowding in holding pens	Subacute	Hyperglycemia (~6.9 mmol/L), high cortisol (>74.7–108.8 ng/mL), pH changes	Beef cattle	Carrasco-García *et al.*, 2020
Fasting/feed deprivation	Preslaughter fasting periods	Subacute to chronic	Glycogen depletion → altered pH Energy metabolism shifts	Pigs, cattle	Arsenoaia and Mălăncuş, 2023
Mixing/novel social stress	Mixing unfamiliar animals during transport/lairage	Acute	Elevated cortisol and behavioral agitation HPA axis activation	Cattle, pigs	Terlouw and Bourguet, 2022
Noise and environmental novelty	Loud abattoir noises, unfamiliar structures	Acute	Stress-related sympathetic response Potential increases in lactate	All livestock	Grandin, 2014
Overcrowding/ space restriction	High stocking density in trailers/ lairage	Subacute	Increased physiological stress markers, mobility issues, bruising	Beef cattle	Sullivan *et al.*, 2024
Bruising and physical injury stress	Rough loading, slips/falls	Acute	Inflammatory response, altered glucose metabolism	Beef cattle	Carrasco-García *et al.*, 2020
Preslaughter acute stress events	Electric prodding, excitement	Acute	Rapid lactic acid accumulation, low muscle pH, altered meat quality	Cattle, pigs	Xing *et al.*, 2019

catecholamines (epinephrine and norepinephrine) to be secreted leading to an immediate response called fight-or-flight response; this in turn results in dramatic increases in heart and respiratory rate, blood pressure, and plasma glucose levels within a few minutes after the stressor began. Examples have been documented in chickens and other species concerning how the release of catecholamine has resulted in increased respiratory and heart rates to facilitate glucose mobilization and improve oxygenation and heat loss, and also through stimulating the breakdown of glycogen into glucose to supply immediate energy requirements. This same endocrine/neuroendocrine activation has been documented in all animal species under acute stressors, such as transport and handling before/after slaughtering (Kumar *et al.*, 2024).

In response to stressors along the hypothalamic–pituitary–adrenal axis, animals release many hormones, including adrenocorticotropic hormone (ACTH), corticotropin-releasing hormone (CRH), and ultimately glucocorticoids. In ruminants, the final product of stressors activated through the HPA axis is cortisol; whereas in poultry and rodents it is corticosterone (Niu *et al*., 2022). When an animal is exposed to a stressful situation, cortisol levels increase dramatically over a short time span (in tens of minutes) following the onset of stress and these elevated cortisol levels can remain elevated for hours or even days if the animal remains under chronic stress (Botía *et al*., 2023). Glucocorticoids also act to stimulate gluconeogenesis (to create glucose from fats/proteins), lipolysis (the breakdown of fat), and protein catabolism (the breakdown of protein for fuel) in order to provide energy substrates for the metabolism of animals. However, glucocorticoids will suppress the function of the immune system, decrease feed intake, and inhibit reproductive endocrinology. Chronic elevations of cortisol or corticosterone have been shown to disrupt lymphocyte proliferation and antibody production, thereby decreasing the overall level of both innate and adaptive immunity in an animal and increasing susceptibility to diseases (Prates, 2025a, 2025b).

Stress causes dramatic metabolic changes in animals, and in an acute stressful situation (i.e., while the animal is experiencing the stressor), catecholamines stimulate glycogenolysis in muscles and liver and thus provide glucose to the general circulation (increased blood glucose levels). As the animal continues to be under stress or continues to experience chronic stress, muscle and liver glycogen will be depleted. The animal will have high blood glucose levels and tissues that are not able to utilize glucose for energy. The increased blood glucose levels are because of the continued breakdown of glycogen and thus similar to the observed increased creatine kinase and urea nitrogen in other studies when animals have been exercising; the increased lactate is as a result of anaerobic glycolysis. Comparison of high epinephrine responders during transport for 180 minutes versus lower responders shows high epinephrine responders have much higher plasma glucose concentrations, indicating that there are significant differences in intensity and variability of metabolic response to the same stressor (Shaik *et al*., 2024).

Heat stress is an environmental stressor that can have negative physiological effects. Heat stress increases body temperature, and it elicits thermoregulation (increased respiration and peripheral vasodilation). Acutely, these are beneficial responses; however, under chronic heat stress, they can lead to an inability to thermoregulate suppression of the immune system and alterations in hormonal function. The level of corticosterone in broilers has been shown to be approximately 1.5–2.5 times higher when exposed to chronic heat stress than under thermoneutral conditions, indicating a significant disruption in adrenal function. By sustaining elevated levels of glucocorticoids, protein synthesis and muscle growth are hampered, nutrients are allocated for maintenance rather than for growth, and there is reduced energy efficiency (Prates, 2025a, 2025b).

Oxidative stress, a result of cellular stress, occurs through the uncontrolled generation of reactive oxygen species (Kanner, Shpaizer and Tirosh, 2025). These species are toxic and can harm lipids, proteins, and DNA in the cell, thereby impacting its vitality. Cattle raised in intensive production systems are subjected to high levels of oxidative stress, which may lead to upregulation of the proapoptotic genes BAX and caspase-3. This indicates the presence of apoptotic signals in the muscle prior to slaughter. The oxidative stress-mediated damage caused to both myofibrillar protein and lipid results in tougher meat and decreased water-holding capability (Tatar, 2024).

Both HSPs and APPs respond to the environmental stresses that occur in our bodies. HSPs are produced by our cells when they are subjected to a multitude of different forms of environmental stress, and HSPs work with the cell to fold, protect, and prevent the denaturation of proteins produced by that cell. While HSPs perform vital functions, their overproduction (overexpression) can also be an indicator of a distressed cell and eventually result in a change in muscle function and thereby affecting the quality of the meat produced. In general, APPs are produced in the liver, and they increase in the blood as a direct consequence of systemic stress, demonstrating that an individual has experienced an inflammatory event or disruption both psychologically and physiologically (Yaghoobpour, Sheikhi and Nazifi, 2025).

Stress physiology has a close connection with the immune system. The release of glucocorticoids that occurs during times of stress inhibits important functions within the immune system (such as the proliferation of lymphocytes and the secretion of cytokines) which causes individual's susceptibility to infection and inflammatory disease processes. Under stressful conditions, elevated levels of proinflammatory

cytokines (e.g., TNF-α, IL-6) and acute-phase proteins have negative effects on nutritional intake and regulation of appetite. These elevated levels further compromise growth performance and overall health (Gouvêa, Cooke and Marques, 2022).

The way an animal's body works affects the quality of its meat. In particular, how fast and to what extent the animal will produce "glycogen" in the muscle tissue after slaughter is influenced by how much glycogen is available in the animal's muscle tissue prior to slaughter. When the animal experiences acute stress, the muscle tissue will experience a sharp drop in its pH level while still warm, resulting in PSE meat that is very soft and has low WHC. In contrast, chronic stress causes a depletion of glycogen stores resulting in the production of DFD meat that has a higher final pH and poorer eating quality compared to PSE. Both increased stress hormones (cortisol and catecholamines) have been statistically correlated with increased final pH levels, more primary drip loss, and a change in color parameters for the meat produced from beef cattle (Xing *et al.*, 2019). Table 3.2 describes the physiological and biochemical responses to stress in muscle preslaughter and post-slaughter.

TABLE 3.2

Physiological and Biochemical Responses to Stress in Muscle Preslaughter and Post-Slaughter

Stress Response	Key Mediators (Hormones / Enzymes / Metabolites)	Muscle-Level Changes	Timing (Pre- or Postmortem)	Relevance to Meat Quality	References
Catecholamine release (e.g., adrenaline/ epinephrine)	↑ Adrenaline / noradrenaline	↑ Glycogenolysis ↑ muscle metabolic rate	Preslaughter	Depletes glycogen → may alter pH decline Linked to DFD/ PSE risk	Terlouw *et al.*, 2021
Glucocorticoid (cortisol) elevation	↑ Cortisol	Systemic mobilization of energy reserves Protein breakdown	Preslaughter	Correlated with altered postmortem pH and drip loss potential	Maghfiroh, Latif and Santoso, 2014
Muscle glycogen depletion	↓ Glycogen reserves	Reduced substrate for anaerobic glycolysis	Preslaughter → early postmortem	High ultimate pH (≥6) → dark, firm, dry (DFD) meat	Carrasco-García *et al.*, 2020
Anaerobic glycolysis acceleration	↑ Lactate accumulation	Rapid pH decline in early postmortem muscle	Immediate postmortem	Low pH in warm muscle → PSE meat traits (pale, soft, exudative)	Terlouw *et al.*, 2021
Muscle pH decline	Lactate, H^+ ions	Acidification from ~7.0 → 5.4–5.7 (normal)	0–24 h postmortem	Influences color, WHC, tenderness, microbial stability	Terlouw *et al.*, 2021
Heat production from stress	Increased muscle temperature	Enhanced metabolism postmortem	Immediate postmortem	Higher temperature + low pH promotes PSE	Čobanović *et al.*, 2020
Rigor mortis onset	ATP depletion, Ca^{2+} accumulation	Cross-bridge formation → muscle stiffening	0–24 h postmortem	Affects tenderness and WHC kinetics	Khatri and Huff-Lonergan, 2023
Oxidative stress markers	Reactive oxygen species, AMP-activated protein kinase	Disrupts cellular homeostasis	Early postmortem	Can affect protein oxidation and color stability	Xing *et al.*, 2019
Muscle fiber structural changes	Cytoskeletal protein modification	Sarcomere shortening Lateral shrinkage	Postmortem	Firmness, decreased WHC, increased drip loss	Ge *et al.*, 2021

Indicators of stress also include elevated heart rate and raised blood pressure (cardiovascular). Furthermore, stress will affect your muscles' metabolism after death. Increased blood lactate and increased levels of creatine kinase due to stress are indicative of muscle fatigue and are associated with a decline in meat quality indicators such as shear force and color stability (Carrasco-García *et al*., 2020). Figure 3.2 illustrates the physiological and molecular cascade of stress in skeletal muscle.

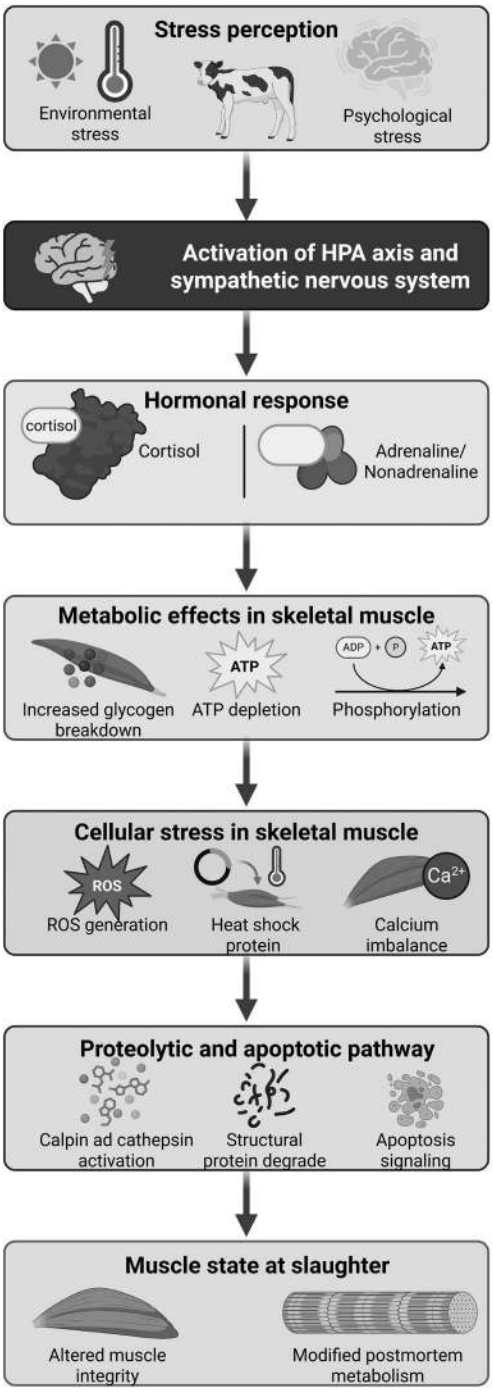

FIGURE 3.2 Physiological and molecular cascade of stress in skeletal muscle.

3.4 Impact of Stress on Meat Quality

The effects of preslaughter animal stress on the biochemical and structural processes that determine meat quality are significant, including measurable changes in pH decline, WHC, color, tenderness, flavor, and shelf life. The physiological effects of preslaughter animal stress initiate a series of physiological responses in animals, including the increase in rate of glycogenolysis in muscle tissue, which affects the transformation of the muscle after death into meat, thus affecting the quality attributes of meat products (Sullivan *et al*., 2022).

Postmortem pH decline is one of the most common ways used to assess meat's physical qualities. In normal, unstressed animals, muscle pH will decline from about 7.0 to 7.2 to its ultimate pH (pHu) of 5.4–5.7 in 18–24 hours after a normal slaughter. Glycogen is key for a healthy meat product, as it is converted anaerobically to lactic acid (Sristi *et al*., 2025). Animals that are stressed prior to slaughter have altered pH results: glycolytic activity is accelerated in response to acute stress, resulting in a faster than normal decrease in pH at the same time that the temperature of the carcass is still elevated, resulting in PSE (pale, soft, exudative) meat due to protein denaturation and poor functional capabilities; chronic or longer-standing stress causes depletion of glycogen, resulting in a DFD (dark firm, dry) product with an ultimate pH level greater than 6.0–6.5 (Sristi *et al*., 2025). Deviation from a normal pH level will create issues with technology as well as sensory quality. A pH level that is low during the early stages denature myofibrillar proteins, which will change the structural integrity and ability to retain water; a pH level that is high at the end of the process will allow for bacterial growth and reduce shelf life (Khatri and Huff-Lonergan, 2023).

Both WHC and drip loss go hand-in-hand in how they can be altered by stress. The WHC of meat measures how well meat retains the intracellular water found within it. As WHC degrades, there is a corresponding increase in both drip loss and cooking loss. Preslaughter stressors (such as handling, transportation, and exposure to elevated temperatures) affect the WHC of meat through the alteration of muscle proteins and the subsequent oxidation of muscle proteins. There was a greater difference seen between the WHC of pigs that experienced 3 hours of transport stress and that of pigs that were at rest prior to slaughter with pigs with the greatest WHC (the lowest amount of drip loss) having significantly fewer and smaller muscle fiber gaps than those pigs that experienced transport stress, which leads to protein denaturation and degradation as mechanisms for moisture loss from meat (Ma *et al*., 2024). Decreased WHC not only decreases juiciness and yield of meat products but also contribute to quality loss and ultimately consumer willingness to purchase and eat these products (Bejaoui *et al*., 2023).

Meat color differences caused by stress correlate with the pH of the meat. High pH DFD meat has a darker color and is firmer due to decreased reflection of light from the surface and a greater amount of water retained in the muscle. This contrasts with the pale/washed out feel of the PSE meat from the denaturing of proteins. In turn, there are fewer chances of the light scattering and more water on the surface of PSE meat (Sristi *et al*., 2025). Not only are there cosmetic differences between DFD and PSE, but due to the high pH of DFD meat, it is more susceptible to bacterial contamination and spoilage, thereby decreasing its shelf life. PSE's reduced WHC and increased softness limit the types of retail cuts that can be sold as "fresh" (González-Blanco *et al*., 2021).

The tenderness and texture of meat are affected by the stress that the animal has experienced. Stress alters the metabolic and structural state of a muscle, resulting in an increase in the amount of shear force needed to cut through a muscle (i.e., tough) and especially to cut through DFD meat that has reached maximum pH levels or has been heat stressed, resulting in oxidative damage to muscle proteins (Bejaoui *et al*., 2023). Conversely, there is evidence that highly stressed muscles may experience short-term increases in tenderness due to proteolytic enzyme activity. However, this increase is often associated with other negative traits in addition to tenderness (Ma *et al*., 2024). Table 3.3 provides relationship between preslaughter stress, biochemical pathways, and meat quality defects.

Finally, both the flavor profile and shelf life of fish meat are affected by stress-induced changes in their biochemistry. Muscle fat and protein are oxidized at an increased rate by stress, resulting in off-flavors and faster rancidity during storage, while the increased pH levels of DFD fish favor the multiplication of

TABLE 3.3

Relationship between Preslaughter Stress, Biochemical Pathways, and Meat Quality Defects

Stress Condition	Dominant Biochemical Pathways	Key Molecular Events	Resulting Meat Quality Defect	Quality Attributes Affected	References
Acute heat stress	Accelerated glycolysis and oxidative stress	Rapid glycogen breakdown → ↑ lactic acid, ↓ ATP ↑ ROS	PSE-like meat	Low pH (<5.6), pale color, low WHC, high drip loss	Mia, Rahman and Hashem, 2023
Chronic heat stress	Glycogen depletion and impaired energy metabolism	Long-term glycogen reduction Downregulated GYS1	DFD (dark, firm, dry) meat	High ultimate pH (>6.0), dark color, high WHC	Mia, Rahman and Hashem, 2023
Preslaughter handling stress	HPA and SAM axis activation Catecholamine signaling	↑ Cortisol/ catecholamines driving rapid metabolic shifts	PSE/DFD depending on stress timing	Altered pH profile, toughness, variable color	Xing *et al.*, 2019
Transport stress (long)	Glycogenolysis and stress hormone cascades	↑ Blood lactate Depleted muscle glycogen	DFD tendencies in beef	High pH, darker color, firmer texture	Hultgren *et al.*, 2022
Oxidative stress	ROS overproduction Antioxidant system imbalance	Lipid and protein oxidation Mitochondrial dysfunction	Increased meat oxidation and quality loss	Poor color stability, increased rancidity	Liao *et al.*, 2022
Mitochondrial dysfunction	Impaired oxidative phosphorylation	↓ ATP generation, decreased ETC complex activity	PSE-like features due to energy deficiency	Soft texture, reduced WHC	Liao *et al.*, 2022
Rapid pH decline (pre-rigor)	Enhanced glycolytic flux	Fast lactate accumulation with high muscle temperature	Protein denaturation and low WHC	Pale color, tough, dry meat	Zaboli *et al.*, 2018
Calcium signaling perturbation	Disrupted Ca^{2+} homeostasis	Altered sarcoplasmic Ca^{2+} RYR1 implications (in pigs)	Stress-linked PSE propensity	Pale color and reduced processing yield	Kudryashova and Kudryashov, 2022
Heat shock protein (HSP) response	HSP upregulation due to cellular stress	Elevated HSPs altering protein folding and stability	Texture and color inconsistencies	Variable tenderness, color instability	Briggs *et al.*, 2024
Gene expression shift	Stress-responsive pathways (MAPK, NF-κB, oxidative response)	Upregulated stress genes (e.g., FOS, SERPINE1)	Complex quality defects, including pH and tenderness issues	pH regulation, color and texture variation	Roudbari *et al.*, 2025

bacteria and decreased microbiological safety, as well as shorter shelf life (Bejaoui *et al.*, 2023). In summary, preslaughter stress negatively alters the traditional biochemical patterns of muscle-forming meat and results in measurable impairments related to pH regulation, water retention, color, tenderness, flavor, and shelf life. Therefore, to provide the best quality meat for consumers, to increase the amount of meat available (yield), and to ensure the safety of the consumers, it is necessary to reduce stress by employing better handling, transportation, and holding practices.

3.5 Biochemical and Molecular Mechanisms

A complex set of biochemistry, molecular biology, cellular homeostasis, metabolism, etc. exist that regulate the conversion from muscle to meat. This is achieved through multiple levels of signaling networks that are regulated at many levels in response to environmental inputs, including energy depletion, changes in intracellular calcium concentrations, activation of proteolytic enzymes, alteration of the structure of proteins, and the balance of oxidizing and reducing agents on the meat during processing. These systems ultimately determine muscle to meat transformation quality characteristics such as tenderness, texture, water-retention capacity, and oxidative stability.

The AMP-activated protein kinase (AMPK) pathway is a major regulator of energy metabolism during the period following the death of an animal. As a sensor of energy for cells, AMPK responds to the increased ratio of AMP to ATP that occurs when ATP levels fall after slaughter. Because AMPK activates several key enzymes involved in the glycolysis pathway, including glycogen phosphorylase and phosphofructokinase, it increases the rate of glycolysis and the resulting increase in acidity in skeletal muscle during the early hours following death. This contributes to the development of muscle tenderness and color (Liao *et al*., 2023). Rapidly changing levels of calcium in muscle cells after acute stressful events are known to activate the upstream kinase CaMKK, which then phosphorylates AMPK, leading to increased activation of AMPK and accelerated glycolysis in muscle tissue after acute stress. Therefore, stress-induced changes in calcium levels can be implicated in metabolic changes in muscle through AMPK (Long and Zierath, 2006).

Calcium signaling is essential for bridging energy sensing, the activation of proteases, and the initiation of apoptotic pathways. An increase in the intracellular concentration of Ca2+ following death occurs from membrane damage and from dysfunctional sarcoplasmic reticulum and results in the activation of calcium-dependent kinases such as CaMKK, which then phosphorylates AMPK and stimulates glycolytic metabolism (Ma *et al*., 2025). In addition to stimulating glycolytic metabolism, the increase of Ca2+ activates endogenous proteases, mainly calpains, and calcium-dependent cysteine proteases that degrade myofibrillar proteins as a function of age. The activation of μ-calpain is mediated through calcium-induced autolysis to produce mature subunits capable of degrading structural proteins such as desmin and titin, which promotes tenderness in meat. Furthermore, calpastatin, a protein that inhibits calpain, itself is subject to posttranslational modification via phosphorylation, which enhances the inhibitory effect on calpain, thereby illustrating how posttranslational modification of proteins can influence the activity of proteases and the rate of tenderness development (Bai *et al*., 2023). The activity and importance of cathepsins released from lysosomes during postmortem aging and their contribution to proteolysis occur more significantly in the late stages and may also alter the flavor precursor profile and texture of meat (Zhang *et al*., 2021).

Protein modifications occurring after death will differ from one individual to another. Depending on the method of protein cleavage and chemical alteration (e.g., phosphorylation, acetylation, *S*-nitrosylation, etc.), proteins will have their activity and function changed. Examples include changes in metabolic enzyme activity and structure (i.e., glycolytic enzymes, protein–protein interactions), which can ultimately impact glycolysis, protein breakdown, and glucose homeostasis postmortem (Ma *et al*., 2025). That said, glycolytic enzymatic activity increases glycolysis and, in turn, contributes to both increased lactic acid accumulation and a more acidic pH (Lu, Hou and Zhang, 2022). Therefore, all PTMs can affect the rate at which an enzyme processes substrate and, consequently, how an entire biochemical cascade will proceed during the period of meat quality development.

Oxidative stress and lipid peroxidation are among the key factors that affect the aging of meat due to an imbalance between oxidant and antioxidant sources after slaughter. After slaughter, there is an absence of blood circulation and thus oxygen supply to the muscle cells, causing a state of ischemia in the muscles, resulting in the production of reactive oxygen species (Kanner, Shpaizer and Tirosh, 2025) via leaks from the electron transport chains of the mitochondria or other sources of enzymes (Kanner, Shpaizer and Tirosh, 2025). ROS are also responsible for initiating lipid peroxidation in the membranes of phospholipids, resulting in the formation of lipid hydroperoxides as well as various types of secondary oxidation products (such as MDA). This lipid hydroperoxidation reduces membrane integrity, lowers

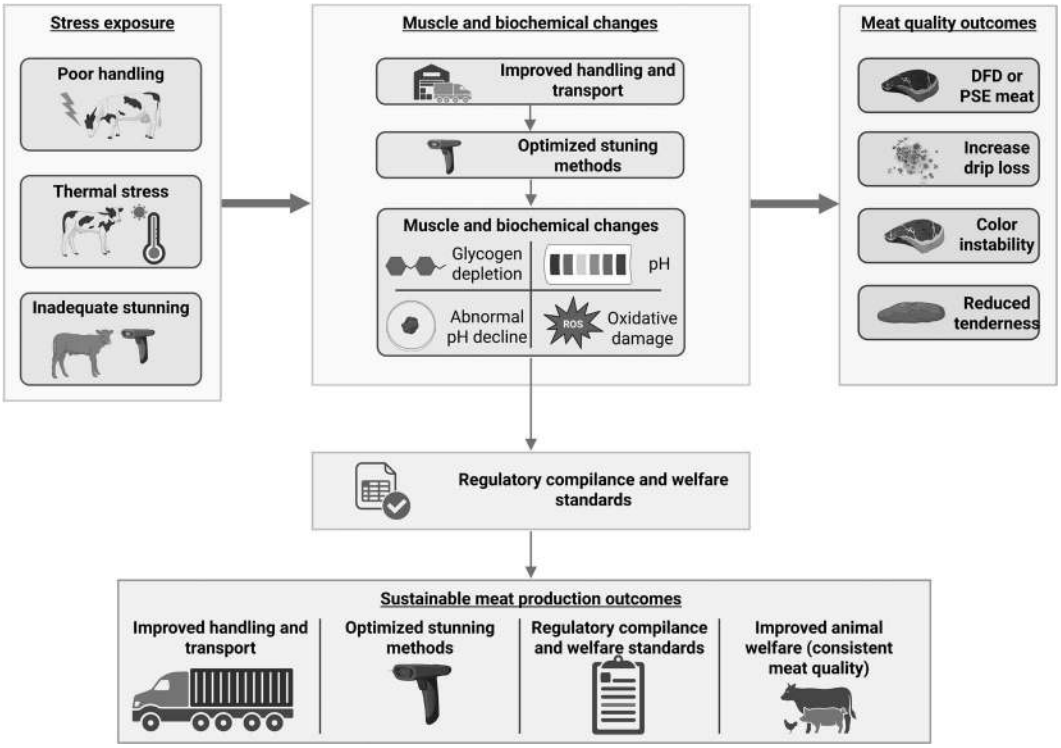

FIGURE 3.3 Stress–meat quality relationship and intervention points in sustainable meat production.

color stability, and provides substrates for formation of off-flavors in animal products (Ribeiro *et al.*, 2025). Additionally, oxidative modification can trigger a series of phosphorylation cascades, resulting in increased permeability of the mitochondrial membrane, activation of caspases and calpains, and the subsequent effects of these events on the degradation of meat proteins (Zhang, Wang and Ge, 2022). Figure 3.3 illustrates the stress–meat quality relationship and intervention points in sustainable meat production.

Preslaughter management, chill storage, and aging management can alter collectively, causing the biochemical and molecular events—energy metabolism through AMPK; calcium signaling; proteolytic pathways; modification of proteins (PTM); oxidative pathways—which take place during the transformation of muscle to meat post-mortem. Changes in any of these pathways through preslaughter management, storage, and aging can assist in improving meat quality (e.g., tenderness, WHC, color stability, flavor) while minimizing detrimental oxidative changes.

3.6 Conclusion

This chapter serves to consolidate the latest scientific studies and outlines the many ways in which preslaughter stress has distinct effects on both animal physiology and the quality of meat produced afterward. Preslaughter stressors are identified as behavioral, environmental, neuroendocrine, metabolic, and molecular through a series of transitions from behavioral and environmental stress to neuroendocrine responses, changes in metabolism, and subsequent changes in metabolism and muscle. These transitions provide a mechanistic pathway linking animal welfare to PSE and DFD meat quality defects. A multidisciplinary approach will link basic science to animal husbandry. A multidisciplinary approach to animal welfare will integrate basic science with animal husbandry and logistics in order to demonstrate that animal welfare is linked to both the sustainable and consistent production of products. Omics

technology will be needed by future researchers to identify robust early markers of stress resilience. The creation of precision livestock farming systems capable of monitoring animal welfare in real time and employing a data-driven approach to implement low-stress handling protocols throughout the supply chain will provide support for achieving a sustainable approach to meat production based upon an holistic, welfare-centered view.

Abbreviations

ACTH	adrenocorticotropic hormone
AMPK	AMP-activated protein kinase
APPs	acute-phase proteins
ATP	adenosine triphosphate
BAX	Bcl-2–associated X protein
Ca^{2+}	calcium ion
CaMKK	calcium/calmodulin-dependent protein kinase kinase
CRH	corticotropin-releasing hormone
DFD	dark, firm, and dry
ETC	electron transport chain
HPA	hypothalamic–pituitary–adrenal
HSPs	heat shock proteins
IL-6	interleukin-6
MAPK	mitogen-activated protein kinase
NF-κB	nuclear factor kappa B
PSE	pale, soft, and exudative
ROS	reactive oxygen species
RYR1	ryanodine receptor 1
SAM	sympathetic–adrenomedullary
TNF-α	tumor necrosis factor alpha
WHC	water-holding capacity

Credit authorship contribution statement

Fizza Saleem: writing–original draft, visualization, software, investigation, data curation.

Fizza Jafar: writing–review and editing, visualization, validation, supervision, resources, project administration, conceptualization.

Fatima Irfan: writing, visualization.

Bariqa Asif: writing—review and editing.

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4

Ensuring Animal Welfare: Pain Management and Humane Slaughter

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4.1 Introduction

Modern biological sciences have developed to encompass some of the physiological stresses that affect livestock as a part of intensive agricultural systems and animal husbandry (Birhanu, 2020). A significant change in understanding has occurred over the past few decades, as farmers are now aware that as farms grew larger and more intensive, their ability to manage and protect the well-being of livestock has been compromised as a result. The stress response in livestock consists of activation of the hypothalamic–pituitary–adrenal (HPA) axis and production of cortisol, which act as stress markers (Narayan and Chauhan, 2022). Chronic stress may compromise immunity, reproduction, and growth and reduce overall livestock welfare and production performance (Prates, 2025a; Thornton *et al*., 2022).

The effects of stress on animal welfare and meat production are significant. Stress can change metabolic pathways and deplete glycogen levels in the tissues that contribute to postmortem muscle biochemistry (Zhang *et al*., 2020), resulting in two types of defects in meat quality: pale, soft, exudative (PSE) or dark, firm, dry (DFD). Illnesses cause reductions in market value (Temple, 2020). Transport, handling, and slaughter are important areas where stress creates opportunity to cause negative effects on both welfare and quality of carcasses (Rebuma *et al*., 2024). Heat stress is further compounded by climate change, which has resulted in decreased feed intake and disruptions of normal rumen function and tissue oxidative damage.

Livestock undergo a multitude of different stressors. These can be classified as physical stress caused by rough handling and transportation, environmental stress due to extremely high temperatures and humidity (Thornton *et al*., 2022), nutritional stress due to an insufficiency of feed resources or product quality, and social stress incurred by being mixed with other unfamiliar animals or high-density housing condition (Morgan-Davies *et al*., 2024). Psychological stress occurs because of fear or unless related to fear responses, and the combination of these triggers the same physiological response in livestock that physical stress does; therefore, it plays a vital role in determining livestock welfare (Narayan and Chauhan, 2022).

This chapter focuses on synthesis of recent developments in neuroendocrinology and behavioral indicators of stress that are measured by directly examining the physiological mechanisms influencing animal-based food product quality defects across different animal species. This has provided the unique opportunity to link the current physiological understanding of stress in animals with the practical application of animal welfare strategies. As such, this chapter will provide a complete "Stable to Fork" approach for improving animal welfare while producing high-quality animal-based foods. In addition, this chapter presents new frameworks and updated data emphasizing an economic argument for humane handling being the foundation for developing sustainable and cost-effective meat technologies.

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4.2 Physiological Basis of Stress

Livestock under stress triggers a series of physiological and biochemical responses that are designed to maintain internal homeostasis. Stress in livestock species such as cattle, buffalo, sheep, goats, and poultry is most often experienced due to factors such as handling, transport, restraint, and slaughter. These stressors initiate the activation of conserved neuroendocrine pathways; if levels of stress are too great for any prolonged period of time, there will be an impact on animal welfare, immune function, productivity, and meat quality (Ferreira *et al*., 2020). Understanding how livestock respond physiologically to stress will allow for the design of livestock management and slaughter systems that minimize pain, fear, and distress and ensure the ethical and sustainable production of livestock (Acharya *et al*., 2022).

4.2.1 Neuroendocrine Responses: HPA Axis and Sympathetic Activation

The physiological processes orchestrated by HPA axis (Kanner, Shpaizer and Tirosh, 2025) and sympathetic–adreno–medullary (SAM) system (Freitas *et al*., 2017) are the primary mediators of the physiology stress response. The first step is that when animals perceive a stressor, they process that stressor through sensory pathways within the CNS (central nervous system), which leads to stimulation of the hypothalamus. Upon activation, corticotropin-releasing hormone (CRH), which stimulates the anterior pituitary gland to release adrenocorticotropic hormone (ACTH), stimulates the adrenal cortex to release glucocorticoids, with the predominant one in ruminant and poultry species being cortisol (Acharya *et al*., 2022). Cortisol aids in releasing energy into the body, regulating the heart and blood vessels, and changing body metabolism during stress. The other response to stress is to activate the SAM system, which involves positive signal from sympathetic nerve pathways stimulating rapid release of catecholamines from the adrenal medulla. This response increases heart rate, respiration rate, blood pressure, and blood supply to the muscles, thus allowing animals to respond effectively to stressful stimuli (Moberg, 2000). Studies on domestic cattle, sheep, and goats showed that routine management procedures rapidly increased in the concentrations of ACTH and cortisol. Similar neuroendocrine mechanisms are present in poultry; however, the primary glucocorticoid involved in the response to stress is corticosterone rather than cortisol (Seid and Ahmed, 2021).

4.2.2 Hormonal Indicators: Cortisol, Adrenaline, and Noradrenaline

Cortisol is a parameter used to assess stress in livestock, and it has become the standard biomarker. It plays a pivotal role by mediating the regulation of metabolism, immune function, and physiological response mechanisms resulting from experiencing psychological and physical stressors. Cortisol levels are elevated in cattle, buffalos, sheep, and goats that have been subjected to transportation, prolonged lair age, exposure to novel environments, and poor preslaughter-handling practices (van Eerdenburg *et al*., 2021). Prolonged elevated levels of cortisol can indicate chronic stress, which correlates directly with decreased welfare outcomes. In response to acute stress, animals quickly produce catecholamines, including adrenaline and noradrenaline, which induce various immediate physiological responses, including increased heart rate, expansion of the airway passages, and usage of stored energy as glucose (Moberg, 2000). Catecholamine activity is indirectly reflected in elevated blood glucose and lactate concentrations, despite the fact that their brief half-life prevents direct detection in normal welfare assessments. Rough handling and novelty stress dramatically increase plasma lactate levels in sheep and goats, indicating increased sympathetic activity (Swanepoel *et al*., 2024). Stress-induced corticosterone elevations in chicken during transit, crating, and catching have been shown to be strongly associated with behavioral and physiological distress (Ncho *et al*., 2025).

4.2.3 Metabolic Consequences of Acute and Chronic Stress

There are metabolic changes triggered in animal stress as a result of the activation of the HPA axis and SAM system during the stress response. Acute stress also results in the glycogenolysis and gluconeogenesis to ensure quick energy is available for fleeing (Narayan *et al.*, 2021). However, excessive acute stress that occurs just prior to slaughter will result in depleted muscle glycogen stores. While this depleting of glycogen stores has been linked to forming DFD meats for both beef and lamb, in chickens, the intense short-term stress triggers the development of PSE meats (Botinestean *et al.*, 2021). These quality defects decrease the economic value of the animal's carcass and represent a significant failure in terms of animal welfare. Chronic stress due to continued exposure to conditions such as inadequate living space, crowding, handling, or unstable social situations can have much longer-lasting adverse effects (Li *et al.*, 2025).

4.2.4 Immunological Alterations Associated with Stress

Neuroendocrine stress pathways and immune systems are interconnected. Glucocorticoids have an initial stimulatory effect on certain components of innate immunity; however, chronic exposure will ultimately suppress portions of the immune system (van Eerdenburg *et al.*, 2021). Livestock experience a number of negative effects due to chronic stress that include decreased lymphocytes proliferation, altered cytokines level, and an impaired ability to produce antibodies, all leading to a greater susceptibility to infectious disease. These negative consequences are particularly problematic in large-scale farms where animals are exposed to multiple forms of chronic stress. In poultry, handling and transport of the animals during the time that they were held before slaughter has been demonstrated to impair the cell-mediated immune system; the disruption to the gut barrier places broilers at risk for bacterial colonization and shedding of pathogens (Ncho *et al.*, 2025). Figure 4.1 summarizes the pathway that connects stressors associated with farming operations with their effects on animal physiology/health, welfare status, and quality of the meat produced by these animals. The diagram depicts a cascade of events leading from exposure to a source of stress to the final product (carcass) (Table 4.1).

4.3 Behavioral Manifestations of Stress

The behavioral expressions of stress in animals are extremely important and sensitive indicators of an individual's emotional/affective state and physiological health, which are key indicators of animal welfare and overall health. Stress responses are the result of the integration of multiple complex neural, endocrine, and behaviorally based systems activated when homeostasis is challenged (impaired) due to internal or external forces (stresses). Importantly, these types of behaviors represent a major area of variation across species, locations, macro-environments, types of stressors (thermal stress, social stress,

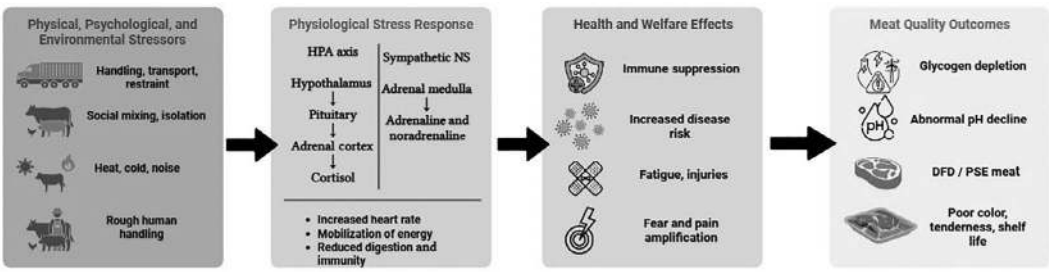

FIGURE 4.1 Integrated stress pathway in farm animals: from stressor to meat quality.

TABLE 4.1

Neuroendocrine and Hormonal Responses to Stress in Animals

Stress Response Component	Primary Hormones	Source/Origin	Physiological Effects	Acute versus Chronic Impact	References
HPA axis—glucocorticoid response	Cortisol (humans)/ corticosterone (nonhuman)	Adrenal cortex (stimulated by ACTH)	Increases gluconeogenesis, protein catabolism, suppresses immune responses Circadian peak post-awakening ~30–45 min in many mammals	*Acute*: rapid increase to mobilize energy *Chronic*: dysregulation leading to impaired feedback and disease risk	James *et al.*, 2023
Sympathetic–adrenal–medullary axis	Adrenaline (epinephrine), noradrenaline (norepinephrine)	Adrenal medulla, sympathetic nerves	Increased heart rate, blood pressure, respiration, metabolic rate Catecholamine surge within seconds of stressor	*Acute*: immediate "fight or flight" response *Chronic*: persistent sympathetic tone leading to cardiovascular load	James *et al.*, 2023
Corticotropin-releasing hormone (CRH)	CRH	Hypothalamus	Stimulates ACTH release Modulates anxiety/behavior	*Acute*: drives HPA activation *Chronic*: expression changes leading to altered stress coping and reproductive suppression	Phumsatitpong, Wagenmaker and Moenter, 2021
Adrenocorticotropic hormone (ACTH)	ACTH	Anterior pituitary	Stimulates adrenal glucocorticoid release Correlates with epinephrine responses across stressors	*Acute*: high secretion in initial response *Chronic*: can drive adrenal hypertrophy	Miller *et al.*, 2022
Growth hormone	GH	Anterior pituitary	Stress-induced increases support metabolism and tissue repair Varies by stressor type and intensity	*Acute*: elevated after intense exercise or acute stress *Chronic*: altered baseline with repeated stimuli	Athanasiou, Bogdanis and Mastorakos, 2023
Prolactin (PRL)	Prolactin	Anterior pituitary	Increases in some acute stress paradigms Effects on metabolism and immune modulation	*Acute*: response depends on stress type *Chronic*: variable regulation with prolonged stress	Athanasiou, Bogdanis and Mastorakos, 2023
Dehydroepiandrosterone (DHEA)	DHEA	Adrenal cortex	Acute stress alters CORT: DHEA ratio, with DHEA often inversely fluctuating against corticosterone in crocodiles	*Acute*: altered immediately after stress *Chronic*: ratio shifts may indicate allostatic load but requires long-term studies	Swanepoel *et al.*, 2024
Glucose and lactate (secondary metabolic markers)	—	Liver, muscle via hormone action	Acute stress increases glucose and lactate Glucose elevated with catecholamine and glucocorticoid release	*Acute*: rapid energy mobilization *Chronic*: extended hyperglycemia can impair metabolism	Swanepoel *et al.*, 2024
Heterophil-to-lymphocyte ratio (HLR)	Immune marker (stress indicator)	Blood leukocytes	Acute stress elevates HLR, reflecting immune redistribution and cortisol influence	*Acute*: marker rises quickly *Chronic*: persistently high HLR indicates sustained physiological stress	Swanepoel *et al.*, 2024
Vasopressin (AVP)	AVP	Hypothalamus	Costimulates ACTH release and modulates water balance under stress Increases with chronic HPA stimulation	*Acute*: less dominant than CRH *Chronic*: prominent in prolonged HPA drive	Ahmad, Jena and Priyadarshi, 2023

physical stress, etc.), and individual animal "coping styles"; thus, a careful observation of animal behaviors is vital to determining their welfare/health. The acute response to varying stresses varies widely, for example, the initial behavioral responses of prey species when faced with an immediate threat may be an avoidance behavior, an escape attempt, or a freezing and increased vigilance and other measures (Karaer, Čebulj-Kadunc and Snoj, 2023).

The initial responses of prey species, which are often characterized as defensive behaviors, may include a "freeze" (immobility) behavior (e.g., crouched posturing) when they perceive a threat (either real or likely), and when this occurs, some measurable degree of sympathetic nerve activation may occur, including increased heart rate and associated changes in behaviors (Cain, 2023). In terms of livestock, changes in barn/environmental temperature due to extreme heat or management stress are associated with various indicators of stress, including an increase in panting or shivering, as a means of coping to these changes. Additionally, there is a subset of animals that exhibits a behavior that may include a clear indication of (1) shade-seeking and (2) changes in feed and water intake, which represent specific coping methods the animals implement to deal with the environmental challenges they are facing (Oke *et al.*, 2025).

The use of species-specific behavioral indicators for animal welfare is important as all animals have different needs, and therefore generalizing these criteria for animals could lead to misclassification of the animal's welfare state. Dairy cattle will display a reduction in rumination and exploratory behaviors and an increase in the amount of time they are "standing idle" following an acute stressor (i.e., milking or udder infection), indicating that the animal is in discomfort and has had a break in its normal behavior. Evidence from empirical studies have indicated that subtle behaviors such as yawning, lip licking, decreased activity levels, and avoidance of eye contact among dogs can be used by veterinary practitioners or caretakers to diagnose early signs of stress and anxiety (Menor-Campos *et al.*, 2022), but the importance of observing and recognizing these behaviors is often overlooked or not fully understood. Behavioral phenotype assessment (understanding welfare risk factors through identification and classification of the behaviors exhibited) has been shown to relate to adoption outcomes for dogs in a study that analyzed 224 American shelter dogs. In that study, the presence of increased panting was found to be strongly associated with animals that were not placed into an adoptive home and that euthanized dogs exhibited a reduced amount of time spent sitting when compared to successfully placed adopted dogs (χ^2 significant at $p < 0.01$) (Powell *et al.*, 2025).

Specific husbandry practices show links between fear, stress, and pain. For example, there are large behavioral changes associated with castration in piglets or sheep, which is a common industry procedure. Castrated pigs will exhibit more vocalization, will not be as active, and will have less tail wagging, with an average count of 102 ± 25.3 standing or sitting in comparison to a control group of pigs. These changes thus demonstrate a direct relationship between pain-inducing events and stress responses (Mota-Rojas *et al.*, 2025). In a similar manner, lambs that have undergone lamb's testicular castration will demonstrate at least some of the same signs of pain-related stress (Mota-Rojas *et al.*, 2025).

In addition, abnormal repetitive actions (stereotypies), which are commonly referred to as chronic stress indicators, occur in many species of agricultural animals. In addition to ruminants, there are documented instances of stereotype behaviors related to speech and oral activity in other livestock, such as tongue-rolling or self-sucking—behaviors indicating a prolonged period of stress and decreased levels of behavioral complexity (Li and Gu, 2024). Table 4.2 provides the behavioral indicators of stress across different animal species.

In general, stress behavior includes activities that are either avoidance- or flight-style behavior, along with the animal being absent from an event or activity, sitting still but displaying unusual behaviors (freezing), having difficulty establishing or maintaining informed relationships with other animals. The identification of stress behavior requires a thorough understanding of "normal" behavior within a species as well as all three of these factors: context-specific indications; frequency of appearance of the behavior, and its characteristic native behavior along with physiological and environmental factors. Therefore, while the behavior may be indicative of immediate distress to the animal, it may also indicate longer-term, continued welfare and productivity outcomes for both animal health and meat quality (Oke *et al.*, 2025).

TABLE 4.2

Behavioral Indicators of Stress across Different Animal Species

Species	Common Stress Behaviors	Interpretation	Related Welfare Concerns	References
Cattle	Increased flight distance, agitation during handling, reduced rumination, altered social interactions	Suggests fear and poor habituation to routine handling Chronic stress linked to poor welfare and productivity	Higher risk of injury, lowered milk/meat yield, chronic fear responses	Harris, Shallcrass and Cohen, 2024
Pigs	Aggression (~81.8% of social stress studies), tail biting, avoidance behaviors, increased *social conflict*	Reflects social stress from regrouping, overcrowding, or dominance instability	Injury risk, lowered growth, immune dysfunction	Guevara *et al.*, 2022
Poultry (chickens)	Feather pecking, panting and wing elevation at ~≥25 °C, reduced feeding, abnormal vocalizations	Stress from heat, high density or social tension Pecking indicates frustration and potential injury	Feather loss, injury/cannibalism, reduced performance	Cartoni Mancinelli *et al.*, 2023
Sheep	Reluctance to move, changes in posture, isolation from flock, hesitant or reduced feeding	Indicates fear, discomfort, or environmental stress	Reduced weight gain, possible chronic fear states	Pain and Animals, 1992
Dogs	Panting, whining, barking, body shake, altered posture (tail low, ears back), reduced social play	Indicates negative emotional states such as anxiety or fear	Poor welfare, possible chronic anxiety if persistent	Flint *et al.*, 2024
Cats	Hiding, anxious posture with flattened ears, reduced activity, altered elimination, vocalizing	Reflects acute stress from novel environments or handling	Compromised welfare, possible chronic distress	Zhang *et al.*, 2022
Atlantic salmon (fish)	Increased darting/kinetic restlessness, reduced feed intake (~87 g drop per day after stress)	Reflects high stress or response to handling/experimental challenge	Reduced growth, poorer health outcomes	Wiese *et al.*, 2023
Goats	Vocalization under restraint/handling, lack of social engagement	Suggests fear or discomfort due to environmental/contextual stress	Welfare compromised under poor handling	Martínez-Yáñez, Mora-Medina and Albertos-Alpuche, 2025
Companion birds (poultry derived)	Vocal distress calls, chronic panting, pacing, head shaking (clinical signs of heat/handling stress)	Reflects environmental, temperature, or social stress	Reduced welfare and productivity	Genc and Ozenturk, 2024

4.4 Preslaughter Stress and Welfare Concerns

Preslaughter stress is a recognized, multidimensional animal welfare issue in modern livestock production that can have direct effects on physiological homeostasis, behavioral expression, carcass characteristics, and ultimately, the quality of the meat produced. The various preslaughter stressors experienced by animals (handling, loading, transportation, unloading, lairage, and being in an unknown abattoir environment) will trigger the activation of the neuroendocrine axes (including the rapid SAM response and the HPA axis) and cause a rapid and dramatic increase in the hormones catecholamines and cortisol. These two hormones have been shown to have strong correlations with poor welfare states and also with measurable differences in the postmortem metabolic state of muscle (e.g., the decreased stores of

glycogen and changing levels of pH) from the quality defects of DFD meats and PSE meats (Carrasco-García *et al*., 2020).

Across all species of livestock, large quantitative population studies have documented the magnitude of disruption to the normal physiology of animals due to preslaughter anxiety and stress. Based on an analysis of 448 beef carcasses, the majority of the animals had a high cortisol content (44.3% of the animals had an average cortisol value of approximately 74.7 ng/mL) at the time of slaughter. In addition to the 44.3% that had high cortisol levels, 22.7% of the carcasses had an extremely high cortisol concentration (average approximately 108.8 ng/mL). More than 90% of the carcasses in the study had a final pH Level of 5.8 or higher, which is consistent with DFD conditions, indicating that the animals experienced issues with water-holding capacity (WHC) and color stability (Carrasco-García *et al*., 2020). The same physiological evaluation has been used to evaluate commercial finishers of pigs (n = 2465) and categorize how animals responded physiologically during the different transport and handling periods, with a significant difference observed in how animals responded to short (3.5 hours or less) versus long (greater than 5 hours) transportation periods and subsequent handling for pigs. Animals that were transported for short periods had increased levels of cortisol and lactate, indicating acute physiological stress. Conversely, animals that were transported for long periods exhibited increased levels of the enzyme creatine kinase in their blood, indicating that they had experienced fatigue and physical strain to their muscles (Huanca-Marca *et al*., 2025). The extent of these studies has been illustrated in cattle with large observational cohorts (e.g., n = 454), showing that cattle that wait in trucks for extended periods and have high lairage (holding pen) densities have higher cortisol and lactate levels and a greater chance of impaired mobility and bruised carcasses, indicating animals that experienced distress and compromised welfare while in the terminal phase of their production systems (Sullivan *et al*., 2024).

Distance traveled and handling methods have also been shown to affect many quality characteristics. Beef that has been transported for 7–250 km (the average distance being 99 km) has been shown to contain higher levels of lactate and ultimate pH compared with that of cattle from a mobile facility purposely constructed to alleviate the stress associated with transportation over long distances; the decrease in tenderness (Warner-Bratzler shear force was approximately 6.9 N different) and changes in the compressive properties when compared to the beef derived from this facility demonstrates the regulatory function that logistical variables have on the welfare of the animal as well as on the quality of the carcasses produced (Hultgren *et al*., 2022). Seasonality has also been found to have an effect on the animal's stress response, as cattle transported during the summer have been shown to have higher than average lactate levels and higher odds of exhibiting impaired mobility and bruising on their carcasses. This suggests that environmental factors, in combination with handling, may exacerbate the welfare-related issues facing captive animals (Sullivan *et al*., 2024).

The physiological and behavioral stress responses of animals subjected to untrained handling are demonstrated by a significant increase in vocalization, heart rates, blood glucose and catecholamine levels, agitation or fleeing behavior, and aggression levels, indicating the significance of human skill in preventing welfare reductions in animals (Kumar *et al*., 2024). Similar to the use of stress indicators across multiple species, a number of most widely used stress biomarker profiles used in assessing contemporary animal welfare are represented by cortisol, CK, lactate, and glucose, and are indicative of the connection between stress and meat quality (Sardi *et al*., 2020).

According to advanced studies, there is a defined set of preslaughter risks associated with animal welfare that can be categorized into hot/cold temperature stress, overexertion, starvation/thirst, limited movement, disruptions within their social group, and emotional stress caused by fear. There are ways of objectively assessing animal welfare based on these hazards, in addition to being able to compare scores across different categories of risks for total welfare score (Health *et al*., 2020). In addition, the presence of bruises on cattle has been widely documented to be an indicator of the prevalence of bruising in large-scale carcass surveys, with a staggering number of carcasses (81%) being reported to have at least one bruise identified. Bruising of carcasses is also closely associated with various biomechanical indicators of stress, and impact the color and drip loss properties of the meat as bruises are viewed as a subclinical injury that are caused by rough handling of the cattle. Bruising of carcasses causes economic loss and degradation of the product. The welfare impacts of being subjected to preslaughter/abattoir stressors and the multiple impacts of these stressors can be identified along the production chain (Figure 4.2) (Carrasco-García *et al*., 2020).

FIGURE 4.2 Preslaughter stress points and welfare risks along the production chain.

4.5 Effects of Stress on Meat Quality

4.5.1 Biochemical Changes Postmortem

Postmortem biochemical changes in muscle tissue are among the most important factors determining meat quality, and the physiological status of the animal at the time of slaughter is a major influence on those changes. Specifically, exposure to stress prior to slaughter affects the manner and time of the chemical processes that lead to the deterioration of meat, with subsequent effects on ultimate product quality. After an animal's blood supply is cut off, muscle tissue no longer receives oxygen and uses up all its ATP very quickly. Following this initial use of ATP, the remaining glycogen in the muscle is converted to lactic acid through anaerobic glycolysis. In animals that do not experience stress, the creation of lactic acid through glycolysis leads to a reduction in pH of the muscle to approximately 5.4–5.8 after 24 hours postmortem; this pH level is optimal for color, tenderness, and WHC (Khatri and Huff-Lonergan, 2023).

The effects of preslaughter stress on biochemical changes after death accelerate or cause changes to the biochemical pathways of muscle postmortem. The loss of glycogen and subsequently generated lactic acid due to preslaughter stress will also result in an increased ultimate pH (>6.0); this is referred to as DFD meat, which is characterized by a dark appearance, greater WHC, and less consumer acceptance (Mato *et al.*, 2019). Alternatively, the effects of acute stress can cause the development of an excessively rapid glycolytic rate, leading to a rapid decrease in muscle pH when the muscle temperature is high, which results in protein denaturation, reduced WHC, a lighter colored appearance, and the PSE condition (Ma *et al.*, 2025).

According to the findings of proteomic and metabolic studies, energy metabolism enzymes and regulatory proteins are affected by stress and this ultimately has an effect on the postmortem proteolysis and aging processes of meat. For instance, the presence of differentially expressed glycolytic enzymes and stress-response–related genes corresponds to both a disruption in the pH regulation of meat and also that these are correlated with the degradation of structural proteins that have an impact on the tenderness and texture of meat (Roudbari *et al.*, 2025). The biochemical alterations produced by preslaughter stress have an influence not only on the ultimate pH and color but also on the meat's water retention capacity and

mechanism of proteolytic breakdown, and subsequently affect meat's juiciness, shelf life, and sensory quality. Therefore, the elimination of preslaughter stress is crucial in producing high-quality beef (Silva *et al.*, 2025).

4.5.2 Stress and Muscle Glycogen Depletion

Skeletal muscle's predominant energy storage is muscle glycogen. It is crucial to the biochemical changes that occur after death that will ultimately determine the quality of meat. The impact on muscle glycogen is considerably altered by preslaughter physiological stressors (i.e., transportation, handling, lairage, temperature exposure) that activate the sympathetic and endocrine stress responses through the substantial increase in catecholamine and cortisol production. These hormones trigger the process of glycogenolysis, which is the breakdown of glycogen to provide energy (i.e., activation of glycogen phosphorylase), thus increasing the blood glucose concentration due to the depletion of intramuscular glycogen (Ogawa *et al.*, 2024).

Glycogen is an essential nutrient in your muscle that gives the muscles the energy they need to perform. If your body's glycogen levels are low (as in stress, for example), your muscles do not have the ability to perform postmortem anaerobic glycolysis. Anaerobic glycolysis converts glycogen into lactate, and the production of lactate lowers your body's pH from about 7.0 to about 5.5–5.6 within 24 hours after death. The pH of meat is one of the factors that help improve the meat's ability to hold water and improve the color and therefore quality of the meat. Glycogen is also used to produce lactic acid. Therefore, if there is not enough glycogen to metabolize to produce enough lactic acid before death, the ultimate pH of the meat will be greater than 6.0. The DFD phenotype will be very DFD because of the lack of lactic acid in the meat, which makes it less light (L^*) and more able to hold water at 24 hours postmortem. Studies have shown that chronic stress that occurs before slaughter can cause the glycogen levels of an animal to drop significantly below the level required to allow for normal acidification of the meat; therefore, chronic stress before slaughter will vary in its ability to lower glycogen and thus reduce the glycolytic potential of the meat and reduce overall meat quality traits such as tenderness and shelf life (Kiyimba *et al.*, 2024). Therefore, to achieve desirable meat quality, it is necessary to implement management practices that minimize stress and maintain muscle glycogen at the time of slaughter (Kumar, 2025).

4.5.3 Meat Defects: DFD, PSE, and Pale/Soft Variants

DFD and PSE meat represent extremely modified muscle metabolism characteristics of meat. DFD meat is produced as a result of prolonged or continuous stress in the animal prior to slaughter. This causes depletion of muscle glycogen and therefore a greatly reduced (postmortem) lactic acid production capability of that muscle. Consequently, the ultimate muscle pH remains high (greater than 6.0–6.2), which appears darker or blacker than normal, is firmer than normal, and retains more water than normal due to less denatured protein. The high ultimate muscle pH also promotes the development of conditions that significantly shorten the shelf life and support microbial growth of DFD meat; therefore, it is commercially undesirable. Conversely, PSE meat is primarily attributed to lightning intense stress to the animal within a short window (acute) prior to slaughter in addition to the effect of the increased elevated carcass temperature during DFD meat production. The dramatic increase in glycolysis from the highly accelerated metabolism rapidly brings the meat pH below approximately 5.6–5.8 while the muscle is still warm. This phenomenon leads to greater denaturation of protein within the muscle of PSE meat than in DFD meat. Characteristics of PSE meat include pale coloration through having a higher "L value", greatly reduced WHC, soft texture with excessively high losses of the exudates of PSE meat, thus compromising significantly the processing quality attributes and sensory attributes (Mia, Rahman and Hashem, 2023).

Studies have shown the prevalence and incidence of PSE conditions to be very high, sometimes up to 43.5%, when broilers are raised under heavy heat (loss of body fluid) stress conditions. The prevalence of DFD meat is lower but can occur under different conditions (Freitas *et al.*, 2017). Table 4.3 provides common meat quality defects linked to preslaughter stress.

TABLE 4.3

Common Meat Quality Defects Linked to Preslaughter Stress

Meat Defect	Cause (Preslaughter Stress Mechanisms)	Biochemical Basis	Meat Quality Impact	Species Most Affected	References
Dark, firm, dry (DFD)	Chronic or prolonged stress depletes muscle glycogen reserves before slaughter	Low postmortem lactic acid → high ultimate pH (>6.0) Minimal acidification	Darker color, firmer texture, high water-holding capacity, shorter shelf life due to microbial risk	Beef, sheep, pork (less common); also reported in poultry under prolonged stress	Mato *et al.*, 2019
Pale, soft, exudative (PSE)	Acute stress minutes before slaughter → rapid postmortem metabolism	Rapid glycolysis and lactic acid accumulation while muscle temperature remains high → protein denaturation	Pale color, soft texture, low water-holding capacity (high drip loss), poor processing quality	Pigs (most affected), also seen in poultry and occasionally in beef	Liu *et al.*, 2021
PSE-like in poultry	Acute stress and high growth selection → stress-enhanced glycolysis	Similar rapid pH decline and protein denaturation, even without classic ryanodine mutation	*Similar to PSE*: pale appearance, poor water retention, lower yield	Broiler chickens, turkeys	Kovačević *et al.*, 2025
Dark cutting beef (a form of DFD)	Prolonged antemortem stress especially during transport and lairage	High ultimate pH (~6.4–6.8) due to glycogen exhaustion	Deep red/dark color, poor consumer acceptance, increased spoilage	Beef cattle	Kirkpatrick *et al.*, 2023
Heat-induced DFD variants	Heat stress during transport/lairage increases metabolic rate and glycogen use	Reduced glycogen → low lactic acid → elevated pH Protein structures preserved	High water binding, darker visual appearance, less tender perception	Beef, pork, sheep	Mia, Rahman and Hashem, 2023
Low water-holding capacity defects	Accelerated pH drop + High carcass temperature postmortem	Protein denaturation → decreased WHC and high drip/cook loss	Increased drip loss and cook loss, dryness, lower consumer appeal	Pigs and poultry	Terlouw *et al.*, 2021
Abnormal pH meat (high pH >6.2)	Chronic stress or fasting preslaughter yielding insufficient glycogen	Elevated endpoint pH due to insufficient lactic acid	Dark color, increased bacterial growth risk, unpredictable tenderness	Multiple livestock (cattle, goats, sheep)	Gonza *et al.*, 2023
Protein denaturation-linked defects	Rapid stress-induced glycolysis before carcass cooling completes	Structural protein changes, reduced functional properties	Soft texture, poor binding in processed products	Pork and poultry	Terlouw *et al.*, 2021
Oxidative stress-related quality decline	Heat and handling stress increase ROS → muscle oxidation	Lipid peroxidation and oxidative modifications influence color stability and flavor	Lower oxidative stability, rancidity, off-flavors, shorter shelf life	Pork and poultry	Bejaoui *et al.*, 2023
Variable ultimate pH patterns	Stress patterns alter pH decline kinetics	PSE: pH <5.8 within ~45 min postmortem DFD: pH stays >6.5 at 24 h	PSE: pale color and low WHC DFD: dark color and high WHC	Cattle, swine, sheep, poultry	Santos *et al.*, 2019

The mechanistic patterns associated with these two defects differ because of the postmortem pH curve associated with the extent and duration of animal stress. The major difference is the rate of acidification and higher ultimate pH values associated with DFD, whereas PSE is associated with faster acidification rates and lower ultimate pH values for DFD. The most contemporary classification system for these defects identifies additional classifications or "intermediate" types of carcass meat (from both defects). Furthermore, the wide range of ultimate pH values, color, and WHC present in DFD and PSE carcasses indicates the considerable influence of environmental factors on carcass quality (Kovačević *et al*., 2025). Therefore, to minimize the incidence of DFD and PSE defects and to ensure that broiler meat meets the industry and consumer quality standards, it is essential that producers practice very good animal husbandry, including minimizing animal stress before slaughter (Mia, Rahman and Hashem, 2023).

4.5.4 WHC, Color, Tenderness, and Shelf Life

Preslaughter stress can dramatically influence many properties or traits of meats. These include WHC, color, tenderness, and shelf life. The connection between these traits involves many biochemical processes that occur prior to and during slaughter. An example of WHC is the amount of moisture that is retained by muscle fluid after death. Increased levels of stress accelerate the process of oxidizing and denaturing protein, thus negatively affecting how water interacts with myofibrils (muscle), thereby increasing the amount of drip loss and cooking loss compared with nonstressed animals. This occurs because stress leads to structural protein unfolding, causing the α-helix to be transformed into a random coil ($p < 0.05$). This loss of structure decreases the capacity of the meat to retain moisture (Ma *et al*., 2024).

The color of muscle is influenced largely by the state of myoglobin and how well it is formed or intact. The light reflection or scattering caused by stress-related metabolic disruption, oxidative injury, and disruption to the normal interstitial matrix proteins of the muscle can cause the muscle to appear lighter (in L^* value) or patchy in its coloration, which can decrease consumer demand (Roudbari *et al*., 2025). The tenderness of the meat decreases along with the light L^* values due to the accelerated glycolytic effects of stress-induced rapid glycolysis and changes in the acidity of the muscle following death altering the activity of natural proteolytic enzymes such as calpains which, in turn, alters the structural integrity and cross-linking of the muscle fibers, causing decreased succulence and texture (Sristi *et al*., 2025).

These changes also shorten shelf life: meat with reduced WHC and compromised color stability is more prone to lipid oxidation and microbial spoilage, especially when combined with higher ultimate pH and protein denaturation; this results in faster quality degradation during storage (Mia, Rahman and Hashem, 2023).For example, heat stress accelerates oxidative processes that both lower WHC and hasten discoloration, undermining storage stability and sensory quality (Prates, 2025b). Collectively, these effects demonstrate that minimizing preslaughter stress through optimal handling practices is critical for maintaining desirable WHC, stable color, optimal tenderness, and prolonged shelf life in meat products (Muleta and Dida, 2025).

4.6 Integrating Stress Management into Humane Slaughter

Slaughtering process comes after a chain of handling steps of animals: loading from farm or market, transporting to slaughter houses, unloading, and then final slaughtering. All these steps may result in stress (Birhanu, 2020). Stress may also arise from physical factors, hunger, high temperature, humidity, water quality, and overcrowded area (Terlouw *et al*., 2008). Stress occurred before slaughter may lead to depletion of glycogen in muscle, which may lead to dark firm dry meat, while acute stress before slaughter leads to precipitate pale soft exudative meat which leads to increase metabolic acidosis (Gregory, 1994).

4.6.1 Stunning Methods and Their Welfare Implications

Recognizing animals as sentient beings, direct slaughter through a neck cut without prior intervention can result in pain and suffering (Berg and Raj, 2015). To address this concern, animals are commonly stunned before slaughter to render them unconscious, insensible, and immobile. The state of

unconsciousness must be maintained long enough to prevent recovery before and during exsanguination (Hillebrand, Lambooy and Veerkamp, 1996). Consequently, stunning prior to slaughter has become a widely accepted practice, and several stunning methods are permitted under existing animal welfare regulations (Berg and Raj, 2015). These methods are designed to meet welfare requirements while also influencing postmortem muscle activity, rigor mortis development, and final meat quality, which can vary depending on the stunning technique used (Joseph *et al.*, 2013).

Mechanical stunning, although applied in some livestock species, has not been validated as a suitable alternative to electrical stunning in poultry, particularly in chickens (Hillebrand, Lambooy and Veerkamp, 1996). Electrical water bath stunning is one of the most commonly used methods in poultry processing and involves passing a sufficient electrical current through the brain to induce unconsciousness (Joseph *et al.*, 2013). However, studies have shown that this method can induce epileptiform activity in poultry brains, affecting a smaller brain region compared to red meat species. Excessive muscle contractions associated with this method often lead to bone fractures and blood splash, ultimately resulting in inferior meat quality (Berg and Raj, 2015).

To overcome the limitations of conventional water bath systems, individual electrical stunning methods have been developed. In head-only electrical stunning, dry electrodes are placed on either side of the bird's head to induce unconsciousness before the animal is transferred to the shackle line for slaughter. A key advantage of this approach is the application of a constant and controlled current to each individual bird, allowing for monitoring of current profiles and identification of birds that are inadequately or partially stunned. Another innovation is head-to-cloaca electrical stunning, where the bird is positioned inverted in a water bath containing one electrode, while the second electrode is applied at the cloaca. This method effectively induces unconsciousness and provides improved meat quality compared to conventional water bath stunning, primarily due to reduced blood splash and less severe muscle contractions (Berg and Raj, 2015).

Gas stunning represents an alternative approach in which birds are exposed to specific gases or gas mixtures. When carbon dioxide is used, the process typically occurs in two stages: an initial exposure to concentrations below 40% by volume in air, followed by exposure to higher concentrations ranging from 80% to 90% once the animal has lost consciousness. This staged approach is necessary because direct exposure to high concentrations of CO_2 can cause pain and distress. Carbon dioxide may also be combined with inert gases such as argon or nitrogen, which possess anesthetic properties and induce hypoxia. However, hypoxia can trigger adverse behavioral responses in some birds, including wing flapping and convulsions. Despite these reactions, gas stunning, often referred to as controlled atmosphere stunning, generally results in better meat quality when compared with electrical stunning methods (Berg and Raj, 2015).

Low atmosphere pressure stunning (LAPS) is another emerging technique in which insensibility is achieved without the use of carbon dioxide (Joseph *et al.*, 2013). In this method, the gradual reduction of oxygen tension within a sealed chamber leads to progressive hypoxia, ultimately causing birds to lose consciousness and become comatose. Similar to gas stunning, the induction of unconsciousness is not immediate. LAPS offers several potential advantages, including the ability to stun birds in their transport containers, thereby eliminating the need for live handling and shackling of conscious animals. However, the widespread adoption of this method depends on continued validation of its humaneness and welfare outcomes (Berg and Raj, 2015).

4.6.2 Minimizing Pain and Fear during Slaughtering

Perception of the surroundings is especially important in the setting of slaughter since information from the senses, such as the scent of blood or fear hormones, stress vocalizations from other animals, and visual dangers, can contribute to a fear response of the animal. Unconsciousness results from injuries made during stunning or slaughter to the significant regions of the cerebral cortex, the reticular formation itself, or the ascending projections. Being unconscious means that no pain is "felt". However, some human research indicates that there may be a little amount of pain in an unconscious state. Before, slaughtering, when animal lose consciousness, then it reduces pain and fear and these methods in which animals lose consciousness is stunning and hypovolemic shock (Berg and Raj, 2015).

4.6.3 Best Practices for Species-Specific Humane Killing

The central aim of any humane killing method is to render an animal insensitive to pain as quickly as practically possible, thereby minimizing suffering. This ethical objective is widely shared across major Western and non-Western philosophical traditions. In international law, humane considerations relating to animals are generally addressed through three approaches: international regulatory regimes, legal frameworks targeting indiscriminate capture, and species-specific agreements. Early international efforts include the 1964 Agreed Measures for the Conservation of Antarctic Fauna and Flora, which prohibit the killing, capturing, wounding, or molestation of native Antarctic birds and mammals. Humane treatment is also embedded within the Convention on International Trade in Endangered Species (CITES), which emphasizes animal welfare during international transport and is supported by national and regional agreements (Gillespie, 2003).

International law has long recognized the problem of indiscriminate capture, particularly the incidental taking of nontarget species. Attempts to restrict cruel hunting practices have often coincided with bans on indiscriminate technologies, such as the historical prohibition of poison use in fisheries, although such practices persist in some regions despite long-standing concern. Species-specific conventions further reinforce humane principles. The 1976 Convention on the Conservation of North Pacific Fur Seals requires killing methods that minimize pain and suffering, while the 1972 Convention for the Conservation of Antarctic Seals mandates research into humane use. Similar protections exist for birds through agreements restricting poisons, traps, and harmful hunting practices, culminating in modern FAO initiatives aimed at reducing incidental seabird capture (Gillespie, 2003).

4.6.4 Linking Welfare Standards with Meat Quality Assurance

Quality assurance in meat production is built around three fundamental components: food safety, animal welfare, and sensory attributes associated with meat quality. These controlled procedures are introduced to monitor production systems, ensure compliance with quality standards, and meet consumer expectations. Meat quality extends beyond sensory characteristics such as color and tenderness and is strongly influenced by conditions of animal production, particularly those related to animal welfare. Consumers increasingly define quality in broader terms, incorporating food safety, animal welfare, environmental impact, healthiness, taste, and lifestyle considerations. Quality assurance measures address food safety through the prevention of foodborne illnesses and proper handling practices, including effective removal of hides and fleece. Animal welfare is improved by minimizing abuse, ensuring appropriate space and living conditions on farms, and applying proper stunning during processing. Meat quality is maintained by preserving color and tenderness through adequate feeding practices on farms and appropriate chilling during processing (More *et al*., 2017).

Countries differ in their public animal health standards, which can create barriers to international trade in animals and animal by-products. To address this, the World Trade Organization (WTO) established the Agreement on the Application of Sanitary and Phytosanitary Measures (SPS Agreement), which seeks to balance the protection of human and animal health with the facilitation of international trade. Under the SPS Agreement, measures must be scientifically justified, harmonized with international standards where possible, recognize equivalency of alternative risk-management approaches, and ensure transparency in implementation. In animal health matters, the WTO recognizes the International Organization for Animal Health (OIE) as the reference body responsible for developing global standards (WTO, 2010). Figure 4.3 illustrates the assessment and mitigation of stress in humane slaughter systems.

While animal health standards are well established internationally, animal welfare standards have progressed more gradually. The European Union has taken a leading role by implementing legislation that sets minimum requirements for the production, transport, and slaughter of farm animals, with individual member states permitted to adopt higher standards. The European Food Safety Authority supports policy development by promoting welfare outcomes based on animal-based indicators. At the global level,

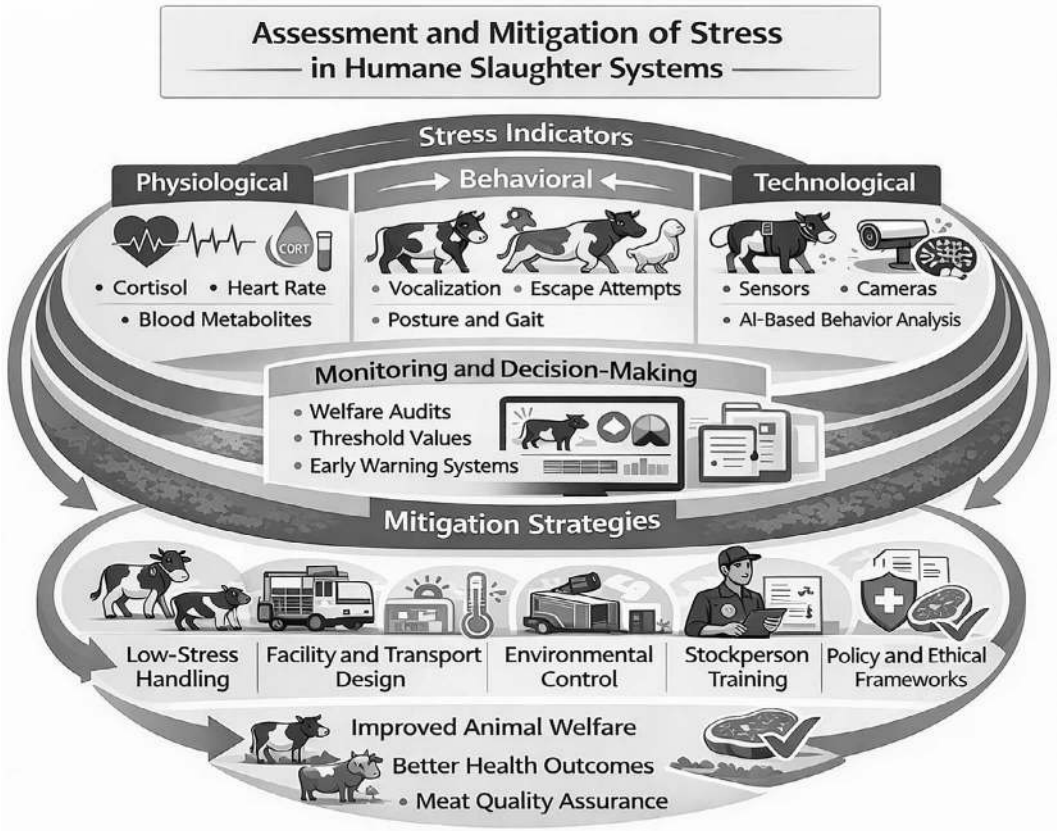

FIGURE 4.3 Assessment and mitigation of stress in humane slaughter systems.

OIE animal welfare standards, adopted by consensus, cover areas of transport, slaughter, disease control, production systems, and the use of animals in research, representing a significant advancement despite regional differences in legal requirements. (More *et al.*, 2017.)

4.7 Conclusion

To optimize the final quality of meat products, it is critical to ensure that humane practices are incorporated throughout the entire livestock production process. What is known from research is that when an animal is stressed, there are multiple physiological and metabolical changes that will negatively impact both the animal's health and the quality of meat, for example, the development of DFD and PSE meat. Additionally, these changes can affect many important quality characteristics such as WHC, color, and shelf life. Due to these associations, it is not only an ethical responsibility but also essential from a commercial viability perspective to lessen preslaughter stress on livestock by using better techniques to handle, transport, and hold animals, as well as adopting effective stun methods. The future of the livestock industry must include greater utilization of precision livestock production technology for real-time monitoring of stress levels. The development and validation of alternative stunning systems (e.g., controlled atmosphere stunning) and enhancement of international welfare standards through policy harmonization will also be required. Additionally, educating consumers about the relationship between animal welfare and product quality will create demand for change in the meat industry and, therefore, a sustainable model of production in which premium products are achieved through the ethical treatment of livestock.

Abbreviations

ACTH	adrenocorticotropic hormone
ATP	adenosine triphosphate
AVP	vasopressin (arginine vasopressin)
CITES	Convention on International Trade in Endangered Species
CNS	central nervous system
CRH	corticotropin-releasing hormone
DFD	dark, firm, dry
DHEA	dehydroepiandrosterone
FAO	Food and Agriculture Organization
GH	growth hormone
HLR	heterophil-to-lymphocyte ratio
HPA	hypothalamic–pituitary–adrenal
LAPS	low atmosphere pressure stunning
OIE	International Organization for Animal Health (formerly Office International des Epizooties)
PRL	prolactin
PSE	pale, soft, exudative
ROS	reactive oxygen species
SAM	sympathetic–adreno–medullary
SPS	sanitary and phytosanitary
WHC	water-holding capacity
WTO	World Trade Organization

Credit authorship contribution statement

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5

Animal Welfare Regulations and Certification: Driving Productivity and Sustainability

Bytyqi Hysen and Ramadani Xhavit

5.1 Introduction

Animal welfare has been an issue in meat production nowadays; it not only an ethical concern but also acts as a driver for productivity, meat quality, and sustainability of farming systems for livestock production (Grandin, 2014; Webster, 2016).

Animal welfare on farms has traditionally been thought of as an ethical topic with emphasis on humane handling of animals and avoidance of palpable suffering.

In recent decades, however, due to consumer culture, social interests, and international trade needs, animal welfare has evolved into a richer problem with regulatory, economic, and sustainability connotations (FAO, 2020; Fraser, 2008).

Accumulating evidence confirms that welfare-based approaches improve physiological and behavioral markers, reduce stress, improve growth and reproduction, and improve carcass and meat quality, ultimately improving economic performance (Grandin, 2014; Larivière-Lajoie *et al*., 2023; Terlouw, Arnould and Auperin, 2008).

5.1.1 Importance of Animal Welfare in Global Meat Production

Additionally, there is a close connection between animal welfare and both ethical imperative and commercial success. Conditions of bad welfare-poorly housed, mistake in handling, over-transport, or inappropriate stunning at slaughter-may potentially destroy physiological and psychological well-being by virtue of high concentrations of stress hormones, immunosuppression, disease susceptibility, and deviancy of behavior (Hemsworth *et al*., 2015; Terlouw, Arnould and Auperin, 2008; Väärikkälä, Hänninen and Nevas, 2019).

Muscle glycogen depletion resulting from physiological stress modifications can be responsible for meat quality faults in the form of pale, soft, exudative (PSE) or dark, firm, dry (DFD) meat that adversely affects tenderness, juiciness, and storage life (Larivière-Lajoie *et al*., 2023; Terlouw, Arnould and Auperin, 2008).

Conversely, welfare compliance, through improvement in housing, environmental enrichment, low-stress handling, and preventive health care, enhances animal welfare as well as economic performance in growth performance, reproductive efficiency, and meat quality (Charles, 2024; Grandin, 2014).

Consumer awareness has emerged as a top welfare driver. Ethical concerns, combined with consumer pressure for food traceability, have spurred the development of certification and labeling schemes such as GAP (Global Animal Partnership), Certified Humane (HFAC: Humane Farm Animal Care, USA), RSPCA Assured (Royal Society for the Prevention of Cruelty to Animals, UK), organic, and free-range schemes. These are facilitators for trust that allow producers to market their produce differently and charge premium prices and enforce conformity to animal welfare (Font-i-Furnols and Guerrero, 2014; Napolitano *et al*., 2010).

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Along with market returns, welfare-based production also contributes to general sustainability objectives, including resource conservation, reduced antimicrobial uses, and innovative conformation to Sustainable Development Goals (SDGs) for the facilitation of interlinkages of economic, environmental, and ethical pillars in animal agriculture (FAO, 2020; Webster, 2016).

5.1.2 From Ethical Debate to Regulatory, Economic, and Sustainability Imperatives

Animal welfare discussions were once morally and intellectually stimulating. The original laws, like as the UK Cruelty to Animals Act of 1822, prioritized moral commitments above quantifiable welfare metrics in an effort to stop egregious cruelty (Rollin, 1995). Scientific research on animal behavior, physiology, and intellect has, however, led to an evolution in welfare standards, and evidence-based laws that connect ethics, productivity, and sustainability are now feasible (Webster, 2016).

Modern welfare concerns are based on market dynamics, corporate culture, and national and international regulatory standards. Regulating harmonization provides access to international trade, judicial protection for animals, and worldwide standards like that of the European Union and OIE (World Organization for Animal Health, 2021; European Commission, 2020; OIE, 2021). Welfare-based systems are more effective and advantageous from an economic standpoint as they reduce illness losses brought on by stress, development retardation, and carcass damage Terlouw, Arnould and Auperin, 2008).

Second, it adds value beyond ethics and productivity by including well-being into sustainability models. Since welfare protocols increase the intake of water and feed, decrease the emission of green gas, decrease drug dependency, and provide social allowances for more dependable individuals and better working conditions, they are a great addition to environmental stewardship (FAO, 2020; Webster, 2016).

5.1.3 Scope and Objectives of the Chapter

This chapter gives an international perspective of animal welfare law and certification schemes and their impacts on productivity, meat quality, and sustainability. Its objectives are (1) to trace welfare standards' historical evolution and moral foundations; (2) to deal with regional and global regulatory contexts through case studies in the European Union, the United States, and newly industrializing economies; (3) to compare certification schemes, audit systems, and technology solutions promoting compliance and transparency; (4) to link welfare compliance with productivity improvement, meat quality, and economic return; (5) to quantify the synergy among welfare rules, sustainability targets, and social responsibility; and (6) to summarize issues, debate, and direction in international welfare policy and practice (Fraser, 2008; Rollin, 1995).

The chapter illustrates how welfare-based tactics lead to concurrent improvements in economic performance, environmental sustainability, and ethical standards by fusing scientific research, regulatory policy, and corporate strategy. The chapter emphasizes how animal welfare in meat production has evolved from a mostly ethical concern to a multifaceted need with obvious connections to market success, productivity, and sustainable livestock production systems.

In conclusion, because of its sustainability, economic productivity, and moral devotion to the law, animal welfare is acknowledged as a normal aspect of the production of meat. Animal health, stress levels, meat quality, and market competitiveness all have all been demonstrated to improve with welfare management. In showing that ethical cattle production is more socially and economically desirable, certification and audit strategies also help build customer confidence. This chapter lays the groundwork for observing the welfare, productivity, and sustainability nexus at the multilateral level for future research on regulations, certification schemes, and policy making to draw upon (Figure 5.1).

5.2 Foundations of Animal Welfare Regulation

Animal welfare lawmaking and adoption is a cross-cutting top priority of social pressure, moral responsibility, and scientific expertise in animal needs. Current legislation seeks to encourage humane handling in conjunction with sustainable and efficient meat production systems (Rollin, 1995; Webster, 2016).

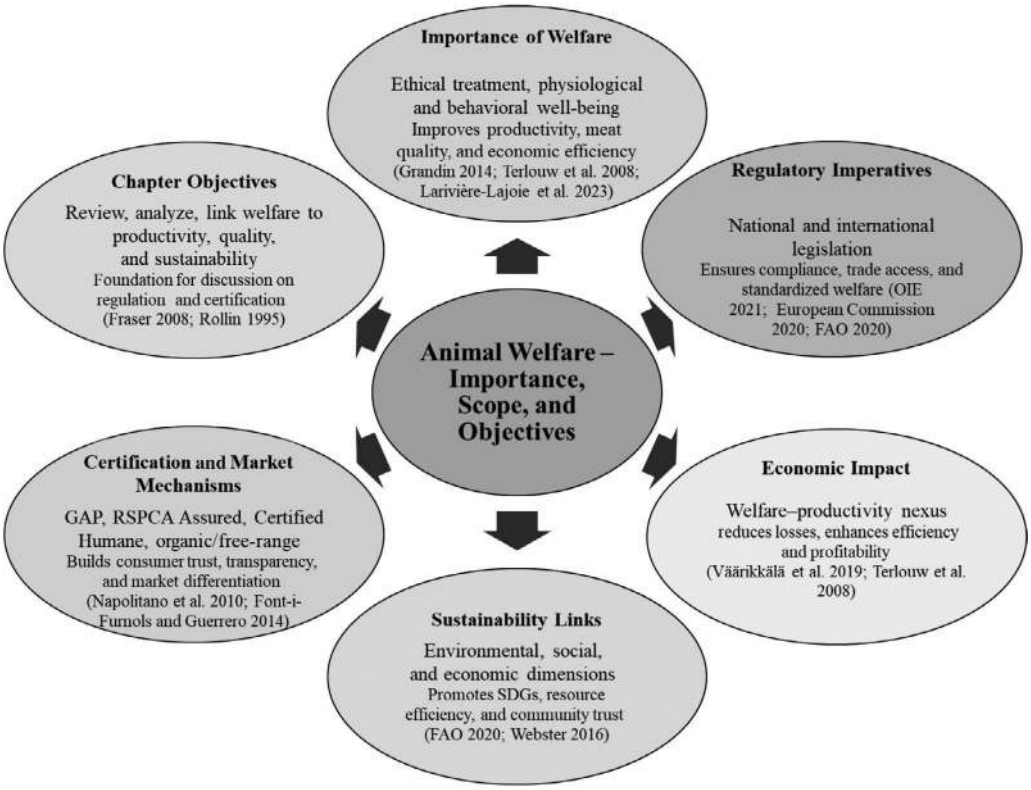

FIGURE 5.1 Chapter overview: Importance, scope, and objectives.

Systems of control are determined by the past, moral tradition, and global advice, forming the legal and practical framework for modern animal welfare compliance.

5.2.1 Evolution of Animal Welfare Standards

Animal welfare management has advanced gradually, frequently in reaction to campaigns, scientific advancements, and protests. The primary goal of early laws, such as the UK Cruelty to Animals Act 1822 and later Protection of Animals Acts, was to stop blatant animal abuse and cruelty (Rollin, 1995). Acts law was not proactive in promoting welfare; rather, it was reactive, addressing evident misery. The emphasis shifted from housing, transportation, and slaughter to farm animal care in the middle of the twentieth century (Fraser, 2008).

A major shift in social policy was brought about by the Brambell Report of 1965, which listed the "Five Freedoms": the freedom from hunger and thirst, discomfort, pain, injury, or sickness, fear and suffering, and the capacity to behave properly. The code offered a practical, globally accepted benchmark for laws, audits, and certification initiatives. Over the next few decades, scientific information, including that from physiology and ethology, was included into welfare evaluations to offer an evidential basis for regulatory requirements.

Through the development of internationally accepted standards and practices, international organizations such as the FAO, the WOAH (OIE), and the International Organization for Standardization (ISO) have facilitated the globalized application of animal welfare standards in the twenty-first century (OIE, 2021; FAO, 2020; ISO, 2019).

They are continued targets of welfare aligned across countries but with flexibilities to evolve with changing environment, economy, and culture. Trade requirements, food safety standards, and sustainability can thereby be balanced against welfare legislation by the governments.

5.2.2 Theoretical and Ethical Basis of Regulations

Modern welfare principles are grounded in ethical as well as scientific paradigms. The Five Freedoms remain a simple model founded on the prevention of adverse states, and the Five Domains approach extends this by including positive experiences like comfort, nutrition, social interaction, and environmental enrichment (Mellor and Beausoleil, 2015). These models inform legal standards, farm-based practice, and certification worldwide, supporting a more integrated concept of welfare.

Ethics form the basis of regulatory thinking, balancing utilitarian and right-based arguments. Utilitarian ethics are more likely to maximize total happiness versus productivity against the alleviation of pain. Rights arguments acknowledge animals as sentient beings with inherent value to be protected even if it is at the expense of efficiency (Fraser, 2008; Rollin, 1995). Cultural and religious beliefs also influence the drafting and implementation of welfare legislation, providing public attitudes and consumer demand with guidance (Webster, 2016).

These ethical and scientific principles are transformed into legally binding requirements for housing, feeding, handling, transportation, and slaughter by modern regulations. Given that humane treatment is linked to production efficiency and economic sustainability, welfare compliance is becoming more and more associated with meat quality, food safety, and customer trust (Grandin, 2014; Larivière-Lajoie *et al.*, 2023). Such qualities are often institutionalized by certification systems in order to allow market differentiation, auditability, and traceability.

In summary, legacy law, ethics theory, and science all come together to provide animal welfare law. Welfare is defined by basic models like the Five Freedoms and Five Domains, and global principles by organizations like the FAO, ISO, and OIE standardize norms across borders. Standards of operation are developed and enforced in accordance with moral theory, which strikes a middle ground between utilitarian and rights theory. Welfare compliance is guaranteed to generate sustainability, meat quality, and productivity in modern systems of livestock (Table 5.1).

TABLE 5.1

Evolution of Animal Welfare Regulation: Milestones, Frameworks, and Ethical Principles

Category	Milestone/Framework	Description	Relevance/Impact	References
Historical legislation	UK Cruelty to Animals Act (1822)	Early law preventing overt abuse	Set foundation for animal protection	Rollin, 1995
Farm animal protection	Brambell Report (1965)	Introduced "Five Freedoms"	Basis for farm animal welfare assessment and policy	Brambell, 1965; Fraser, 2008
International Standards	OIE Terrestrial Animal Health Code (2021)	Global welfare standards for transport, slaughter, and husbandry	Harmonizes international trade and welfare compliance	OIE, 2021
International guidelines	FAO Codes of Practice (2020)	Technical guidance for sustainable livestock management	Aligns welfare with food security and environmental goals	FAO, 2020
Standardization	ISO 22005 ISO 1087 (2019)	certification and traceability standards, including welfare considerations	Ensures compliance across supply chains	ISO, 2019
Ethical frameworks	Five Domains (Mellor and Beausoleil, 2015)	Expands Five Freedoms to include positive experiences	Guides welfare assessment, law, and certification	Mellor and Beausoleil, 2015
Ethical debate	Utilitarian versus rights-based approaches	Balances productivity and intrinsic animal value	Shapes legislation, enforcement, and public expectations	Rollin, 1995 Fraser, 2008

5.3 Global Animal Welfare Legislation

Cultural values, political agendas, economic expansion, and the development of scientific understanding of animal requirements all have an impact on regional variations in animal welfare legislation. Since current legislation is more in accordance with international trade requirements and science-based welfare standards, the ethical treatment of livestock enhances productivity, meat quality, and market access (Grandin, 2014; OIE, 2021). As a result, good fortune serves two purposes: it promotes animal welfare and provides meat production chains with sustainable and profitable bottom lines. Regional frameworks, upcoming laws in emerging nations, and the effects of global trade and agreements on welfare standards all are covered in this chapter.

5.3.1 EU Framework

The European Union is one of the largest and most comprehensive systems for animal welfare. Essential legislation makes the whole process of cattle breeding: housing, transport, and slaughter a subject to regulation. Council Directive 98/58/EC establishes overall standards of welfare for farmed animals, and Council Directive 2008/120/EC sets detailed housing and enrichment standards for pigs in terms of space allowance, bedding, and housing groups. Vehicle construction, journey duration, and rest times all are governed by Regulation (EC) No. 1/2005, which also concerns the welfare of animals in transit. Regulation (EC) No. 1099/2009 prohibits killing, and humane stunning is employed, along with lairage planning and careful observation to lessen suffering and stress (European Commission, 2020). By connecting ethical production to economic and environmental outcomes, including resource efficiency and consumer trust, the European Green Deal strategy and Farm-to-Fork Strategy align well-being with broader sustainability goals (European Commission, 2020).

5.3.2 The United States

State and federal legislation concerning animal welfare are in effect in the United States. Farm animals are mostly excluded from the Animal Welfare Act (AWA, 2007), which regulates animals used for research, display, transit, and sale. Minimum space requirements for breeding pigs, laying hens, and veal calves are regulated by state legislation, such as California's Proposition 12 (Bursey and Thomas, 2018), which has an impact on production techniques outside of the state (Mench et al., 2014). This consumer-driven approach relies on consumer expectation, litigation, and certification programs to augment federal law. US welfare standards increasingly mirror international norms in an attempt to address foreign market access and welfare-sensitive export demands.

5.3.3 Asia and Developing Regions

Asian, African, and Latin American animal welfare law is varied and in development. Humane treatment is promoted by China's national policy for handling slaughter and farmed animal transportation, but the enforcement remains extremely uneven (Marchant *et al*., 2021). Indian Prevention of Cruelty to Animals Act provides law to humane treatment, and greater production-focused welfare emphasis is on the rise (FAO, 2020). Under the overall direction of EU and US commercial interests, South American countries such as Chile, Brazil, and Argentina have species-specific legislation for housing, transport, and slaughter (Grandin, 2014). OIE recommendations are a significant driver of welfare enhancement in Africa; however, weak training and physical facilities restrict enforcement, which is the biggest hindrance to practice being aligned with the demands of international trade (FAO, 2020).

5.3.4 Trade and International Agreements

Welfare compliance is being increasingly incorporated in international trade as an entry requirement into the market. Welfare-based non-tariff barriers are permitted under WTO (World Trade Organization) law

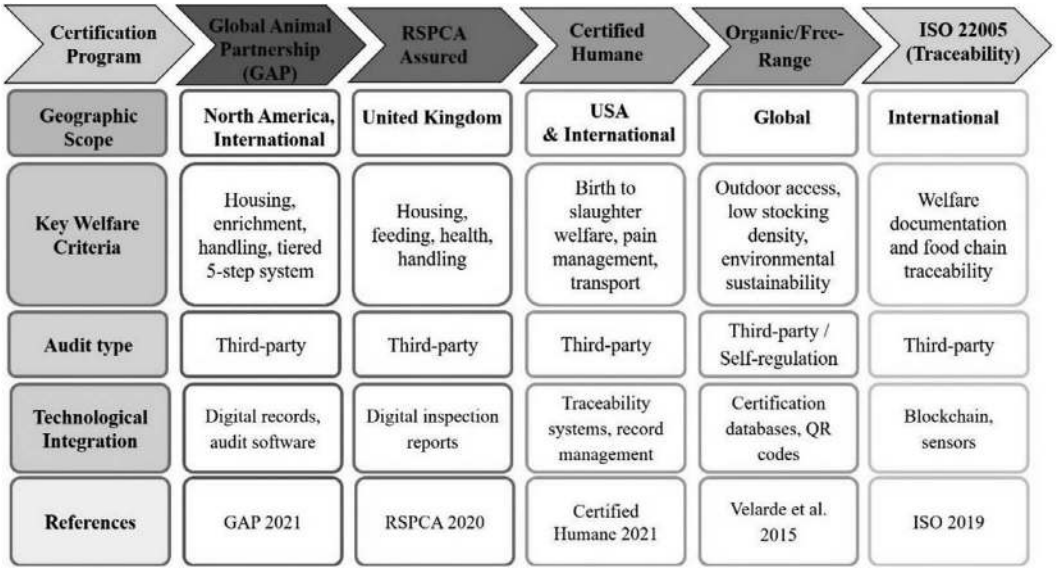

FIGURE 5.2 Major animal welfare certification programs and auditing approaches.

(Matsushita *et al*., 2015), as long as they are not disguised protectionism. Codex Alimentarius (2020) standards harmonize humane slaughter methods and treatment as well as animal hygiene, which assists with harmonization between import–export countries. World Organization for Animal Health (OIE, 2021) standards are global standards for compliance in welfare, whereby such compliance tends to be a condition for export certification, and thus cross-border acceptance of practice in welfare. The drivers lead to the convergence of welfare standards globally and force manufacturers to adopt welfare-centered practices that are commercially acceptable and ethical.

Due to cultural, economic, and regulatory variations, international animal welfare legislation continues to be multilateral. The United States has a federal–state cooperation; Asia, Latin America, and Africa have various emerging legal systems; and the European Union offers comprehensive, evidence-based legislation. Welfare-based practices enable moral, efficient, and market-driven meat production systems, and global trade policies and standards such as the WTO, Codex, and OIE are causing harmonization (Figure 5.2).

5.4 Certification and Assurance Schemes

Growing public concern for animal well-being, along with consumer ethics, has placed certification and assurance programs as central components of today's meat business. Going beyond what regulations command, certification programs ensure transparency, encourage consumers' confidence, and enhance competitiveness in the domestic and export markets (Lundmark, Rydhmer and Lundeheim, 2020; Velarde, Dalmau and Manteca, 2015). These schemes bridge the gap between welfare requirements for legislation and consumer expectations and give producers a motive for implementing enhanced welfare measures.

5.4.1 Role and Significance of Certification

Certification schemes play a number of roles down the meat supply chain. First, they offer transparency, with consumers being able to have confidence that welfare standards are met through verifiable evidence. Labeling, audit certificates, and electronic traceability systems allow consumers to make informed choices and assess ethical production practice. Second, certification raises consumer trust that

is converted to greater willingness to pay premiums for welfare-compliant products. Independent verification, for instance, third-party audits, enhances credibility and reduces skepticism toward assertions of welfare (Harper and Henson, 2001). Third, certification makes a company more competitive in the market. In countries like the EU, UK, and North America with strict regulations on animal protection, companies that obtain welfare certificates can enter premium markets. Above all, the schemes can establish a virtuous feedback loop, linking moral treatment to economic and productivity gains. Welfare-standard farms have lower mortality rates, better growth, and less stress-related meat deformities (Grandin, 2014; Webster, 2016).

5.4.2 Major Certification Programs

Several domestic and international initiatives provide official welfare certification programs:

- *Global Animal Partnership (GAP 2021)*: The North American program rates environmental enrichment, housing, and human treatment in five phases. Manufacturers are encouraged to continuously improve and raise welfare standards by progressive approaches.
- *Royal Society for the Prevention of Cruelty to Animals (RSPCA 2020)*: This program covers cattle, pigs, and poultry and offers feedlot, food, health, and handling standards along with a third-party evaluation for compliance.
- *USA and International Certified Humane*: This offers the necessary space, pain relief, conveyance, and well-being from birth until the slaughterhouse. Independent checking is done by accredited checkers (Humane Certification, 2021).
- *Organic and Free-Range Labels*: Focusing on incorporating sustainability and environmental results first, these labels will probably incorporate animal welfare standards like outdoor access and reduced stocking rates, providing an additional ethical guarantee (Velarde, Dalmau and Manteca, 2015).

5.4.3 Animal Welfare Auditing Systems

The legitimacy of certification systems is guaranteed by auditing. By using scoring systems, template checklists, and on-farm inspections, third-party evaluation lowers the likelihood of "welfare washing" and permits independent verification. However, self-regulation has a higher risk of bias and less external responsibility, but it also enables producers to self-enforce compliance.

Recent technology has revolutionized traceability and welfare auditing in the recent past. Blockchain and digital traceability enable real-time tracking of animals through the supply chain and back to consumer labels, with attached welfare records. Ongoing objective quantification of welfare indicators is facilitated by automated welfare scoring by means of sensor-based behavior monitoring and AI-driven video analysis (Kampan, Tsusaka and Anal, 2022; Lundmark, Rydhmer and Lundeheim, 2020). Accuracy improves, cost is avoided on auditing and compliance is facilitated by international requirements, thereby making certification more scalable and trustworthy.

Certification and assurance schemes thus play a very important part in aligning animal welfare standards with market needs. Facilitating a culture of transparency, confidence, and competitiveness, such programs promote improved welfare practice. Connection to technology also enhances auditing, traceability, and continuous improvement to guarantee ethical practice is achieved in measurable terms of productivity, meat quality, and sustainability (Figure 5.3).

5.5 Linking Welfare Regulations to Productivity and Meat Quality

Animal welfare law precedes moral duty to become compelling drivers of performance, meat quality, and enterprise in modern-day livestock production. Welfare management that works minimizes physiological and psychological stress, enhances growth and reproductive performance, and can lead

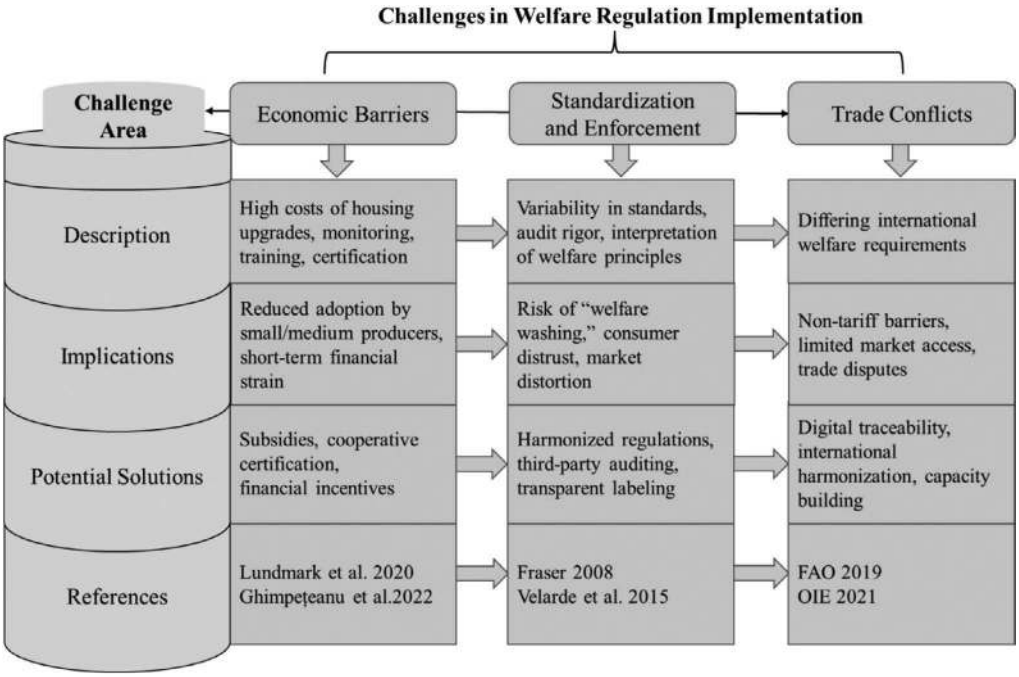

FIGURE 5.3 Key challenges in welfare regulation implementation.

to improved market value of meat products by fulfilling consumers' needs for morally produced meat (Grandin, 2014; Webster, 2016). Stricter application of welfare regulation, therefore, balances moral duty with business and commercial interest, and places welfare in the public sphere as a necessary part of sustainable livestock farming.

5.5.1 Welfare–Productivity Nexus

Productivity and well-being have a well-established link. According to Hemsworth and Coleman (2010), lowering stress in livestock enhances growth rates, feed efficiency, reproductive success, and general health outcomes. According to Nicol (2001), overcrowding, poor housing, physical handling, and extended transportation are some of the stresses that increase cortisol and catecholamine levels at the expense of metabolism, immunological function, and reproductive cycles. There is evidence that welfare-enhancing measures, including minimal-stress handling, optimal stocking density, and enriched housing, improve growth and reproductive efficiency while reducing mortality and veterinary expenses. For instance, pigs raised in enriched housing systems record better weight gains and reduced lesion rates, which are framed in the context of farm-level profitability (Van de Weerd and Day, 2009). Furthermore, chickens that get environmental enrichment exhibit better feed efficiency and less stress-related behavior, which strengthens the link between production outcomes and welfare practices (Lundmark, Rydhmer and Lundeheim, 2020). The long-term benefits of implementing welfare-friendly methods include decreased losses, increased productivity, and access to high-value markets, even if doing so may need an initial financial outlay (Grandin, 2014).

5.5.2 Welfare Impacts on Meat Quality

Animal welfare has direct and immediate effects on meat quality, particularly in relation to the control of stress prior to slaughter. Severe stress depletes the glycogen stores, having an effect on postmortem drop in pH and causing defects such as PSE pork and poultry meat, while chronic or ongoing stress may result in DFD beef in cattle (Larivière-Lajoie *et al.*, 2023). Regulation of welfare of law-proper handling by

humans, good transportation, and humane stunning—avoids quality flaws, promoting tenderness, flavor, color, and shelf life. Low stress also minimizes bruising, carcass damage, and drip loss, improving aesthetic and commercial quality of meat products (Grandin, 2014; Webster, 2016).

5.5.3 Consumer Perceptions and Market Value

Consumer concern for welfare practices had a significant part to play in consumer buying behavior and market forces. GAP, RSPCA Assured, and Certified Humane are some of the schemes providing compliance certification, instilling trust in ethical production and leading consumers to pay premium prices (Harper and Henson, 2001). The customers are ready to pay even a 10–30% premium for European, North American, and Asian urban market welfare-friendly products that are certified in Europe- and North America–based origin (Lundmark, Rydhmer and Lundeheim, 2020; Velarde, Dalmau and Manteca, 2015). From the price point, welfare certification also decides brand loyalty, market segmentation, and export-led or domestic high-value entry market. Its link to meat productivity and quality thus places a synergistic value, blending moral and economic worth with consumer pleasure.

In summary, animal welfare legislation generates benefits of complexity. Reduced stress improves growth, reproduction, and health, with assured improved meat quality attributes such as tenderness, color, and shelf life. Certification and compliance programs establish consumer trust, typically leading to price premiums and access into high-value markets. Strategic integration of welfare standards into livestock production systems, therefore, contributes ethical responsibility, economic rewards, and sustainable production practices (Table 5.2).

TABLE 5.2

Global Animal Welfare Legislation: Regional Overview

Region / Country	Key Legislation/ Guidelines	Scope/Focus	Implications for Meat Production	References
European Union	• Council Directives 98/58/EC 2008/120/EC • Council Regulations 1/2005, 1099/2009 • Farm-to-Fork • Green Deal	• Housing • Transport • Slaughter sustainability integration	• Comprehensive standards support productivity • Meat quality and market access	European Commission, 2020
The United States	• Animal Welfare Act (2007) Proposition 12 (California)	• Research exhibition Farm-level housing and transport	• Partial federal coverage • State initiatives influence production practices	Mench et al., 2014 Grandin, 2014
China	• National Guidelines for Livestock Transport and Slaughter	• Transport • Humane handling	• Emerging standards • Variable enforcement • Export-driven compliance	Marchant et al., 2021
India	• Prevention of Cruelty to Animals Act • Livestock-Specific Guidelines	• Humane treatment • Minimum welfare standards	• Limited farm animal legislation • Growing focus on production systems	FAO, 2020
Latin America	• Chile, Brazil, Argentina—Species-Specific Welfare Standards	• Housing • Transport • Slaughter	• Export-oriented compliance • Alignment with EU/US markets	Grandin, 2014
Africa	• OIE-guided welfare improvements	• Basic welfare • Transport • Slaughter	• Resource and infrastructure constraints • Adoption guided by international trade	FAO, 2020
International Trade	• WTO • Codex Alimentarius • OIE standards	• Trade facilitation Non-tariff measures	• Welfare compliance required for export access • Harmonization of practices	OIE, 2021; Codex Alimentarius, 2020

5.6 Welfare Regulations and Sustainability Goals

Policy for animal welfare is increasingly becoming recognized as one of the most important ingredients of sustainable beef production, ranging from social enjoyment, environmental, ethical, and economic performance (Fraser, 2008; Lundmark, Rydhmer and Lundeheim, 2020). In addition to supporting animal production and health, welfare-based approaches can be employed to pursue more universal goals such as community development, food security, and climatic mitigation. Producers attain the co-benefits of producers beyond ethical acceptability through the integration of welfare standards in animal production systems to attain healthy, sturdy, and socially acceptable meat production.

5.6.1 Welfare as a Pillar of Sustainable Livestock Systems

Sustainable livestock systems integrate economic, social, and environmental dimensions in alignment with the United Nations Sustainable Development Goals (SDGs). Animal welfare directly intersects with multiple SDGs, demonstrating its role as a sustainability driver:

- *SDG 2—Zero Hunger*: Healthy, well-managed animals exhibit higher growth and reproductive efficiency, increasing food availability and contributing to national and global food security (FAO, 2019).
- *SDG 3—Good Health and Well-Being*: Welfare-focused livestock management reduces disease prevalence, lowering pathogen transmission risks for both animals and humans (Weary and Robbins, 2019).
- *SDG 12—Responsible Consumption and Production*: Compliance with welfare standards fosters efficient resource utilization, ethical production, and reduced waste in livestock systems (Van Zanten, Van Ittersum and de Boer, 2019).
- *SDG 13—Climate Action*: Well-managed, low-stress animals demonstrate improved feed conversion efficiency, reducing greenhouse gas emissions per unit of meat produced (Herrero, Henderson and Havlík, 2016).

Thus, including welfare concepts into industrial processes guarantees moral adherence while both increasing output and lessening environmental impact.

5.6.2 Environmental Co-Benefits of Welfare-Oriented Systems

Welfare-based practice of management bestows immense environmental advantage:

1. *Lower Disease Incidence*: Appropriate care, housing, and ventilation lower reduced disease incidence. By minimizing chemical interference and environmental pollution, proper care, shelter, and ventilation reduce vulnerability to infectious illnesses brought on by stress (Weary and Robbins, 2019).
2. *Decreased Antibiotic Use*: To prevent exposure to antimicrobial resistance, animals in good health and which adhere to welfare standards need less medications (Ghimpețeanu, Pogurschi and Popa, 2022).
3. *Efficiency of Resources*: Reduced land, water, and energy inputs per unit of meat are achieved by improved nutrition, proper stocking densities, and environmental stimulation, which also improve feed conversion and growth (de Vries, Bokkers and Van Reenen, 2015).

These mechanisms equate to welfare compliance as a co-benefit driver that accrues not just to animal health but also to the environmental impact of livestock production.

5.6.3 Social Sustainability

Welfare standards contribute to social sustainability as well by favoring safer, ethical, and more transparent production systems:

- *Welfare of Farmers*: Good welfare practice training and low-stress handling improve staff job satisfaction, safety, and morale (Grandin, 2014).
- *Community Trust*: Social certification of welfare achieves community trust in humane livestock production, earning social license to operate and industry accreditation (Velarde and Dalmau, 2012).
- *Labor Conditions*: Occupational health, handling, and training standards improve the quality of the work environment and professional capacity (FAO, 2019).

By sustaining social responsibility, welfare legislation supports economic and environmental goals for sustainability, which yield multidimensional benefits.

In conclusion, welfare legislation provides moral, environmental, social, and economic advantages promoting the sustainability of livestock systems. Welfare-oriented strategies improve meat quality, market access, and output via reductions in stress and disease incidence, improvement of resource use efficiency, and improving working and community performance. To this end, including compliance with welfare is a strategic option that improves the long-term sustainability of meat production systems along with economic resilience, environmental stewardship, and ethical behavior (Table 5.3).

5.7 Challenges and Controversies

Although there are apparent benefits of animal welfare standards to ethical compliance, productivity, meat quality, and sustainability, their implementation is constrained by numerous problems. Farmers, the regulator, and industry stakeholders have to deal with economic, regulatory, and trade-driven limitations to achieve real welfare compliance and maintain economic sustainability. It helps to grasp such challenges for policymaking and designing systems that reconcile welfare aspirations with reality.

TABLE 5.3

Effects of Animal Welfare Regulations on Productivity, Meat Quality, and Market Value

Welfare Intervention	Productivity Impact	Meat Quality Effect	Market/Consumer Outcome	References
Enriched housing, proper stocking density	Improved growth, feed efficiency, reduced mortality	Lower bruising, fewer defects	Higher marketable yield, price premium	Van de Weerd and Day, 2009; Grandin, 2014
Low-stress handling and transport	Reduced stress, improved reproductive performance	Reduced PSE/DFD occurrence	Enhanced meat appearance, tenderness, and shelf life	Larivière-Lajoie et al., 2023; Czycholl et al., 2015; Hemsworth and Coleman, 2010
Pre-slaughter stunning and humane slaughter	Minimized acute stress responses	Improved pH stability, color, tenderness	Consumer confidence, certification compliance	Grandin, 2014 Webster, 2016
Welfare-certified labeling (GAP, RSPCA, Certified Humane)	Indirect via compliance incentives	Consistent high-quality products	Willingness to pay premiums, market differentiation	Harper and Henson, 2001; Velarde et al., 2015

5.7.1 Economic Barriers for Farmers

The top-down enforcement of welfare standards will at times involve substantial investment in housing, technology, training, and audit. Supervisors may be required to refurbish barns or pens to accommodate the needed space, ventilation, and environmental stimulation, install monitor technologies such as sensor-based welfare scoring, or pay for third-party certification audits (Lundmark, Rydhmer and Lundeheim, 2020; Velarde, Dalmau and Manteca, 2015).

Small- and medium-sized producers frequently experience temporary financial pressure even though welfare-friendly techniques typically increase output and provide access to premium markets. There is evidence that initial investment costs might be higher than early economic returns, especially in developing nations with inadequate technical and infrastructure capabilities (Ghimpețeanu, Pogurschi and Popa, 2022; Hemsworth and Coleman, 2010). Economic obstacles can be lessened by financial assistance systems, including cost-sharing plans, cooperative certification programs, and subsidies. However, methods that balance profitability and welfare compliance are necessary to ensure long-term adoption.

5.7.2 Standardization and Enforcement Issues

One of the greatest welfare regulation challenges is that standards and enforcement vary widely between regions and certification programs. There are variations in the definition of welfare standards, such as minimum space, environmental enrichment, and maximum transport durations. Similarly are audit frequency and intensity, ranging from self-certification to independent third-party audits. Ethical models, such as the "Five Freedoms" or the "Five Domains", vary in interpretation across regulatory, commercial, and cultural contexts (Fraser, 2008; Webster, 2016).

This heterogeneity increases the risk of "welfare washing", where products are labeled as being welfare-compliant with very little regulation. Consumer trust is diminished, markets are distorted, and producing businesses that are genuinely complying can be penalized by such actions (Lundmark, Rydhmer and Lundeheim, 2020; Velarde, Dalmau and Manteca, 2015). Thus, trust needs to be underpinned by more standardization, more transparency, and the incorporation of independent auditing procedures, particularly for companies wanting to export to high welfare standard markets.

5.7.3 Future of Trade Conflicts

Animal welfare requirements increasingly function as non-tariff trade barriers when they are included into global commerce. Nations with less restrictive regulations can face market access controls, higher levels of compliance costs, or WTO rule-based dispute if welfare regulation is seen as protectionism instead of evidence-based (OIE, 2021; FAO, 2019). Exports could require housing, transport, and slaughter techniques to meet EU or North American levels in an attempt to ensure market access, for instance.

Digital traceability technology and certification programs can help importers comply by giving them verified welfare data. To combine domestic welfare gains with worldwide market involvement, trade-related disputes still pose a threat, highlighting the necessity of international harmonization, capacity-building, and stakeholder cooperation.

In conclusion, laws pertaining to animal welfare face several obstacles in spite of their moral and economic advantages. International commerce increases complexity and costly compliance costs for small businesses, while inconsistent regulations can lead to welfare washing and consumer mistrust. Stakeholder participation, comprehensive audits and certification, welfare standard harmonization, and targeted financing all are required to address these concerns. By eliminating these barriers, welfare rules can effectively produce ethical, fruitful, and long-lasting outcomes in cattle systems.

5.8 Future Perspectives and Policy Directions

The calls for technological change, stakeholder interaction, policy alignment, and incorporation into sustainable agriculture approaches are shaping the trajectory of animal welfare law. Existing law has pushed

the bar high in safeguarding animals, but developing issues like stress due to global trade, environmental change, and changing consumer preferences require forward-looking strategies in which welfare is embedded in robust and regenerative livestock systems (Lundmark, Rydhmer and Lundeheim, 2020; Velarde, Dalmau and Manteca, 2015).

5.8.1 Strengthening Regulatory Frameworks

Global harmonization of welfare levels is a goal for the future. Facilitations toward compliance are restricted by current diversity among countries, especially those exporters who want to sell to high-welfare countries (OIE, 2021). Making provision for the ability to set overall standards for handling, housing, feeding, and healthcare through the development of global minimum levels of welfare on science-based models such as "Five Freedoms" and "Five Domains" is an option. Mutual recognition arrangements by trading partners also cut down on the barriers but at high welfare levels, so that there is equal market access and regulatory certainty. Moreover, linking the welfare agenda to all-around sustainability goals, including climate action and social justice, strengthens the integrity of livestock governance and aligns compliance with regulations with the United Nations Sustainable Development Goals (SDGs) (FAO, 2019).

5.8.2 Role of Innovation and Technology

Technological innovation is capable of revolutionizing welfare monitoring and enforcement. Sensor networks, robot feeding, and temperature control systems are some of the precision livestock farming (PLF) technologies that allow monitoring of animal activity and environment at all times. This enables one to respond promptly to avoid stress or disease (Berckmans, 2014). Artificial intelligence–based auditing platforms and electronic certification platforms allow checking for compliance in real time, which lessens the need for the time-consuming aspects of inspections while increasing accuracy as well as transparency (Lundmark, Rydhmer and Lundeheim, 2020). Blockchain traceability platforms supplement these impacts further by linking welfare data to in-retail consumer labels directly, enabling differentiation of the market and premium prices (Velarde, Dalmau and Manteca, 2015). Overall, these innovations maximize efficiency, accountability, and scalability of welfare compliance programs.

5.8.3 Education, Advocacy, and Stakeholder Engagement

Welfare regulation takes effect depending on their awareness and stakeholder participation. Farmers require training in specialized skills such as low-stress handling, nutritional care, construction of housing, and disease control to effectively implement welfare-friendly practices. Policymakers are better served by evidence-based learning in order to design incentives, subsidies, and regulations toward facilitating compliance. Consumers and retailers exert market pressure, ethical consumption restoring economic value for conformity with welfare (Harper and Makatouni, 2002). Structured interaction in the forms of participatory workshops, certification training courses, and public–private partnership exerts collaboration and shared responsibility, motivating all to be involved in ethical and sustainable livestock production.

5.8.4 Integration into Circular and Regenerative Agriculture

Welfare is a key sustainability component of circular and regenerative farm systems, which are being adopted by next-generation animal production systems. Resource use efficiency reduces the stress that animals experience at the cost of reduced feed, water, and energy. Rotational grazing and pasture management are two regenerative practices that improve soil health, biodiversity, animal welfare, and carbon sequestration at once. Closed-loop nutrition cycles and precision feeding optimize growth on a low environmental price tag, demonstrating welfare's overlap with ecological resilience and economic resilience (Herrero, Henderson and Havlík, 2016). By integrating welfare into systems, animal agriculture is primed to be ethical, socially responsible, and climate-aware.

TABLE 5.4

Co-Benefits of Welfare-Oriented Livestock Systems

Welfare Focus Area	Environmental Benefits	Social Benefits	Economic/Productivity Benefits	References
Housing and enrichment	Improved air quality, reduced stress-related emissions	Safer, more satisfied workers	Better growth, lower mortality	Grandin, 2014; Weary and Robbins, 2019
Nutrition and feeding	Optimized feed conversion, reduced resource use	Enhanced worker engagement through precision feeding	Improved weight gain, reproductive efficiency	de Vries et al., 2015; Herrero et al., 2016
Health and disease management	Lower antibiotic use, reduced pathogen spread	Improved public trust, community health	Reduced veterinary costs, higher productivity	Ghimpețeanu, Pogurschi and Popa, 2022; FAO, 2019
Welfare certification	Supports traceability, compliance with SDGs	Builds community confidence, ethical branding	Access to premium markets, price premiums	Velarde et al., 2015 Lundmark et al., 2020

In conclusion, harmonization, innovation, stakeholder involvement, and integration into sustainable agro-ecosystems are crucial pillars of future visions regarding animal welfare. Learning and advocacy allow stakeholders to adopt welfare-conformant practices, and circular, regenerative systems link ethical livestock farming to environmental and economic resilience. All these in combination provide a complete blueprint for moving the animal welfare agenda forward in the realm of modern sustainability, market, and ethics priorities (Table 5.4).

5.9 Conclusions

Animal welfare laws and certification schemes have recently become common in livestock production, fusing sustainability, meat quality, and productivity objectives with moral considerations. As welfare standards have evolved from their inception as the UK Cruelty to Animals Act (1822) to their current frameworks based on the Five Freedoms and Five Domains, there has been a noticeable shift away from ethical care and scientific understanding and regulatory control. Global regulation shows the increasing convergence of welfare into market access, trade compliance, and sustainability policy goals. Examples of this include EU directives, US federal and state regulations, and upcoming regulations in Asia, Latin America, and Africa.

Programs of certification and assurance such as GAP, RSPCA Assured, and Certified Humane are required to facilitate welfare norms and maximize consumer confidence, competitiveness, and transparency. Welfare-based strategies create room for premium price and market segmentation and minimize stress, improve growth and reproductive performance, and improve meat quality, according to scientific evidence. Welfare compliance strengthens social objectives like farmer welfare, worker protection, and public confidence as well as environmental sustainability by improving resource efficiency, minimizing the use of antibiotics, and minimizing disease prevalence.

Despite these advantages, there are also implementation issues, such as possible trade disputes, inconsistent enforcement, and financial obstacles. Stakeholder involvement, technology advancement, regulatory alignment, and welfare integration into circular and regenerative livestock systems all are highlighted in a future vision. All of these methods demonstrate that, in addition to being morally required, animal welfare is a key factor in the development of robust, sustainable, and profitable meat production systems across the world (Table 5.5).

TABLE 5.5

Future Strategies for Strengthening Animal Welfare Compliance

Strategy Area	Key Actions	Expected Outcomes	References
Regulatory harmonization	• Establish global minimum standards • Mutual recognition agreements	• Consistent compliance • Reduced trade conflicts	OIE, 2021; FAO, 2019
Innovation and technology	• Precision livestock farming • AI auditing • Blockchain traceability	• Real-time monitoring • Cost-efficient • Enforcement • Transparency	Berckmans, 2014; Lundmark et al., 2020
Education and stakeholder engagement	• Training farmers, policymakers, and retailers • public advocacy	• Improved adoption • Ethical consumption • Market-driven compliance	Harper and Makatouni, 2002; Velarde et al., 2015
Circular and regenerative integration	• Pasture-based systems • Rotational grazing • Closed-loop nutrient cycles	• Enhanced welfare • Sustainability • Productivity • Climate resilience	FAO, 2019; Herrero et al., 2016

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6

Animal Selection and Management Strategies for Meat Quality and Sustainability

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6.1 Introduction

The livestock sector is very important for global food security; the trends of demographic growth and urbanization continue to increase the demand for animal-based protein (Davis and White, 2020). Worldwide, per capita meat consumption increased from 25 kg in 1961 to 48 kg in 2013, with predictions indicating further growth of 75–145% by 2050 (Godfray *et al*., 2018). Additionally, consumers increasingly expect meat products to deliver consistent quality and nutritional value while maintaining animal welfare and sustainability (de Araújo *et al*., 2022; Grunert, Bredahl and Brunsø, 2004; Regan, Henchion and McIntyre, 2018). These standards redefine the concept of quality, going beyond basic productivity to include requirements such as aesthetic fulfillment, reliability, and sustainability.

The quality of meat is multidimensional and strongly influences market acceptability and profitability. Visual elements, such as color, remain key drivers of purchase decisions, whereas tenderness and water-holding capacity influence eating experience and economic value through effects on juiciness and purge loss (Balage *et al*., 2018; Garmyn, Miller and Bekhit, 2017). Chemical composition, such as intramuscular fat and a more generalized nutrient composition, also adds to palatability and perceived value (Geletu *et al*., 2021; McCrickerd and Forde, 2016). Importantly, these traits are not static but arise from biological processes and are influenced by genotype and by management conditions during the life of the animal, especially at times of high risk, for example, during transport, in lairage, and in slaughter.

Tougher sustainability and welfare parameters now control quality enhancement. Livestock contributes to the emission of greenhouse gases (GHGs) and requires land and water resources, and intensification can raise welfare issues and increase pressure on antimicrobial use (Cowie *et al*., 2018; Dalin *et al*., 2018; Schneider and Tarawali, 2021). Animal welfare is increasingly treated as a key element of sustainable food production rather than an optional add-on (Del Campo *et al*., 2025; Meijboom, 2013). Strategies that enhance productivity while compromising welfare or environmental performance are becoming difficult to justify both scientifically and socially. Genetic improvement with the help of marker-assisted selection and prediction via single-nucleotide polymorphisms can relocate the breeding goals from mere growth to carcass and eating quality characteristics and resilience (Wakchaure et al., 2015). However, when productivity is selected without proper management, this may increase the biological load and threaten welfare within limited environments; thus, trade-offs arise, which require explicit and transparent decision-making (Ducrot et al., 2024). There is a strong need to implement stress-reduction measures, especially in diet, residence, and handling, to reduce the occurrence of defects such as dark, firm, and dry (DFD) meat under practical conditions (Kumar *et al*., 2023).

This chapter synthesizes the interaction between selection and management and their effects on meat quality and sustainability outcomes. It summarizes major selection principles and tools, reviews management strategies that influence sensory traits and carcasses, and explains these approaches in light of ethical and modern environmental expectations.

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6.2 Animal Selection for Meat Quality

6.2.1 Principles of Selection

Meat quality is economically important in farm animals and encompasses a range of sensory, nutritional, and technical attributes (Wu *et al*., 2022). It is assessed on the basis of sensory attributes, fat content, tenderness, water-holding capacity, color, oxidative stability, uniformity, chemical composition, physical–chemical properties, nutritional value, and safety (Damez and Clerjon, 2013). However, meat quality is influenced by several factors, including breed, genotype, feeding, fasting, preslaughter handling, stunning, slaughter methods, chilling, and storage conditions (Rosenvold and Andersen, 2003). The traditional evaluation of meat quality involves sensory assessment and laboratory analysis, which often require intensive testing, such as pH, moisture, fat, and protein analysis (Kamruzzaman, Makino and Oshita, 2015). In contrast, nondestructive methods such as imaging, spectroscopy, hyperspectral analysis, and AI-based systems enable rapid, accurate, and real-time quality evaluation without damaging samples (Davies, 2009; Su, He and Sun, 2017). Meat tenderness is an important issue in beef cattle production because it significantly affects consumer satisfaction. Indeed, the meat quality trait is complex to improve through traditional selection because its heritability is low, and it is difficult to measure, expensive, and assessable only after slaughter (Gao *et al*., 2007).

Various studies have revealed that genetics and breeding play crucial roles in the development of desirable meat traits in livestock (Rebezov *et al*., 2024). Genetic selection has been a very successful tool for the long-term improvement of livestock populations, and the rapid adoption of genomic selection (GS) has doubled the rate of gain in some populations (Gao *et al*., 2007). Furthermore, livestock genetic and breeding programs are changing as a result of advances in modern technologies such as genome editing and advanced sequencing, with a particular emphasis on improving meat quality traits across a variety of animals (Wray-Cahen *et al*., 2022). The correct selection of breeds or lines is crucial for the genetic basis since the genetic influence on meat quality varies significantly between breeds and even within the same breed. For thousands of years, selective breeding has been used in vast populations of domestic animals. In particular, in the last several centuries, this strong selection has led to the accumulation of novel mutations with beneficial phenotypic effects (Andersson, 2001).

The meat quality trait is influenced by multiple factors and an unknown number of QTLs. The primary purpose of genomic research in farm animals is to identify and define trait loci (Gao *et al*., 2007). Over the last 25 years, several QTLs have been mapped using genetic markers, paving the way for MAS. However, the MAS approach was less efficient for two main reasons: (1) They are (1) limited and overestimate the genetic variance explained by these few QTLs. (2) There is low association between QTLs and markers at the population level (Boichard *et al*., 2016). To address these limitations, a novel approach that can estimate breeding values from markers spanning the entire genome was proposed (Meuwissen, Hayes and Goddard, 2001). With this approach, the overall breeding value of any animal can be predicted from estimates of genetic effects for each marker, as illustrated in Figure 6.1. This calculation of marker effects is performed in a reference population, which is a large sample of individuals with information on both marker genotypes and phenotypes. These effects are then applied to candidates for selection that do not yet have known phenotypes but have marker genotype information. This method is highly demanding in terms of the number of individuals genotyped and the number of markers across the genome to be effective, although its use was previously impossible owing to the lack of affordable, large-scale genotyping techniques (Boichard *et al*., 2016).

6.2.1.1 Genotypic and Phenotypic Correlations with Meat Quality

Meat quality traits generally exhibit moderate heritability, with estimates ranging from 0.15 to 0.30 for attributes such as meat tenderness, meat color, polyunsaturated fat content, mineral content, and muscle oxidative capacity, with notable exceptions of intramuscular fat (IMF) (0.48), ultimate pH (0.08), and fresh meat color (Mortimer *et al*., 2014). The influence of IMF on meat tenderness is driven more strongly by animal-related factors than by processing conditions. Although processing factors, particularly the

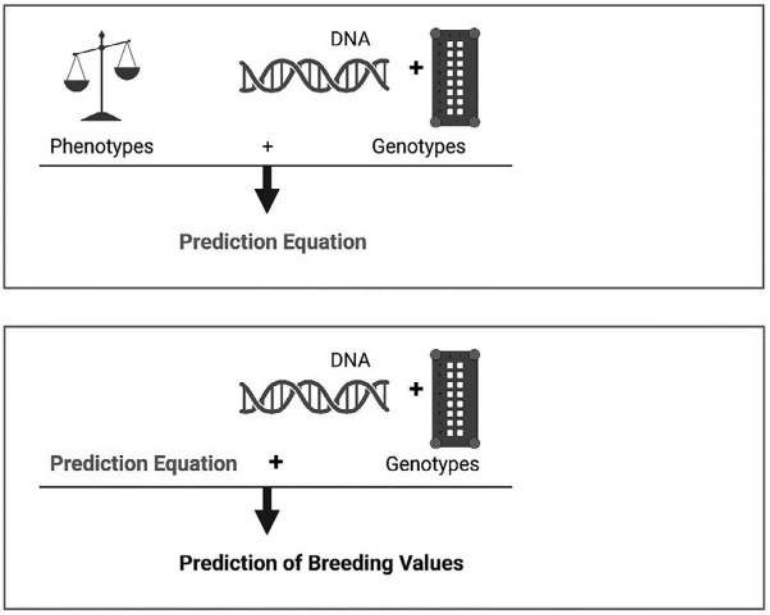

FIGURE 6.1 Principles of genomic selection. (Modified from Boichard *et al.*, 2016.)

rate of postmortem pH decline, play a critical role in determining tenderness, achieving consistently high tenderness ultimately requires adequate IMF levels, which are governed mainly by the lamb's genetic makeup (Jacob and Pethick, 2014).

Some of the important correlations are outlined in Table 6.1. The genetic correlation between myoglobin and iron concentrations was very high, indicating that these traits are highly correlated and accurately describe the same genetic traits in lambs. The myoglobin concentration clearly influences meat color, and iron concentration significantly influences nutritional value (Jacob and Pethick, 2014). IMF and SF5 correlations were similar in some beef studies (Reverter *et al.*, 2003). IMF is linked to other color parameters, as higher IMF values increase lipid content and myoglobin oxidation (Faustman *et al.*, 2010). Several studies have also reported a phenotypic correlation between L^* (lightness) and myoglobin in beef muscle. On the one hand, tenderness and eating quality are associated with isocitrate dehydrogenase activity (ICDH) and SF5. Therefore, this effect seemed unlikely to be caused by the IMF, as there was only a 0.03 genetic correlation between the IMF and the ICDH.

TABLE 6.1

Examples of Traits are Closely Correlated

Trait 1	Trait 2	Genotypic Correlation	Phenotypic Correlation
Myoglobin	Iron	0.97	0.35
Retail hue	Retail redness (R630/R580)	–0.90	–0.52
Retail chroma	Retail redness (R630/R580)	0.80	0.83
Myoglobin	Fresh *L* value	–0.81	–0.21
pH 24LL	Retail color	0.62	0.21
IMF	SF5	0.65	0.30
Linoleic acid	IMF	0.63	0.34
HCWT	pH 24LL	–0.32	–0.12
ICDH	SF5	–0.27	–0.12
Arachidonic acid	IMF	–0.22	–0.05

Source: With Mortimer *et al.* (2014).

The genetic correlation between IMF and shear force in cattle indicates that selection for increased IMF will reduce shear force and improve tenderness (Wolcott *et al.*, 2009). This study also revealed that selection for a relatively high growth rate would lead to genetic improvement in a range of meat quality traits, including sensory tenderness and shear force. Typically, genetic improvements are greater in temperate breeds than in tropical breeds. According to a study by Cafe, McKiernan, and Robinson (2014), on divergent Angus selection lines, selection for the muscling score did not affect a variety of meat quality attributes, such as shear force value, meat color, ultimate pH, cooking loss percentage, and sensory eating quality attributes (tenderness, juiciness, satisfaction, and overall liking). Following selection for a higher muscling score, the retail meat yield percentage increased concurrently. Boukha *et al.* (2011) reported that Piedmontese cattle with superior growth potential have inferior carcass conformation and paler meat, with lower tenderness and water-holding capacity, on the basis of genetic correlation estimates. Furthermore, selection for growth in Pirenaica cattle did not affect carcass or meat quality traits (Altarriba *et al.*, 2005).

6.2.1.2 Candidate Genes Associated with Meat Quality in Farm Animals

Selection on the basis of body composition, particularly the relative proportion of muscle to fat tissue, is crucial in meat-producing animals. During the past 50 years, there has been intensive selection for lean growth in several breeds. Several genes that influence body composition have already been identified or are close to being identified (Gao *et al.*, 2007). The genes responsible for meat quality in different domestic animals have been identified (Table 6.2).

Genomic- and multiomics-guided systems have replaced phenotypic confirmation-based methods for selecting animals for meat quality. Traditional breeds are shaped by phenotypic selection, whereas modern breeds prioritize genotypic precision, enabling the enhancement of complex, low-heritability traits such as tenderness and marbling (MARB). Combining multitrait selection indices, genetic prediction, and enhanced phenotyping provides approaches to balance productivity with sustainability, animal welfare, and customer pleasure.

6.2.2 Genetic Architecture of Meat Quality Traits

6.2.2.1 Heritability of Marbling, Tenderness, Flavor, and Juiciness

The characteristics of meat, including sensory attributes such as MARB, tenderness, flavor, and juiciness, are primary drivers of consumer preference and market value. Knowledge of the genetic architecture of these traits is essential for implementing breeding programs to improve production efficiency

TABLE 6.2

List of Genes Associated with Meat Quality in Farm Animals

Animal	Candidate Genes	Traits	References
Pig	Halothane gene	Meat quality/stress	Milan *et al.*, 2000
	MC4R	Growth and fatness	Gerbens *et al.*, 1998
	Rendment Napole gene, PRKAG3	Meat quality	Ciobanu *et al.*, 2004
	AFABP/FABP4	IMF tenderness	Van Laere *et al.*, 2003
	HFABP/FABP3	Growth and fatness	
	Calpastatin (CAST) gene		
	Insulin-like growth factor 2		
Cattle	CAST	Meat tenderness	Mullen *et al.*, 2006
	Leptin/thyroglobulin	Marbling	Thaller *et al.*, 2003
	Myostatin	Growth and composition Marbling	
	DGAT1		
Sheep	Callipyge, GDF8	Muscular hypertrophy	Clop *et al.*, 2006
Chicken	EX-FABP, L-FABP	Fatness	Wang *et al.*, 2006

and feeding quality. Estimates of heritability for meat quality traits vary widely ($h^2 = 0.12–0.54$) (Zheng *et al.*, 2025), which reflects varying degrees of genetic determinism, physiological mechanisms, and environmental sensitivity.

6.2.2.1.1 Marbling

As the foremost consideration in MARB, IMF has consistently shown the highest heritability among meat sensory traits reported in the literature, with estimates of $h^2 = 0.4–0.54$ (Xie *et al.*, 2023). MARB shows a moderate genetic correlation ($r = –0.33$ to 0.45) with other sensory traits, underscoring its importance for flavor and juiciness. In cattle, heritable variability in marbling is observed in taurine (*Bos taurus* taurus) and indicine (*Bos taurus* indicus) breeds, with taurine breeds typically exhibiting greater MARB than indicine breeds. For example, the Nellore breed has lower IMF (2.46%) levels than Angus (7.1%), Hereford (6.3%), or Wagyu (34.3%) (Park *et al.*, 2018). Nonetheless, the lower MARB trait in indicine cattle has sufficient phenotypic and genetic variation to be utilized in selection, with heritability estimates of 0.33–0.55, and Guzerá cattle have a lower MARB heritability of 0.24, whereas taurine or crossbred beef populations present genetic variation (0.19–0.57) (Mateescu *et al.*, 2015; Saatchi *et al.*, 2014). Additionally, the high genetic correlation (0.80 ± 0.05) between preslaughter ultrasound IMF and postmortem MARB scores suggests that early phenotyping can reliably predict carcass quality (McAllister *et al.*, 2011).

In pigs, IMF is influenced by a plethora of differentially expressed genes (DEGs), such as ACSF3, IGF2BP1, ACSL5, ACACA, and CREB1, which regulate FA synthesis, oxidation, and energy homeostasis (Jin *et al.*, 2024). Long noncoding RNAs (lncRNAs), microRNAs (miRNAs), and circular RNAs (circRNAs) also mediate these biological processes by modulating lipid metabolism and the differentiation of preadipocytes (Jin *et al.*, 2024; Zhang *et al.*, 2019). Functional enrichment indicates that IMF-related genes are enriched in lipid-related processes, including insulin signaling, AMP-activated protein kinase (AMPK) signaling, Foxo signaling, insulin resistance, intestinal lipid absorption, phosphatidylinositol-3-phosphatase activity, and lipid digestion (Jin *et al.*, 2024; Yang *et al.*, 2023). Competitive endogenous RNA (ceRNA) networks illustrate that lncRNAs, circRNAs, miRNAs, and mRNAs may interact and work in a coordinated genetic regulatory fashion to modify IMF deposition (Jin *et al.*, 2024; Peng *et al.*, 2023).

6.2.2.1.2 Tenderness

Tenderness, measured by the Warner–Bratzler shear force or a related proxy, is moderately heritable ($h^2 = 0.2–0.4$) (Zheng *et al.*, 2025). MARB indirectly impacts tenderness by altering the connective tissue structure and increasing the WHC, ultimately lowering the shear force (thus meat chewiness) (Font-i-Furnols *et al.*, 2015). There are several indications that the effectiveness of genetic selection for improving tenderness can be enhanced through better management of carcass traits after harvest (Silva *et al.*, 2021).

6.2.2.1.3 Flavor

Flavor is generally associated with the lipid content in the muscle as well as the FA makeup, which serve as lipid precursors for lipid-derived volatile compounds that form during cooking (Park *et al.*, 2018). Flavor is moderately heritable ($h^2 = 0.3–0.4$) in color traits (L^*, a^*, b^*), indicating that selecting for MARB may indirectly influence flavor (Font-i-Furnols *et al.*, 2015). Flavors of beef differ perceptibly between taurine and indicine breeds because of the differences in IMF content. Premium markets often prefer taurine or crossbred meat because of these flavor differences.

6.2.2.1.4 Juiciness

Juiciness is a descriptive term that describes water-holding capacity, which is measured by drip loss (DL24, DL48) and is moderately heritable ($h^2 = 0.2–0.4$), with high genetic correlation between measures ($r = 0.85$) and strong negative correlations for both initial muscle pH values ($r = –0.68$ to $–0.77$) (Zhang *et al.*, 2018; Zheng *et al.*, 2025). A higher IMF helps retain more moisture. There are also other environmental effects, such as chilling, cooking, and processing, that affect juiciness and could slow the genetic progress of these traits relative to MARB.

6.2.2.1.5 Genetic Correlations with Other Traits

Selection for MARB has negligible negative correlations with growth, reproduction, and feed efficiency. In Nellore cattle, weaning and yearling weights had near-zero correlations with MARB (−0.04 to −0.02), and reproductive traits such as SC365 and EH had negligible correlations (−0.03 and 0.01, respectively) (Torres-Vazquez and Spangler, 2016). There are low-to-negative correlations of MARB with residual feed intake (RFI) (−0.09 to −0.41), which can allow selection for efficiency and meat quality (Cancino-Baier *et al.*, 2019; Moraes *et al.*, 2016). RFI has low to moderate heritability (0.19–0.33) and weak correlations with MARB, further reinforcing the need for direct selection for IMF (Silva *et al.*, 2021).

6.2.2.1.6 Strategic Breeding Implications

The most effective approach to increasing marbling (MARB) is direct selection using genomic evaluation and early ultrasound measurements, either alone or in combination, as these strategies are strongly associated with improvements in meat tenderness, flavor, and juiciness. Crossbreeding with taurine sires (Angus × Nellore) also rapidly increases carcass quality traits to meet the needs of premium markets (Pereira *et al.*, 2015). Using MARB as a trait in selection indices helps improve meat quality while simultaneously improving growth, reproduction, and feed efficiency.

6.2.2.2 Muscle Fiber–Type Composition and Intramuscular Fat Deposition

Mammals exhibit a variety of skeletal muscle fiber types that differ in morphology, metabolism, and contractile function. In mammals, such fiber composition is influenced by genetic and/or environmental factors (age, physical activity, nutrition, and selection pressure) (Picard *et al.*, 2006). Muscle fibers are mainly categorized as type I (slow-twitch oxidative/STO), type IIA (fast-twitch oxidative/FTO), or type IIB (fast-twitch glycolytic/FTG) (Furuichi *et al.*, 2014; Schiaffino and Reggiani, 2011). Among these fibers, STO has abundant mitochondria and high myoglobin levels, uses oxidative phosphorylation for ATP regeneration, and contains more intracellular lipids and less glycogen (Choi and Kim, 2009). In contrast, FTG has fewer mitochondria and myoglobin. Therefore, they rely on glycolysis, exhibit contraction rates that are approximately threefold higher, and quickly fatigued (Picard *et al.*, 2002). FTO falls between the oxidative and glycolytic fiber types (Schiaffino and Reggiani, 2011). These muscle fiber types are dispersed differently across muscles within species, reflecting functional specialization. Contracting muscles, such as postural and respiratory muscles, have abundant STO fibers, whereas dynamic locomotory muscles are composed primarily of FTG fibers (Briand *et al.*, 1981).

Fiber composition is further influenced by nutritional management and genotype. Kids raised on milk replacers had substantially fewer slow oxidative fibers than their on-dam siblings did (Rivero *et al.*, 2022). Sheep grazing on pasture had greater proportions of oxidative fibers than pen-fed sheep did (Hou *et al.*, 2020). This manipulation also affects the IMF, as oxidative fibers can store more lipids than fast glycolysis fibers can (Ryu and Kim, 2006). The characteristics of muscle fibers and IMF are heritable within breeds, with estimates of heritability for MARB (h^2) of approximately 0.12–0.54 and for fiber areas of 0.25–0.40 (Wegner *et al.*, 2000). Pork is a clear example of how IMF can influence tenderness, flavor, and juiciness, as it is the second most consumed meat in the world. The IMF is composed of cholesterol, triglycerides, and phospholipids and is the final stage of lipid deposition in muscle (Liu *et al.*, 2020). During cooking, FA oxidation releases volatile compounds with flavors through the Maillard reaction. Thus, IMF is directly related to sensory quality (Alfaia *et al.*, 2019).

At the molecular level, noncoding RNAs (ncRNAs), including circRNAs, long noncoding RNAs (lncRNAs), and miRNAs, are important regulators of IMF development by competing endogenous RNA (ceRNA) interactions (Cheng *et al.*, 2021; Hu *et al.*, 2020; Wang *et al.*, 2019). For example, miR-34a inhibits porcine intramuscular preadipocyte differentiation by targeting PDGFRα via the Erk pathway; lncRNA-IMFNCR enhances adipogenesis via upregulation of PPARG through miR-128-3p and miR-27b-3p; and circRNA06424 inhibits the expression of PPARD through sequestering-specific miRNAs, which regulate both subcutaneous and IMF deposition (Feng *et al.*, 2022).

6.2.2.3 Differences across Species: Cattle, Sheep, Goats, Pigs, and Poultry

The sensory and nutritional characteristics of meat, specifically flavor, odor, and FA composition, differ among species (such as cattle, sheep, goats, pigs, and poultry). This variation is due to the complex interactions of genetics, metabolism, and environmental factors that regulate muscle biochemistry, lipid accumulation, and carcass structure. In addition to differences in sensory characteristics, the proportions of cuts and carcass anatomy can also vary considerably among species, which may influence both economic value and consumer choice.

6.2.2.3.1 Pigs: Genetic Regulation of Carcass Segmentation and Meat Cut Traits

Pigs differ dramatically among livestock in carcass composition and cut proportions, which are important determinants of both meat quality and market value (Gong *et al*., 2011; Liu and Sun, 2010). The recent modernization of the pork industry in China has moved from traditional manual segmentation of pork carcasses to more efficient, standardized, and automated systems that ensure yield and hygiene (Grunert, 2006). The segmentation of carcasses into differentiated cuts adds commercial value (Qin, 2019), as Qin reported that selling pork by individual cuts generated 19% more gross revenue (not accounting for processing) than selling the carcass. This study has prompted genetic studies to examine the underlying mechanisms controlling meat cut proportions (MCPs) and carcass structure.

Research shows that carcass weight, sex, and breed composition significantly affect MCP, as demonstrated by the coefficient of variation ranging from 4.2% to 25.3%, suggesting that appropriate phenotypic variation is needed (Xie *et al*., 2023). Generally, heritability estimates are moderate to high across breeds, reinforcing the genetic potential for improvement (Khanal *et al*., 2019; Van Limbergen *et al*. (2018). The selection is complicated by correlated responses to selection because, for example, selecting the middle cut proportion increases the belly fat and IMF while also increasing the backfat thickness (BT). Additionally, GWASs have identified several QTLs associated with carcass segmentation, including a causal SNP (g.19034 $A > C$) in the VRTN gene, determining the number of thoracic vertebrae and the proportions of middle cuts and shoulder cuts (Duan *et al*., 2018). Other genes, including bone morphogenetic protein 2 (BMP2), HMGA1, and CCND2, regulate skeletal development and carcass morphology (Xie *et al*., 2023). These results indicate that advances in our understanding of genetic architecture in relation to the diversity of pig carcasses reveal novel targets to improve genetic selection through both marker-assisted and GS breeding programs.

6.2.2.3.2 Sheep and Goats: Genetic and Metabolic Underpinnings of Flavor and Fatty Acids

The flavor and odor of mutton are major sensory characteristics associated with consumer acceptance in small ruminants. Guizhou black goat (GZB) and Yunnan black goat (YBG) are genetically related goat breeds from China that differ markedly in flavor and FA metabolism. GZB is a native goat breed from the cold mountain regions of the Yunnan–Guizhou Plateau and has superior mutton quality on the basis of its amino acid umami content, lower hexanoic and decanoic acid concentrations, lower cholesterol content, and intermediate fat content. The YBG was selected from indigenous goats for improvement of fertility and growth and has different sensory characteristics on the basis of metabolic differences from the GZB (Chang *et al*., 2024; Lanr and Yang, 2019).

Flavor development during mutton production is tightly linked to amino acid composition. The prime umami amino acids important to lamb flavor include aspartic and glutamic acids (Cheng *et al*., 2022; Lu *et al*., 2022). Additionally, GZB has considerably higher concentrations of glutamate and argininosuccinate than YBG goat meat does, which accounts for its more intense flavor. Supplementation with dietary glutamic acid improved FA composition while decreasing subcutaneous backfat depth, indicating that the relationship between amino acid metabolism and FA quality may be present in animals in addition to goats (Hu *et al*., 2017a, 2017b).

Volatile branched-chain fatty acids (BCFAs), specifically 4-methyloctanoic acid (MOA), 4-methylnonanoic acid (MNA), and ethyloctanoic acid (EOA), are important contributors to the characteristic mutton odor (Watkins and Frank, 2019). Compared with YBG meat, GZB meat had significantly lower levels of MOA and MNA, a much milder odor, and greater consumer acceptance. Similar reports for sheep indicated that Merinoland breeds had higher 4-alkyl BCFAs than Ile de France × Merinoland

hybrids did, suggesting that odor-related compounds are under genetic control (Kaffarnik, Preuß and Vetter, 2014). From a nutritional perspective, the n-6/n-3 polyunsaturated fatty acid (PUFA) ratio and the polyunsaturated/saturated fatty acid (P/S) ratio are considered meaningful measures of health quality during meat consumption. The optimal n-6/n-3 PUFA ratio should not exceed 4, and the P/S ratio should exceed 0.4 (Wood *et al*., 2004). Compared with YBG meat, GZB meat presented favorable values (2.42 and 0.11 versus 15.61 and 0.40, respectively), whereas Lori goats and Hu sheep presented intermediate values (3.8 and 0.6; 3.43 and 0.2, respectively) (Kiani and Fallah, 2016; Kong *et al*., 2023). These differences demonstrate the possibility of selecting nutrients for specific breeds. Genes regulating cholesterol and FA metabolism, including HMGCR, HMGCS1, FDPS, CYP51, TM7SF2, EBP, SC5D, and DHCR7, may serve as potential molecular markers across small ruminants. The commonalities in genetic architecture across the species are briefly discussed in Table 6.3.

TABLE 6.3

Differences in Genetic Architecture across Species

Species	Key Sensory Traits (Flavor, Odor, Tenderness)	Major Genetic Regulators	Fatty Acid and Nutritional Characteristics	Carcass Structure and Cut Proportions	Breeding Goals	References
Cattle	Flavor/tenderness heavily influenced by MARB	DGAT1, CAPN1, LEPR regulate muscle growth, MARB, and tenderness (comparative genomics)	Breed-dependent PUFA profile MARB linked to FA metabolism	High-value loin/rib regions Species-specific cut structure	Selection for MARB and feed efficiency (comparative genomics)	Grunert, 2006; Wood *et al*., 2004
Sheep	Mutton odor driven by BCFAs MOA, MNA, EOA Breed variation	Cholesterol and *FA genes*: HMGCR, HMGCS1, FDPS, CYP51, SC5D, DHCR7	n-6/n-3 and P/S ratios vary Healthier profiles in some breeds	Carcass fat distribution is breed dependent	Selection for reduced odor and better FA health value	Kaffarnik, Preuß and Vetter, 2014; Kiani and Fallah, 2016; Kong *et al*., 2023; Watkins and Frank, 2019; Wood *et al*., 2004)
Goats	GZB mild flavor Lower MOA and MNA YBG stronger odor	*Flavor/lipid genes*: CYP2B6, ACOT12, LPIN1, ADCY4, FXR, LDLR, HMGCS1, SCARB1, SCD	GZB has healthier PUFA ratios (2.42 n-6/n-3) versus YBG (15.61)	Lean carcasses with breed-specific fat deposition	Breeding to improve odor, flavor, and FA composition	Chang *et al*., 2024; Gunawan *et al*., 2018; Kong *et al*., 2023; Lanr and Yang, 2019; Yang *et al*., 2022
Pigs	Flavor affected by IMF and BT	VRTN SNP g.19034A>C HMGA1, BMP2, CCND2 regulate carcass segmentation	FA composition responsive to selection for lean versus fat traits	Large variation in cut proportions Segmentation adds 19% revenue	GS for balanced lean yield and fatness	Duan *et al*., 2018; Khanal *et al*., 2019; Miar *et al*., 2014; Van Limbergen *et al*., 2018; Xie *et al*., 2023
Poultry	Mild flavor Influenced by muscle fiber type (comparative genomics)	GH1, MC4R, IGF1 control growth, fat deposition (comparative genomics)	Naturally, high PUFA Low total fat improves health profile	Simple carcass division Strong focus on breast muscle yield	Selection for feed efficiency and rapid growth (comparative genomics)	Wood *et al*., 2004

6.2.2.3.3 Molecular Mechanisms and Structural Variants Affecting Meat Quality

With increased access to whole-genome sequencing (WGS), we can identify structural variants (SVs) that influence flavor, fat metabolism, and carcass traits. Compared with long-read WGS (lrWGS), short-read WGS (srWGS) is the most economical method, with an accuracy of 93.8% (Chaisson *et al*., 2019; Zhao *et al*., 2021). For example, Delly, Manta, and Dysgu are tools developed in goats for SV calling, whereas GRIDSS, Lumpy, SVseq2, and SoftSV (Bartenhagen and Dugas, 2016) provide additional capabilities for improved accuracy. Traits associated with odor and lipids in goats and sheep are related to the genes CYP2B6, ACOT12, LPIN1, ADCY4, FXR, LDLR, HMGCS1, SCARB1, and SCD (Gunawan *et al*., 2018; Yang *et al*., 2022; Zhao *et al*., 2022). Analogous studies in pigs revealed that HMGA1, VRTN, and BMP2 similarly affect skeletal and carcass development (Xie *et al*., 2023). Overall, our findings illustrate that similar genomic pathways can influence meat quality traits across livestock species.

6.2.3 Modern Genetic and Genomic Tools

6.2.3.1 Marker-Assisted Selection (MAS) and Genomic Selection (GS)

MAS and GS have become integral components of modern pig breeding procedures, specifically for improving and enhancing meat quality, FA profiles, and carcass traits, which are often complex, expensive, or time-consuming for obtaining phenotypic observations. Traditional selection that aims to achieve a phenotypic record is frequently impeded by generation intervals, delayed trait expression, and possibly negative genetic correlations between production traits and quality traits (Chen *et al*., 2020; Michas, Micha and Zampelas, 2014). Accordingly, MAS and GS utilize single-nucleotide polymorphisms (SNPs) as molecular markers to rapidly and precisely select traits of economic and nutritional relevance within logistical time frames. The definition that accommodates all aspects of pork quality comprises meat color, pH, MARB, WHC, IMF, tenderness, cooking loss, and drip loss (Noidad *et al*., 2019).

Nonetheless, changing consumer preferences for high-quality pork, coupled with rising living standards, have led to a change in breeding objectives to improve meat quality traits (MQTs) (Fan *et al*., 2010). Because MQTs have low to moderate heritability and can be measured only postmortem, selection for MQTs via conventional approaches (phenotypic and genetic) remains difficult (Khanal *et al*., 2019; Lee *et al*., 2015). IMF and FA parameters are important traits of meat quality in pigs because they influence tenderness, flavor quality, oxidative stability, and nutritional value. For example, a Chinese obese pig has a 74 kg market weight and a 74% carcass yield (Chen *et al*., 2020) and has 25 FAs in the longissimus dorsi, with the majority being saturated FAs (SFAs) and the relative amount of monounsaturated fatty acids (MUFAs) being the highest (Crespo-Piazuelo *et al*., 2020; Jiang *et al*., 2018). Interestingly, docosahexaenoic acid (DHA), which is an essential omega-3 FA, was found only in Ningxiang pigs. Correlation analyses demonstrate that IMF positively correlates with MUFAs, negatively correlates with PUFAs, and correlates only slightly with SFAs, thus establishing complex lipid assimilation relationships with meat quality (Zeng *et al*., 2023). These phenotypic patterns are consistent with those of Iberian pigs in terms of management traits, where selection for IMF and carcass traits is a determining factor in balancing meat quality, yield, and the premium weight of cuts.

GWASs have enabled the identification of candidate genes and QTLs influencing IMF and FA composition. In Ningxiang pigs, 74 genome-wide significant SNPs were found across 37 loci, most of which are in intronic or intergenic regions, impacting SFAs, MUFAs, and PUFAs. The genes related to SFAs include *hnRNPU*, *CEPT1*, *ATP1B1*, *DPT*, *DKK1*, *PRKG1*, *EXT2*, *MEF2C*, *IL17RA*, *ITGA1*, and *ALOX5*, which are involved in RNA biogenesis and adipogenesis and lipid metabolism (Mi *et al*., 2017; Zayed *et al*., 2021). The genes related to MUFAs include *ALOX5AP* and *MEDAG* (Elias *et al*., 2016; Gozalo-Marcilla *et al*., 2021), *ISL1*, *RXRB*, *CRY1* (Griebel *et al*., 2014), and *CDKAL1* (Choi *et al*., 2020) and are involved in regulating FA biosynthesis, desaturation, and storage. The genes related to PUFAs include *NDUFA4L2*, *SLC16A7*, *OTUB1*, *EIF4E*, and *ROBO2*, which are involved in lipid metabolism, mitochondrial function, and the translational regulation of lipid-related mRNAs (Laursen *et al*., 2021; Mohammadi *et al*., 2022). The moderate-to-high heritability estimates for these FAs indicate that selection for these loci could be an effective means of modifying FA profiles and the IMF content.

SNP arrays in genome-wide association studies (GWASs), such as the GeneSeek Porcine SNP50K BeadChip or Illumina PorcineSNP60K, have identified numerous QTLs for meat quality in breeding programs, including Duroc × Landrace × Yorkshire (DLY) pigs (Gao *et al*., 2021; Liu *et al*., 2015). Although WGS-based GWASs have increased the number of SNPs in the analysis to millions and have detected important candidate genes (e.g., CXXC5, RYR3, BNIP3, and MYCT1) that are associated with meat quality traits such as meat pH or meat color (Ji *et al*., 2018; Wu *et al*., 2020), the expense of sequencing the genome can be perceived as prohibitive.

The candidate genes implicated in different traits included GRM8 (pH 45), ANKRD6 (meat color), MACROD2, ABCG1 (MARB), TMEM50A, RRM2 (water loss), PIP4K2A (cooking loss), and CDYL2, CHL1, ABCA4, FA2H, ZAG, SLC1A2, and SIL1 (drip loss). The rs327708082 SNP within SIL1 explained 16.32% of the DL phenotypic variance, suggesting that it may be useful for MAS (Wang *et al*., 2023). The incorporation of both MASs and GSs into a breeding program can facilitate the concurrent improvement of multiple MQTs and facilitate the conservation of breeds while maintaining sustainable production practices. For example, validated low- to medium-density SNP panels targeting PRKAG3, ADIPOQ, CAST, FASN, ELOVL6, MTTP, CAPN1, and NR6A1 can provide an affordable avenue to improve IMF and FA composition in Iberian pigs while maintaining target carcass yield levels. As in Iberian pigs, incorporating MAS and GS into hybrid and commercial pigs using high-density SNP data can enable rapid detection of superior breeding candidates (Palma-Granados *et al*., 2023).

6.2.3.2 SNPs, QTLs, and Gene Expression Markers Associated with Meat Traits

SNPs, QTLs, and gene expression markers have emerged as essential tools for understanding the genetic basis of economically important livestock traits. Molecular tools provide insight into the polygenic nature of growth, carcass composition, and meat quality. Consequently, precision breeding to promote productivity and quality metrics has been possible. Researchers built upon the foundation of genomic data and selection indices to enhance trait evaluation, thereby building the capacity to identify animals with favorable alleles for meat tenderness, color, water-holding capacity, or IMF, which are reliable predictors of consumer preference and economic return.

Genomic technologies have significantly improved the characterization of meat quality traits in pigs, the world's largest animal protein source, which comprises approximately 33.7% of total meat consumption in 2023 (Augustyniak and Pomorska-Mól, 2023). Traditional breeding practices for pigs have historically emphasized improving carcass yield at the expense of other meat quality-related traits, such as IMF and MARB, both of which are significant determinants of flavor and tenderness. The Iberian pig industry has maintained cultural and economic importance in certain regions. The Montanera system has been established as a distinctive production system for studying the trade-offs between yield and quality. The traditional extensive production system is based on acorn and pasture resources from Mediterranean oak forests and accounts for approximately 19% of the 3.2 million Iberian pigs slaughtered in 2022 (García-Gudiño *et al*., 2025). Although crossbreeding programs with Duroc lines constitute nearly 40% of the Iberian pig population, 360,000 pure Iberian pigs are raised each year under Montanera conditions to preserve the genetic quality of dry-cured meat products.

A number of genes and polymorphisms have been identified as important in regulating meat quality. For example, mutations in the GH gene have been shown to affect fat thickness and average daily gain (AGD) (Franco *et al*., 2005). However, the LEPR c.1987C>T mutation has been shown to increase body weight (BW), BT, and IMF while reducing the yield of premium cuts (Muñoz *et al*., 2011). Additionally, further developments using SNP panels designed specifically for Iberian pigs have identified significant associations between several genes and traits related to IMF, backfat composition, and muscle properties. For example, Fernández-Barroso *et al*. (2020) reported that some SNPs in the *PRKAG3*, *MYH3*, *CASP3*, and *CTSL* genes influence shear force and water loss, and Palma-Granados *et al*. (2023) reported that polymorphisms in the *ADIPOQ*, *FASN*, and *ELOVL6* genes are associated with IMF and FA (FA) composition. The use of these SNPs in low-density arrays provides a practical alternative for local breeding programs, which are of particular interest to small- and medium-scale farms where resources are often limited.

Among the important loci, PRKAG3_rs319678464G>C has demonstrated repeated strong associations with muscle color (*L**, *b**), pH, and drip loss (Ciobanu *et al*., 2001; Otto *et al*., 2007). The expression of this gene has been reported to be correlated with glycolytic potential and IMF (Galve *et al*., 2013; Ryan *et al*., 2012), and allelic variants of this gene, such as PRKAG3_rs1108399077G>A, have been associated with fat deposition (Galve *et al*., 2013). Additionally, ADIPOQ_rs3476515794T>G has been related to the IMF, loin depth, and BT (Cieslak *et al*., 2013; Dall'Olio *et al*., 2009). The G allele increases IMF and PUFA, which could alter the oxidative stability of cured products. Similarly, CAST_rs196949783G>A polymorphisms have been associated with IMF, tenderness, and WHC (Alves *et al*., 2017; Urbański *et al*., 2015), which has the potential to increase IMF without negatively affecting carcass yield. Other, less common but notable SNPs that strongly influence lipid metabolism also strongly influence FA composition. The allelic variants of FASN, ELOVL6, MTTP, and ACACA have been suggested to impact FA composition, and favorable variants of ELOVL6 (ELOVL6_rs3473714672A>G) and FASN (FASN_rs331694510G>A) reportedly improve the MUFA/SFA ratio and enhance sensory quality (Palma-Granados *et al*., 2023). In addition to the above loci, several other loci contribute to tenderness and carcass composition (e.g., CAPN1_rs81358667G>A, CTSL_rs321623592A>T, and MYOD_rs345162462T>C) (Ropka-Molik *et al*., 2014) or vertebral number, carcass length, and growth rate (e.g., NR6A1_rs326780270T) (Fontanesi *et al*., 2014; Li *et al*., 2021).

SNP-based tools have improved the understanding of meat quality traits in other species beyond pigs. The Hair Sheep (CHS) populations, Pelibuey, Ethiopian, and Sudan, found in Colombia, are important genetic resources because of their adaptive traits for low-input systems and their significance to rural livelihoods (Flórez *et al*., 2020; Revelo *et al*., 2020). Traditional low-input systems result in a lack of performance recording and genetic improvement. GWASs have identified several SNPs associated with meat pH and WHC. These two traits are consistent drivers of consumer acceptance and market value (Leal-Gutiérrez *et al*., 2014; Navarro, Mendoza and Osorio, 2015). For example, WHC values of 41.69 in CHSS, 36.8 in CHSP, and 30.63 in CHSE and pH values ranging from 5.70 to 5.75 present optimal red, firm, and nonexudative (RFN) meat (Gallo and Tadich, 2008).

Moreover, ELOVL2 and ARAP2 in CHSE are genetic markers that influence the regulation of long-chain PUFA synthesis and cytoskeletal organization (UniProt Consortium, 2015; Bolormaa *et al*., 2016), whereas PRKCQ, IFRD1, and KDM8 in CHSS are markers associated with myoblast differentiation and cellular signaling (Cheng and Han, 2020). In CHSP, polymorphisms in DAPK1, FBN2, TPM2, and NANS are important for muscle structure, apoptosis, and elasticity (Stelzer *et al*., 2016).

6.2.3.3 Gene-Editing and Transgenic Technologies: Ethical Considerations

Decades of selective breeding, along with optimizing nutrition and managing the environment, have increased the output of meat from modern livestock systems. Genetic improvement has been a major focus of modern livestock breeding systems, but selective breeding focused on traits related to growth and production, such as increased BW and growth rates in meat-type chickens and pigs, has been common for several decades (Chen *et al*., 2002; Zuidhof *et al*., 2014). The availability of genomic technologies, DNA sequencing, and enhanced genomic prediction tools has enabled livestock breeders to employ QTLs and other genetic markers to select livestock on the basis of the best available genetics while improving the accuracy and efficiency of breeding programs (T. H. Meuwissen, Hayes and Goddard, 2001, 2013). In addition to traditional breeding, genome editing technology has altered livestock genetics by enabling specific, precise modifications of genes associated with economically and biologically significant traits.

Gene editing has been used in livestock to improve traits important for growth, carcass yield, and feed efficiency. Myostatin (MSTN), a known negative regulator of muscle growth, has been presented in studies focused on MSTN knockout animals, including cattle, pigs, goats, sheep, chickens, rabbits, and quail; MSTN knockout caused an increase in muscle mass either through hypertrophy and/or hyperplasia (Li *et al*., 2020; Zheng *et al*., 2022). Gene editing resulting in MSTN disruption also caused a shift in muscle fibers toward Type II fibers, which supported growth performance (Kim *et al*., 2020, 2023). In addition to increased growth performance and carcass yield, MSTN knockout decreases IMF deposition while maintaining or improving carcass yield and feed efficiency (Lee *et al*., 2021; Zhu *et al*., 2020). However,

decreased IMF can also negatively impact the tenderness, juiciness, and flavor of the meat, such as when muscling Belgian Blue cattle (Fiems, 2012), thus requiring management strategies for integrative approaches, such as targeted feeding intervention during finishing (Duckett, 2003; Kang *et al*., 2022).

Regulatory systems vary across the world. The European Union refers to any organisms modified by mutagenesis as GMOs, whereas Brazil, Japan, Australia, and the United States are less interventionist in addressing mutagenesis-modified organisms when there are no foreign DNA molecules added and use many of the same methods to create certain gene-edited animals as those used in traditional livestock breeding (Ledesma and Van Eenennaam, 2024; Lim and Choi, 2023). Ethical frameworks include welfare, biodiversity, sustainability, and talk at the societal level that emphasize the importance of transparency and public interest in matters of the application of genome-editing technologies. CRISPR-utilized hypoallergenic cats (Lee *et al*., 2024) or correct PRLR modifications in cattle for heat tolerance are examples where human interest and animal interest can coalesce (Harrison, 2022; Liu and Verma, 2022). The bottom line is that the diverse and expansive capabilities of gene-editing technologies and transgene technologies have afforded society unprecedented opportunities to positively impact meat quality, growth performance, feed efficiency, and sustainability in livestock production when utilized.

6.2.4 Management of Exotic Breeds for Sustainable and High-Quality Meat

The benefits of exotic breeds include high productivity. Nevertheless, to manage meat quality sustainably, advanced breeding techniques, disease monitoring, proper feeding, and careful blending of foreign genetics with local conditions are needed to improve meat quality, such as tenderness, and reduce its environmental impact. Breeds appropriate for the local environment must be selected and managed to optimize resource use and reduce disease risk, ensuring both high-quality meat and ecological sustainability (Kumar *et al*., 2023). The selection criteria for exotic breeds include evaluating the breed's disease resistance, climate adaptability, and greater genetic potential for meat yield, growth rate, and feed conversion (Hoffmann, 2013).

6.2.4.1 Exotic Breeds: Angus, Wagyu, and Duroc

6.2.4.1.1 Angus Breed: Perspectives on Sustainability and Meat Quality

The Angus breed is a mainstay of sustainable beef production because of its exceptional beef quality and versatility, which are acknowledged worldwide. Angus cattle are known for producing consistently high-quality meat that is soft, well-marbled, and highly rated by consumers for flavor and overall liking (Bureš and Bartoň, 2018). Compared with other European and local breeds, Angus and Angus-cross beef frequently receive "better than average" quality grades because of their favorable FA profile and softness (Liu *et al*., 2022a). Genetic studies have identified specific genes in Angus linked to MARB, flavor, and tenderness, supporting ongoing selection for premium meat traits (Taye *et al*., 2018).

These characteristics, including longevity, reproductive efficiency, and environmental adaptation, help sustain Angus production. Higher weaning weights and lower mature BWs in Angus cows result in greater resource efficiency, less environmental impact, and greater profitability (Márton *et al*., 2025). Without sacrificing carcass characteristics, crossbreeding with Angus can improve meat sustainability and quality in both domestic and commercial herds (Roholt *et al*., 2024). Adhering to quality criteria for breeding stock and choosing genetic lines with the best longevity and reproductive qualities are essential components of effective management (Hayes, Lewin and Goddard, 2013). Careful selection and crossbreeding can further enhance the sustainability and quality of meat.

Japanese black, brown, shorthorn, and polished cattle are the four breeds officially recognized as Wagyu in Japan, although Wagyu production has expanded to countries such as Australia and the United States (Gotoh *et al*., 2018; Smith, Gotoh and Greenwood, 2018). Owing largely to genetic selection, the longissimus muscle of Japanese black cattle currently has an intramuscular fat content of approximately 30% (Motoyama, Sasaki and Watanabe, 2016). Compared with other beef breeds, Japanese black cattle also have higher percentages of monounsaturated fatty acids (Smith, Gotoh and Greenwood, 2018). However, the development of more sustainable feeding systems is essential because of the dependence

on imported feed, high production costs, problems with waste disposal, and biosecurity hazards related to feed-borne viral infections (Gotoh *et al.*, 2018). For Wagyu beef production, researchers are currently working on future systems that include metabolic programming and an information and communications technology (ICT, or Internet of Things) management system (Gotoh *et al.*, 2018).

Sirloin (51.5%) and entrecote (59.6%) had more intramuscular fat, entrecote had more unsaturated fatty acids (55.8%), and sirloin (46%) and entrecote (47.5%) had more oleic acid. Greater thrombogenicity (0.82 and 0.92), hypocholesterolemic/hypercholesterolemic indices (1.9 and 2.1), and atherogenicity (0.6 and 0.55) were demonstrated by WY and Wagyu-by-Angus (Wangus, WN). The nutritional qualities of beef are therefore influenced by breed/crossbreed, age at slaughter, and cut; the samples from WY and WN presented a healthier lipid content. A study by Vázquez-Mosquera *et al.* identified key metabolites and candidate genes affecting meat quality in Chinese Wagyu beef cuts (Vázquez-Mosquera *et al.*, 2023). This information is helpful for the molecular breeding of high-quality traits in beef cattle (Zhang *et al.*, 2023). Although Wagyu meat quality can be improved by crossbreeding with other breeds, purebred Wagyu always exhibit the best marbling. Purebred Wagyu always present the highest levels of fat and marbling (Setyani *et al.*, 2024). The environmental impact is increased by long fattening times and a reliance on grain-based diets. The development of more effective feeding methods, the use of nearby grazing resources, and the use of technology for improved management are all attempting to increase sustainability. A possible route for more sustainable production is the ability to increase feed efficiency without sacrificing the quality of the meat (Guarnido-Lopez *et al.*, 2024).

6.2.4.1.2 Duroc Pig Management: Juxtaposing Sustainability and Meat Quality

Because of their desirable meat quality characteristics, including marbling, juiciness, and color, Duroc pigs are frequently used in pork production. The efficient management of Duroc genetics, feeding, and breeding practices enhances both the sustainability of pork production systems and the quality of meat (Dekkers, 2025). Compared with other breeds, Duroc pigs and their crossbreeds consistently exhibit greater IMF, marbling, and juiciness, enhancing sensory attributes such as flavor and tenderness (Cameron *et al.*, 1990). Because of their moderate to high heritability, genetic selection for traits such as IMF, marbling, and pH is effective, enabling focused breeding initiatives to improve meat quality. Although it may also alter fat composition and sensory qualities, crossbreeding Duroc pigs with domestic or other commercial breeds can improve growth rates, carcass yield, and particular quality features (Willson *et al.*, 2019).

Optimizing feed efficiency, reducing medicine use, and considering environmental effects are all parts of sustainable Duroc management. Crossbreeding can increase feed conversion and growth rates, promoting more effective resource use, whereas purebred Duroc pigs may need more drugs and cost more to produce (Santos *et al.*, 2016). Outdoor rearing and alternative feeding strategies can influence carcass composition and meat quality, but may sometimes reduce tenderness and juiciness. Programmes for genetic improvement that incorporate both quality and productivity attributes can aid in striking a balance between environmental sustainability and economic viability (Suzuki *et al.*, 2005).

6.2.4.2 Local/Indigenous Breeds: Cultural Value, Adaptability, and Resilience

Bangladesh's agricultural economy depends heavily on livestock, which also play a major role in food security and rural livelihoods. Red Chittagong cattle, a native breed, are notable for their versatility, resilience to disease, and capacity to produce both meat and milk. Bangladeshi cattle populations exhibit low genetic diversity (Bhuiyan *et al.*, 2021). Native sheep in Bangladesh are widely spread and extremely adaptable. They exhibit strong disease resistance, low feed requirements, and adaptability to harsh climatic conditions under minimal housing and management systems (Rakib *et al.*, 2022). Numerous case studies and miscellaneous research papers on Bangladesh's indigenous sheep have been published. However, a thorough analysis of their diverse morphometric physiognomies, reproductive and productive performance, and capacity for climatic adaptation has not been performed. Research on sheep biodiversity, morphometric traits, feeding and nutrition, reproductive and production performance, diseases and health management, and the challenges and opportunities of sheep farming in Bangladesh has been conducted (Rakib *et al.*, 2022). In total, 22 M high-quality SNPs were found via whole-genome sequencing

of three local chicken types from Bangladesh (Common Deshi, Hilly, and Naked Neck). These SNPs can be used as resources for GS in breeding plans to produce more resilient and productive poultry stocks (Rabbani *et al.*, 2024).

6.2.5 Climate Adaptation and Thermotolerance Genetics

Genetic selection is a viable, long-term strategy to mitigate the significant impacts of climate change on cattle productivity and meat quality (Osei-Amponsah *et al.*, 2019). Alterations in temperature and the environment exacerbate climate-related issues, particularly heat stress (HS), which can impede the expression of genetically advantageous traits such as marbling and yield. The incorporation of resistance traits into selection indices is crucial, not merely a supplementary objective, for environmentally sustainable meat production systems. Genetic variation exists in the capacity of ruminants to endure HS, and emerging genomic technologies enable the accurate use of this knowledge (Osei-Amponsah *et al.*, 2019).

6.2.5.1 Physiological Consequences of Heat Stress on Muscle Development and Meat Quality

The exposure of cattle to elevated temperatures adversely affects their physiological functioning, resulting in diminished growth and inferior meat quality (Prates, 2025). HS stimulates the hypothalamic–pituitary–adrenal (HPA) axis, leading to significant endocrine changes and increased production of stress hormones such as cortisol. This stress response inflicts cellular damage through oxidative stress and induces inflammation in muscle tissue (Prates, 2025). The metabolic alterations that occur when the body overheat significantly affect the quality of the meat products. The distribution of nutrients varies between the development of lean muscle and the accumulation of fat, perhaps resulting in increased overall fat storage (Prates, 2025). Certain studies indicate that HS may assist in diminishing intramuscular fat (IMF) in specific instances; nonetheless, an increase in total fat accumulation frequently elevates the levels of PUFAs (Swanson *et al.*, 2020). These PUFAs are likely to oxidize lipids, resulting in an unpleasant taste and odor in the meat (Prates, 2025). Furthermore, antemortem hyperthermia can directly affect muscle membrane permeability and metabolism, resulting in considerable postmortem quality complications. In poultry, HS-induced myopathy presents as muscular disorders, including newly identified myopathies known as white striping (WS) and wooden breast (WB), characterized by oxidative damage and difficulties in muscle regeneration (Malila *et al.*, 2022). These valuable characteristics, including marbling in genetically superior breeds (e.g., Angus), are obtained through intricate metabolic pathways (Pozzebon, Guldbrandtsen and Sandøe, 2024). However, if an animal cannot withstand environmental heat, these processes are compromised, leading to product deterioration.

6.2.5.2 Identification and Utilization of Thermotolerance Genes: SLICK Locus

The identification and integration of specific critical genes and quantitative trait loci (QTLs) linked to thermotolerance offer a definitive strategy for developing climate-resilient animals. The SLICK phenotype, characterized by a short, smooth haircoat, is strongly associated with increased heat tolerance (Pozzebon, Guldbrandtsen and Sandøe, 2024). This disorder is typically attributed to a decrease in the prolactin receptor (PRLR) gene, which augments the ability of an organism to dissipate heat through enhanced evaporative cooling (Fajardo *et al.*, 2025). Compared with their nonslicked counterparts, cattle displaying this feature have been reported to maintain internal body temperatures of approximately 1 °F lower throughout the summer months (Pozzebon, Guldbrandtsen and Sandøe, 2024).

The ability to incorporate this SLICK characteristic, either through traditional breeding (leveraging naturally occurring mutations in suitable breeds) or through modern intentional genomic alteration (IGA) techniques such as CRISPR, allows breeders to rapidly instill heat tolerance in temperate breeds (Fajardo *et al.*, 2025). The incorporation of the SLICK gene into commercially important breeds such as Angus allows producers to maintain high carcass yield and marbling characteristics, even in subtropical and tropical locations where these breeds often experience severe production reductions owing to HS

(Pozzebon, Guldbrandtsen and Sandøe, 2024). In addition to the PRLR locus, genomic investigations have identified multiple QTLs related to thermoregulation, including those affecting sweat gland area (SGA) and thermoregulatory efficiency (TSS) on bovine chromosome 1 (BTA1), thereby providing additional markers for selection programs (Zayas *et al.*, 2025).

6.2.5.3 GS for Climate Resilience: Balancing Quality and Adaptability

In dynamic contexts, successful genetic enhancement initiatives require sophisticated selection indices that achieve an optimal balance between productivity and resilience. Research, particularly in high-yielding ruminants, has revealed a genetic conflict between optimal productivity, such as increased milk production or an increased growth rate, and resilience to HS (Carabaño, 2016). Prioritization solely for optimal growth may inadvertently compromise an animal's long-term health. In these circumstances, practical meat breeding requires improved genomic indices that assess thermotolerance markers alongside established growth and yield indicators to ensure sustainable production (Osei-Amponsah *et al.*, 2019). However, genetic adaptations have downstream benefits for meat quality under HS, as illustrated in Figure 6.2. Heat-adapted animals cope with hot slaughter conditions more robustly, preventing the acute depletion of muscle glycogen that causes meat defects.

To achieve this balanced selection, it is necessary to integrate information from phenomics, genomics, and transcriptomics (Carabaño, 2016). Novel phenotypes for selection encompass objective assessments of physiological responses, such as body temperature and respiration rates, which provide real-time data regarding an organism's capacity to manage HS in a commercial environment (Carabaño, 2016). GWASs using commercial DNA chips or comparative sequencing of acclimated and temperate breeds yield significant molecular-level genomic insights. This chapter employs this information to ascertain the estimated breeding values for heat tolerance, enabling precise breeding (Carabaño, 2016). Transcriptome analysis, such as RNA sequencing, can identify genes with differential expression, including heat shock proteins (HSPs), which serve as molecular indicators of the cellular stress response and adaptability (Osei-Amponsah *et al.*, 2019). The application of these methodologies enables breeders to make

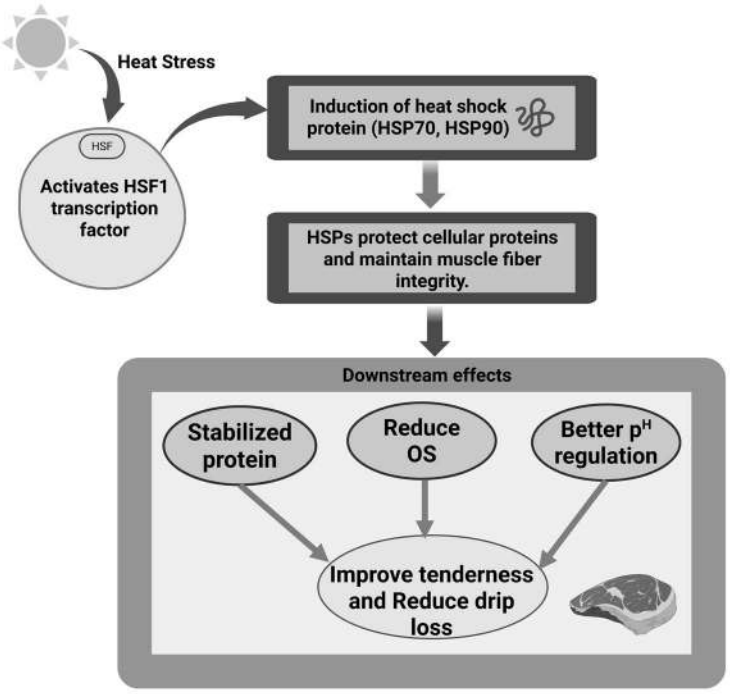

FIGURE 6.2 Molecular pathways in thermotolerance and their effect on meat traits.

TABLE 6.4

Summary of Key Thermotolerance Genes and Their Impact on Production Traits

Gene/Locus	Species	Phenotypic Trait	Mechanism of Action	Meat Quality Rationale	References
PRLR (SLICK)	Cattle	Short, slick hair coat	Enhanced evaporative cooling Reduces core body temperature	Stabilizes growth and development Preserves IMF and reduces heat-induced oxidative damage	Pozzebon, Guldbrandtsen and Sandøe, 2024; Prates, 2025
QTLs on BTA1/BTA18	Cattle	Hair length, sweat gland area (SGA)	Improved thermoregulatory efficiency	Selection target for sustaining productivity in hot zones	Carabaño, 2016; Zayas *et al.*, 2025
HSPs (27, 70)	Ruminants/ poultry	Cellular heat shock response	Cellular protection and improved heat dissipation	Indicator of muscle integrity and stress resilience, mitigating myopathies	Malila *et al.*, 2022; Osei-Amponsah *et al.*, 2019

informed selections on trait preferences, ensuring that genetic improvements in meat quality are safeguarded by sufficient adaptability to diverse environments. Table 6.4 summarizes how thermotolerance genes impact production traits.

6.2.6 Low-Methane Genetics

Reducing livestock methane (CH_4) emissions is crucial for minimizing the environmental impact of agriculture. Low-CH_4 animal genetic selection provides a long-term, cumulative answer, and management techniques can further reduce emissions. The integration of feed efficiency and microbiome data into breeding programs, selection indices, and the heritability of CH_4 characteristics are all topics of recent research. The approaches and strategies for low-CH_4 genetics are illustrated in Figure 6.3.

6.2.6.1 Genetic Selection Strategies for Low-Methane Emissions

6.2.6.1.1 Heritability and Trait Selection

The mitigation of enteric CH_4 emission in ruminants is a critical research priority because of its strong association with global warming. While nutritional and microbial interventions have been widely investigated, exploiting natural genetic variation offers an underutilized strategy for reducing CH_4 yield (Zhao *et al.*, 2025). Direct measurement of emissions remains challenging; hence, the selection of correlated traits such as RFI or CH_4 predicted from intake and diet composition provides a practical alternative. The establishment of phenotypic and genetic variation in the predicted CH_4 output highlights the feasibility of genetic approaches. GS of more efficient dairy cows could reduce CH_4 emissions by 11–26%, accelerating climate-resilient dairy production (de Haas *et al.*, 2011). In dairy cattle, selective breeding can reduce enteric CH_4 emissions by 24% by 2050, making it an affordable, long-term, and cumulative mitigation technique (de Haas *et al.*, 2021). Dairy animals contribute nearly 18% of total global GHG emissions, predominantly enteric CH_4, which represents the major component of the livestock sector's carbon footprint (Min *et al.*, 2022). Enteric CH_4 production is a multifactorial process influenced by the host genotype, rumen microbiome, physiological attributes, and dietary inputs. While nutritional strategies and feed additives offer transient mitigation, durable reductions require genetic improvement through the selection of low-emitting animals. GWASs have identified key QTL regions and SNPs linked to rumen microbial composition, suggesting that CH_4 emission is a heritable, quantitative trait amenable to GWAS (Mahala, Kala and Kumar, 2022).

A recent study evaluated three CH_4 emission phenotypes, daily CH_4 production, CH_4 yield, and CH_4 intensity, evaluating moderate heritability across all traits and confirming their suitability for genetic selection programs. Strong genetic correlations among these traits suggest that selection on a single trait

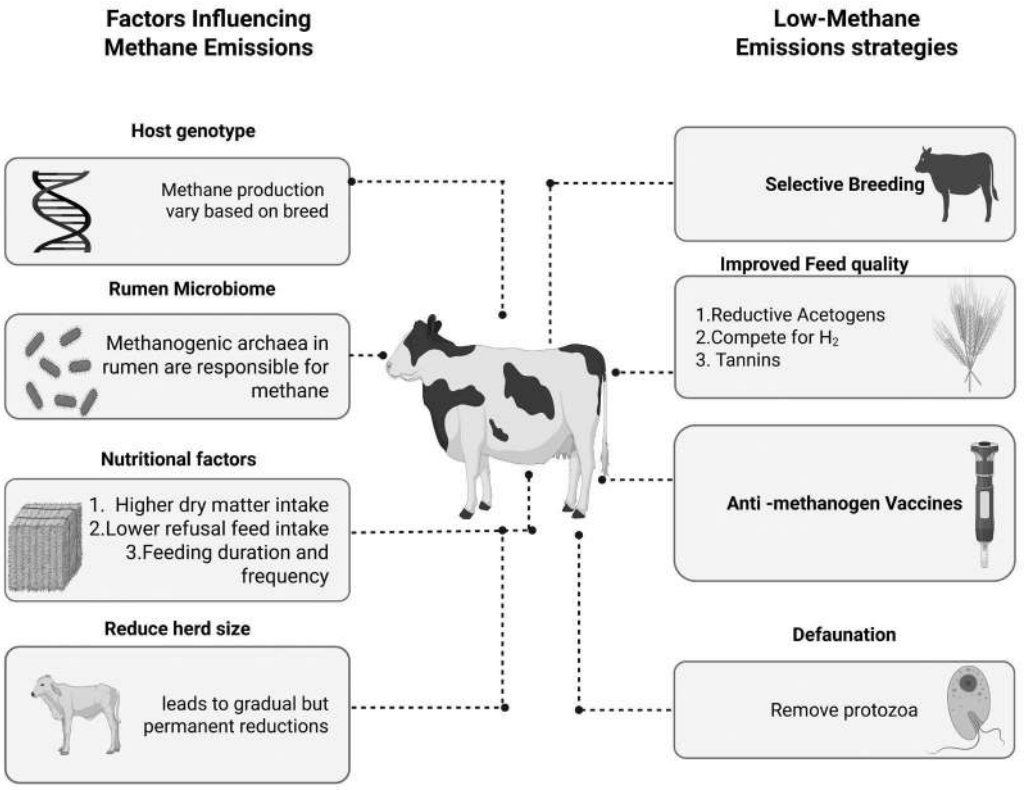

FIGURE 6.3 Factors and strategies of low-methane genetics.

can elicit favorable indirect responses in others. Notably, the high genetic correlation (rg = 0.94 ± 0.23) between daily CH_4 production and CH_4 intensity underscores the potential for reducing emissions per unit of milk yield through targeted selection. These findings highlight the feasibility of the use of genomic strategies to mitigate CH_4 emissions in Holstein cattle while sustaining productivity (Kamalanathan *et al.*, 2023).

Understanding CH_4 emission dynamics between and during lactation is crucial for optimizing dairy cow phenotyping techniques (Difford *et al.*, 2018). Methane concentration (MeC) has a lower but more stable heritability than methane production (MeP), with strong genetic correlations in early lactation that weaken between early and late stages. MeP, particularly during first lactation, is strongly associated with energy-corrected milk yield and dry matter intake (DMI) (Lassen and Løvendahl, 2016; Manzanilla-Pech *et al.*, 2022a). These patterns indicate lactation stage–specific genetic structures of CH_4 characteristics that must be considered in breeding goals (Manzanilla-Pech *et al.*, 2022a).

6.2.6.1.2 Genetic (Co)Variation

In recent years, multiple countries have integrated RFI into breeding objectives as a measure of feed efficiency. The evidence demonstrates a favorable correlation between RFI and CH_4 emissions, indicating that improved efficiency coincides with reduced emissions. Consequently, selection for low-RFI animals provides a practical short-term pathway to mitigate enteric CH_4, contributing to the EU Commission's 2030 target of a 55% reduction in GHG emissions (Manzanilla-Pech *et al.*, 2022b).

6.2.6.1.3 Selecting Breeds

Genetic selection for RFI represents an effective indirect strategy to mitigate enteric CH_4 emissions in beef and dairy cattle. RFI is moderately heritable (0.26–0.43), repeatable across diets (0.33–0.67), and

largely independent of body size, production, and body fatness when adjusted for ultrasound backfat (RFIfat). Accurate feed intake measurement over ≥35 days is essential, as intake exhibits moderate repeatability (0.29–0.49), and diurnal variation is influenced by genotype, diet, and cattle type. Low-RFIf cattle emit 15–25% less CH_4 due to their reduced DMI, shorter feeding duration, and favorable rumen microbial profiles that increase digestibility. Overall, selection for RFIfat is expected to yield 0.75–1.0% annual genetic gain in feed efficiency while sustainably lowering CH_4 emissions without compromising productivity or adaptability (Basarab *et al.*, 2013). Selective breeding can achieve up to a 20% reduction in CH_4 emissions over a decade; however, this requires assigning a substantial weighting (≈33%) to CH_4 in the selection index, which consequently slows genetic gain for production traits by 6–18%. These findings underscore the feasibility of integrating environmental traits into breeding objectives while maintaining herd profitability, thereby balancing sustainability with productivity (González-Recio *et al.*, 2020).

Advances in high-throughput sequencing and analytical tools have further enabled the discovery of metabolic biomarkers, candidate genes, and SNPs associated with CH_4 emissions, providing a genomic basis for sustainable mitigation strategies (Worku, 2024). Methane emissions can be predicted from rumen microbial profiles, reflecting both dietary influences and host genetic control over microbial fermentation pathways that affect energy utilization, rumen physiology, and body composition. Although conventional sequencing remains cost-prohibitive for large-scale selection, genotyping-by-sequencing now enables rapid, low-cost, high-throughput microbiome profiling through a reference-free approach. Notably, microbial profiles are heritable and correlated with both CH_4 emissions and feed intake, highlighting their potential as selection tools for sustainable cattle breeding (Rowe *et al.*, 2020).

6.2.6.2 Complementary and Management Strategies

6.2.6.2.1 Health and Productivity

In subsistence systems, reducing herd size can increase feed availability and individual productivity, thereby lowering CH_4 emission intensity. Increasing the nutritive value of low-quality feeds can further improve herd performance without increasing overall CH_4 output. While RFI may help identify low-emitting animals, evidence linking RFI to reduced CH_4 yield per unit of intake or product remains limited. Additionally, decreasing slaughter age and feedlot duration offers a practical strategy to mitigate GHG emissions in beef and other meat production systems (Hristov *et al.*, 2013).

Methanogenesis is integral to ruminant digestion, with methanogenic archaea producing CH_4 as a metabolic by-product. However, ruminant-derived CH_4 significantly contributes to GHG emissions, exhibiting a 28-fold greater global warming potential (GWP) than CO_2 and accounting for ~15% of anthropogenic emissions. While chemical interventions can reduce emissions, their adoption is limited due to health, safety, and consumer concerns. Consequently, genetic selection and the use of biological feed additives, including probiotics and plant secondary metabolites, have emerged as sustainable strategies to mitigate enteric CH_4 emissions (Króliczewska, Pecka-Kiełb and Bujok, 2023).

Ruminants are pivotal in converting lignocellulosic biomass into high-quality protein for human consumption, yet their digestive physiology generates CH_4, contributing ~40% of agriculture's carbon footprint and ~6% of global GHG emission (Malyugina, Holik and Horky, 2025). Dietary supplementation with antimethanogenic compounds can target rumen methanogens or limit methanogenesis substrates (H_2 and CO_2), effectively reducing enteric CH_4. Additionally, low-effort mitigation strategies, such as antimethanogen vaccines, hold promise for broad adoption by producers if they are demonstrated to be efficacious (Smith *et al.*, 2022).

6.2.6.2.2 Nutrition and Food Challenges

Advances in molecular and next-generation sequencing technologies now enable the identification and selection of animals with superior genetic merit for reduced CH_4 emissions. Genetic selection offers a permanent, cumulative reduction in CH_4 per unit of milk or meat, whereas integrative nutrigenomic approaches provide a practical, eco-friendly avenue to simultaneously mitigate emissions and improve ruminant productivity (Kader Esen, Palangi and Esen, 2022).

6.2.6.2.3 Considerations and Challenges

Methane mitigation strategies remain limited due to the absence of economic incentives for farmers and the short-lived efficacy of most interventions. This underscores the critical need for multidisciplinary research on sustainable CH_4 reduction. Coordinated international initiatives, such as methagene, offer a valuable platform for cross-border collaboration, knowledge exchange, and the development of long-term, impactful mitigation strategies (Lassen and Difford, 2020). However, if selection for lower CH_4 emissions were to occur, there would not be much agreement on which phenotype to look for: CH_4 in liters or grams per day, CH_4 in liters per kilogram of energy-corrected milk or DMI, or a residual CH_4 phenotype, in which CH_4 production is adjusted for milk production and cow weight (de Haas *et al.*, 2017).

6.2.7 Future Perspectives in Genetic Improvement

6.2.7.1 Precision Livestock Farming (PLF)

The number of farmers is declining, whereas the number of animals is increasing. As a result, each farmer has significantly larger herds. Therefore, it is becoming increasingly difficult for farmers to manage and control their farms. Simultaneously, the livestock industry needs to address several problems, including minimizing environmental impacts and monitoring animal health and welfare. PLF aims to offer a real-time monitoring and management system for farmers (Berckmans, 2017). PLF is a term that encompasses sensors for collecting biological information, algorithms for processing the data, and interfaces for its use. It is expected to optimize animal production, health, and welfare (Kleen and Guatteo, 2023). PLF has spread worldwide for its application on livestock farms in both intensive and extensive systems, although it has only recently been adopted (Lovarelli, Bacenetti and Guarino, 2020). The market for precision farming, across all sectors, is expected to grow at an annual rate of 13%, reaching US$12.9 billion in 2027 (Kleen and Guatteo, 2023). The PLF consists of robots or sensors that gather and generate data, which are then processed via specified methods (algorithms) to produce relevant information. The algorithms look for relevant data (such as "alarms") that can serve as justification or a basis for decisions, which the farmer mostly makes. The PLF, therefore, implies a system with components, sensors, algorithms, and interfaces for making practical use of data from livestock farming; the decision-making process, either automatic or supported by applications, is an integral part of the PLF itself. A short overview of PLF is depicted in Figure 6.4. Various components of the PLF have been applied; only some parts have been evaluated scientifically. The effects on animal health, production, and welfare remain largely unknown.

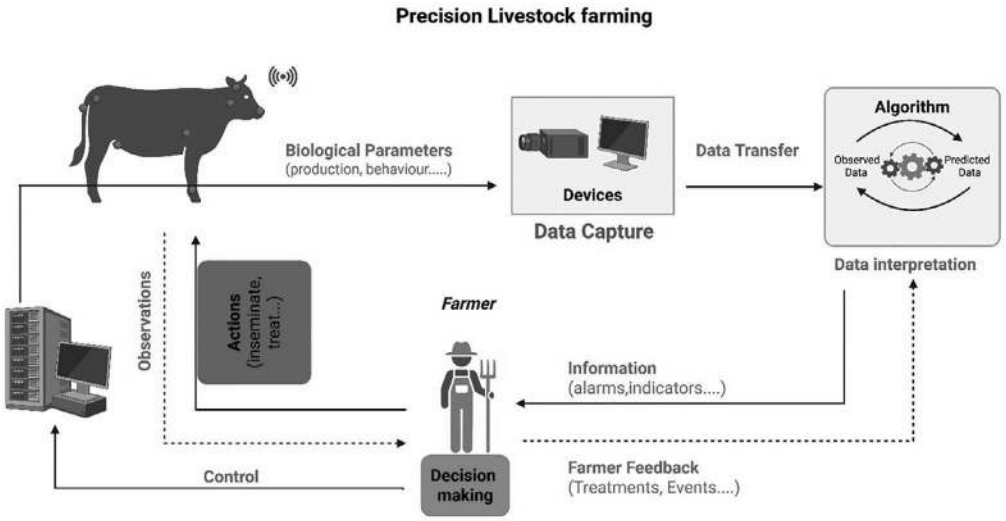

FIGURE 6.4 Overview of precision livestock farming. (Modified from Neethirajan, Reimert and Kemp, 2021.)

6.2.7.2 Elements of the PLF

6.2.7.2.1 Sensors

A "sensor" is defined as "a machine that is used to record that something is present or that there are changes in something". In animal husbandry, sensors are still limited to automated heat detection. According to Kempf (2016), activity monitoring for oestrus detection has a 95% regular detection rate and is generally more effective than visual heat detection. Furthermore, the use of these sensors is economically profitable (Adenuga *et al.*, 2020). These sensors can measure many parameters, such as the rumination rate, which can be recorded via accelerometer (Reiter *et al.*, 2018). Pressure sensors at the head (Shen *et al.*, 2020) or microphones (Vanrell *et al.*, 2018). Scheurwater *et al.* (2021) showed how an intra-articular pressure sensor may be used to measure ruminating or other activities. The device's accuracy, sensitivity, and specificity for detecting rumination were 0.92, 0.97, and 0.90, respectively. Combining activity and rumination rates with other farm data, such as animal health and production data, can provide more precise detection of events such as oestrus (Kleen and Guatteo, 2023). The algorithms that perform this identification (see below) are trained to identify patterns in the data, forecast relevant events, and generate predictions on the basis of these patterns. Thus, animals at risk of a particular disease can be recognized early and given extra care (Abuelo *et al.*, 2021; Sturm *et al.*, 2020). Grinter, Campler, and Costa (2019) monitored the behavior of dairy cattle by using a collar characterized by a behavior-monitoring series of sensors. They examined the rates of ruminating, feeding, and resting behaviors and oestrus events. The findings revealed that cows with mastitis, metabolic disorders, or those nearing calving eat and ruminate less than usual and lie more than normal. Additionally, several authors have examined these collar sensors and the accuracy of the results achieved with these instruments (>90%), whereas visual human observation is far less accurate.

There is hardly any regulatory framework concerning sensors in terms of both expected efficacy and safety. The disposal of sensors still occurs after slaughter, and the potential to endanger food safety after culling may be seen as a risk to human health and the environment. Furthermore, there is a risk of system malfunction. Therefore, a licensing system, approval, and guarantee scheme are preferable for the use of these sensors.

6.2.7.2.2 Algorithms

An "algorithm" can be defined as a "set of mathematical instructions or rules that will help to calculate an answer to a problem". For algorithms to be effective and enable proactive decision-making, algorithms typically need to include a prediction component that finds significant future events (Rosa, 2021). These challenges can be overcome by applying "machine learning" (ML), in which algorithms are trained to recognize relevant patterns in a pool of information. The development of an algorithm occurs in two ways: (1) Information or events that are already known can be examined on the basis of their informational attributes and subsequently utilized by an algorithm to recognize similar patterns in another dataset. (2) The algorithm autonomously detects relevant info within sensor data and establishes event definitions by identifying distinctive patterns that can later be associated with specific events of interest. Accordingly, this analytical process can be categorized as either supervised or unsupervised learning (Lokhorst, De Mol and Kamphuis, 2019). Reiter *et al.* (2018) validated an accelerometer-based algorithm, providing an example of a supervised learning approach. The study revealed strong agreement between visual observation and sensor recognition. For example, the sensor identified an average of 1,508 seconds of rumination per hour of the resting phase; human observation recorded 1,492 seconds of rumination. The specific structure of algorithms used in commercially available systems is generally not disclosed. Since these algorithms constitute proprietary intellectual property, their details are typically not published or made publicly accessible (Kleen and Guatteo, 2023).

6.2.7.2.3 Applications

The data produced by sensors and algorithms are raw or processed, and these data need to be accessible and meaningful. The applications that accomplish this are frequently farm-installed computer systems that create a database of data related to the farm, such as milk production or fertility and production data. A move toward cloud-based solutions has taken place in recent years, where farm data, including

sensor data, is sent to an external data storage facility for central processing (Michie *et al*., 2020). The farm has access to relevant data through websites, apps, or alarms, such as those on a mobile device (Michels, Bonke and Musshoff, 2019). Relatively few academic studies have focused on the nature and impact of these applications.

6.2.7.2.4 Interfaces

Interfaces are necessary to connect data originating from various sources; they connect electronic farm-specific data (insemination dates) with external data (milk recording data) and sensor system data. Ferris, Christensen, and Wangen (2020) presented an integrated system that makes use of all the information accessible at the farm level, as well as data such as weather and pricing. The application of such a system was demonstrated by Cabrera *et al.* (2020), who used the udder health situation as an example. It is possible to determine which animals are more likely to develop mastitis as early as their first lactation. Animal behavior, production data from the milking parlor or milk recording, and genetic information (Gengler, 2019) are used to classify. For this species, the system suggests early culling or removal from breeding because of its low potential. Another concept that integrates data is the "digital twin" (Verdouw *et al*., 2021).

6.2.7.3 Role of AI in Selection Programs

Over time, technological advancements have made performing conventional farming activities simpler. In particular, it is now feasible to interpret daily data acquired for animal control in cattle production (Vranken and Berckmans, 2017). The use of ICT in the livestock industry has enabled the use of these data to predict and describe the behavior linked to more efficient animal husbandry (Espinosa, Bastidas Duque and Naranjo Arroyave, 2016). To make these predictions, ML is often used for several components of a dairy farm, such as livestock-behavior classification, animal monitoring, grass intake and rumination, insemination monitoring, lameness detection, 3D computer vision models in PLF, etc. (García *et al*., 2020). Some of the models are outlined here.

6.2.7.3.1 Livestock-Behavior Classification

Some researchers consider online learning algorithms and the *k*-nearest neighbors (KNN) algorithm to be effective mechanisms for long-term in-field monitoring systems. The suggested technique uses data from an embedded edge device—a triaxial gyroscope sensor to categorize relevant sheep behavior (Vázquez-Diosdado *et al*., 2019). Another alternative to the KNN algorithm for behavior classification is hierarchical ML (Suparwito *et al*., 2019). In addition to classifying behavior as active or inactive, one may also use an inventory of animal actions to categorize behavior. This type of inventory is referred to as an ethogram (Fogarty *et al*., 2020). The decision tree (DT) algorithm accurately classifies three types of biologically relevant behaviors: lying (77.42% sensitivity, 98.63% precision), standing (88.00% sensitivity, 55.00% precision), and feeding (98.78% sensitivity, 93.10% precision). Global positioning system (GPS) data are also important sources of information for behavior classification (Williams, James and Rose, 2019). Other ML works on livestock behavior classification can be found here (García *et al*., 2020).

6.2.7.3.2 Grass Intake and Rumination

The statistical model is an ML algorithm used to predict cattle rumination and grass intake. The scientists installed smartphones on 19 grazing cows of various breeds and captured daily video clips of various fodder pastures. The final algorithm employs a two-step discriminant tree using the average and standard deviation of the two signals. The rotation rate on the same *x*-axis (Rx) represents the motions of the cow's jaws, whereas the gravitational acceleration on the *x*-axis (Gx) represents the movements of the cow's head. After validation on a separate database, the average detection accuracy was 92%, with rumination having a higher detection rate (95%) than grass ingestion (91%) (Andriamandroso *et al*., 2017). Another approach is called the Chew-bite Intelligent Algorithm (CBIA) (Chelotti *et al*., 2018).

6.2.7.3.3 Animal Monitoring

For better health records and management of the farm, logistic regression models and data from calving and oestrus sensors were used (Benaissa *et al*., 2020). Labrecque and Rivest (2018) proposed a unique

method based on real-time behavior analysis to ascertain the best moment for disseminating insemination. Real-time analysis enables the use of behavior-pattern recognition to determine the statistically optimal time for insemination. For 21 months, 20,485 weaned sows from seven commercial farms were kept in the system. The technology made it simple to handle 99.78% of the sows when used in conjunction with daily heat detection. The most used ML techniques for livestock growth management are support vector machines (SVMs) and DTs. There are several possible explanations. For example, SVM has gained widespread acceptance because it can discriminate among data of different types via kernels: the theoretical basis of kernels in SVM makes it an exceptional tool for generalization in complex problems (Lemaire *et al*., 2019).

6.3 Management Strategies for Meat Quality

There are quality control processes for meat to maximize nutrient content and intake and processing methods to increase the taste, texture, and nutritional value of meat. Meat quality control techniques highlight how heredity, nutrition, and management practices can be best exploited to enhance desired attributes that most importantly involve firmness, flavor/taste, juiciness/succulence, and nutritional value. Stunning methods, such as electrical and gas stunning, ensure rapid collapse and reduce damage, whereas poststun bleeding improves color and reduces contaminants. This ensures that customers are satisfied and compliant. Nutritional techniques that enhance flavor with stable oxidation include the use of antioxidants such as vitamin E and selenium. Dietary interventions, including the use of antioxidants such as vitamin E and selenium, help preserve flavor and improve oxidative stability.

6.3.1 Nutritional Management

6.3.1.1 Balanced Ration for Optimal Muscle Deposition

A balanced diet provides an animal with the right amount and proportions of nutrients for growth, maintenance, or production. Proper nutrition and nutritional control are essential for optimal animal performance and meat quality. Several studies have demonstrated that different feeding systems and diets affect the yield, quality, and composition of ruminant meat (Chilliard *et al*., 2007). Variations in fat content, FA composition, and flavor primarily depend on macronutrients such as protein, fat, and carbohydrates, as well as on digestion and absorption (Kearns *et al*., 2023). Lipid and FA levels also affect sensory qualities such as aroma, taste, and mouthfeel, as well as nutritional value, thereby influencing consumer preferences (Vasta and Priolo, 2006). IMF in skeletal muscle is crucial for beef quality, particularly in countries such as Korea, Japan, Australia, and the United States. Its deposition depends on factors such as genetics, breed, management, and nutrition, which influence fat metabolism, feed digestion, the roughage-to-concentrate ratio, and the availability of glucose, starch, and vitamins A, D, and C. However, efforts to increase IMF in lambs have resulted in higher levels of monounsaturated and saturated FAs (such as C18:1 and C14:0) and BCFAs (Realini *et al*., 2021).

Higher IMF enhances tenderness and flavor, making marbled beef more appealing. In Korean cattle fattening, concentrated diets are aimed mainly at high MARB (Park *et al*., 2018). Wilson, Ross and Harris (1988) reported that maternal nutrition influences offspring muscle fiber numbers, with 30% dietary restriction during pregnancy decreasing fiber counts in the soleus and lumbrical muscles. Many countries consider an IMF level above 30 g/kg in the longissimus muscle essential for tenderness, although in the UK, pigs with less than 10 g/kg fat have a weaker association between fat content and tenderness. Additionally, muscle lipid content can indicate the presence of red oxidative (type 1) fibers, which are linked to tenderness in muscles and carcasses (Wood and Enser, 2017). Recently, nutritional strategies, such as developmental programming via metabolic imprinting, have been suggested to alter IMF potential during the fetal and neonatal stages in rodents and livestock. Since multiple factors impact the IMF, combining customized approaches may better meet consumer preferences.

6.3.1.2 Nutritional Interventions to Enhance the Flavor and Fatty Acid Profile of Meat

Nutritional interventions in ruminant livestock management are essential for producing high-quality meat that can compete globally. The quality of meat is often assessed visually by examining features such as color, flavor, and appearance, usually through human sensory evaluation. Modifications in fat content, FA composition, and sensory qualities are achieved through adjustments in feeding practices and dietary formulations. The sensory attributes of meat are mainly determined by fat content and FA composition, both of which are influenced by the animal's diet and nutrient utilization. The diets of both small and large ruminants significantly influence meat quality. Modifications in feeding practices, production systems, concentrate feeding (feedlots), and types of supplements (oils and meals) can influence meat palatability, nutritional value, and sensory attributes (Wood and Enser, 2017). Offering sheep with grain-rich concentrate diets may increase carcass fat, ω-6 FAs, and the ω-6/ω-3 ratio in meat (Ponnampalam *et al*., 2017). IMF in beef contains higher levels of FAPUFAs than do subcutaneous and visceral fats (Nguyen, Nguyen and Malau-Aduli, 2021). However, efforts to increase IMF in lambs have resulted in increased levels of monounsaturated and SFAs (such as C18:1 and C14:0) and BCFAs (Realini *et al*., 2021). The link between IMF and specific FAs is believed to affect the sensory attributes of meat (Bonny *et al*., 2015). However, elevating these FAs may alter taste and aroma unless antioxidants are used. A balanced diet of forages, crop residues, and agricultural by-products can sustainably improve both the quantity and quality of meat.

FA composition affects the physical and textural properties of adipose tissue and the oxidative stability of muscle, thus influencing flavor, juiciness, tenderness, color, and overall attractiveness. The digestion of lipids in monogastric animals mainly occurs in the small intestine, where pancreatic lipase breaks down triacylglycerols into 2-monoacylglycerol and free FAs. These products form micelles, are absorbed by the intestinal mucosa, and are transported through the bloodstream, with tissue uptake mediated by lipoprotein lipase (Woods and Fearon, 2009). In swine and avian species, dietary lipids largely remain unchanged until absorption, resulting in tissue lipid profiles that are strongly affected by diet. The digestion of lipids in ruminants is more complex because of microbial activity in the rumen–reticulum. This leads to ruminant meat having diverse FA profiles, which are often different from those of dietary FAs (Vahmani *et al*., 2015). Unsaturated FAs, especially PUFAs, can harm some rumen microbes (Maia *et al*., 2007). To address this, the rumen microbiota produces enzymes that break the ester bonds of esterified FAs, lowering unsaturation through reduction, isomerization, or hydration.

Lipolysis and biohydrogenation convert dietary PUFAs into saturated FAs, thereby limiting their transfer from the rumen. However, incomplete biohydrogenation creates FA intermediates, including trans double bonds (Shingfield, Bonnet and Scollan, 2013), which are later absorbed and utilized in tissue lipogenesis. To develop nutritional strategies that accurately predict and regulate the FA composition of ruminant meat, it is important to understand these systems, including the microbiota and their enzymes. The investigation of FA profiles in meat primarily aims to produce healthier meat with a higher ratio of PUFAs to saturated fats and a better balance between n-6 and n-3 PUFAs. Ruminant foods are rich in n-3 PUFAs because of the presence of alpha-linolenic acid (ALA) (18:3) in grass. Grass-fed beef and lamb naturally contain relatively high levels of 18:3 and long-chain n-3 PUFAs, which influence flavor and contribute to a distinctive grass-fed taste associated with other grass components.

Nutritional strategies can alter muscle FA profiles to improve nutritional balance by increasing the PUFA-to-saturated FA ratio and lowering the n-6:n-3 PUFA ratio. Higher PUFA levels might influence flavor because they are more prone to oxidative breakdown, leading to the formation of unusual volatile compounds during cooking. In swine, adding whole linseeds to the diet can effectively supply approximately 3 mg of α-linolenic acid (18:3) per 100 mg of muscle and adipose tissue. Many studies suggest that this level may cause off-flavors and odors, although some do not support this claim. In cattle and sheep, feeding whole linseed increases muscle 18:3 levels from approximately 7 mg/100 mg to more than 1 mg/100 mg while increasing long-chain n-3 PUFAs such as eicosapentaenoic acid (EPA) (20:5) produced from 18:3 (Wood and Enser, 2017). Although this increase promotes greater oxidative lipid breakdown during storage and yields many lipid-derived volatile compounds during cooking, it does not

affect odor or flavor. When 18:3 ratios increase in lamb and beef from grass feeding, the flavor becomes more intense than in grain-fed animals, which typically consume and deposit more linoleic acid (18:2) (Wood and Enser, 2017).

6.3.1.3 Role of Supplements: Antioxidants, Amino Acids, Probiotics, and Phytogenics

Livestock farming focuses on improving growth by reducing chronic inflammation and stress and promoting animal well-being rather than just addressing immune issues. While there is no single solution for these complex challenges, studies indicate that probiotics, microbes, prebiotics, and phytochemicals support gut health with anti-inflammatory, antioxidant, and immune-boosting effects. Animals raised without antibiotics rely on natural additives to prevent inflammation and the spread of disease, thereby ensuring health and food safety (Shehata *et al*., 2022).

Phytogenic compounds are natural bioactive substances derived from plants that positively influence animal growth and health and are commonly found in essential oils, botanicals, and herbal extracts (Puvača *et al*., 2013). Some EOs possess antibacterial, antiviral, antifungal, and antioxidative properties (Brenes and Roura, 2010) and have long been used as alternative or complementary treatments to enhance human health or combat diseases. Phytogenic feed additives, also known as phytobiotics, improve feed quality, animal productivity, and product quality (Wang *et al*., 2024). These compounds include a broad spectrum of plant-derived bioactive substances, with essential oils being a major group. Their influence on anti-inflammatory responses, gut chemosensing, and bacterial quorum sensing may account for the improved production performance observed in animals fed phytogenic additives.

Since 2006, the EU has banned the use of antibiotic growth promoters in food animals, prompting other countries to follow suit. The removal of antibiotics poses challenges, notably in terms of cost-effectiveness for sustainable animal farming. Owing to their diverse active ingredients, phytogenic compounds are among the most promising alternatives to antibiotics. However, their use in food animals remains limited because of inconsistent effectiveness and incomplete understanding of their mechanisms. It is also crucial to assess potential risks to animal health and human safety when using phytogenic substances, regardless of their GRAS status (Yang *et al*., 2015). Compared with antibiotics, natural and phytogenic substances offer various advantages, particularly in terms of profitability and a reduced risk of resistance. As a result, they are considered better alternatives to antibiotic growth promoters. The incorporation of essential oils, plant extracts, and herbal extracts as phytogenics in swine feed improves growth performance, nutrient digestibility, biochemical profiles, gene expression, hypocholesterolemic effects, immunity, meat quality, FA profiles, and amino acid levels. It helps reduce the impact of diseases and environmental stressors on gut health. The incorporation of phytogenics into swine feed is suggested to alleviate stress by inhibiting the NF-κβ and Nrf2 pathways and increasing the production of anti-inflammatory cytokines (Madesh *et al*., 2025).

Ren *et al.* (2025) reported that adding 0.8% of a phytogenic feed additive to the diet offers multiple benefits for white-feathered broilers. This additive increased the ADG, highlighting its role as a natural growth promoter. It enhances meat quality and adds value by altering the gut microbiota and affecting postmortem glycolytic and lipid peroxidation processes. The additive induced changes in the cecal microbial community, increasing beneficial taxa such as Deinococcus-thermus, Bacteroidetes, Actinobacteria, and Cyanobacteria while reducing opportunistic pathogens. This prebiotic-like effect may improve nutrient absorption, strengthen the intestinal barrier, and support immune balance, thereby explaining the observed growth advantages. Its phytochemicals likely work together to influence host–microbiota interactions and metabolic pathways, offering a sustainable alternative to antibiotics (Ren *et al*., 2025).

6.3.2 Feeding Systems and Production Environments

6.3.2.1 Pasture-Based and Intensive Feeding

The positive effects of pasture-based systems on the FA profile of sheep meat remain consistent despite fluctuations in pasture quality. Lambs grazing on lush tropical pastures often produce excess nitrogen,

mainly ammonia, resulting from protein breakdown. Animal performance also varies with pasture quality, generally improving in high-quality, accessible pastures; sometimes, concentrations are used to increase energy intake and nitrogen use efficiency. The integration of high-quality pastures with a total mixed diet provides a beneficial alternative to concentrate feeding, which can increase nitrogen efficiency and reduce the risk of acidosis. Zhang *et al.* (2022) studied lambs raised under two feeding methods—pasture grazing and concentrate feeding in a sheep pen—and revealed that the rearing environment and forage affected growth performance, meat texture, and FA composition. Using TMR after weaning on pasture resulted in faster growth and improved eating quality, with meat showing a redder, brighter color, tender texture, and a healthier FA profile suitable for humans.

Compared with stall-fed sheep, pasture-grazing sheep presented significantly lower ADG, slaughter live weight (SLW), and carcass weight but maintained a similar dressing percentage ($p < 0.05$). However, sheep that grazed on pasture with supplementation presented characteristics comparable to those of stall-fed sheep ($p > 0.05$). The longissimus muscle of lambs fed solely on pasture or on pasture supplemented with concentrate had notably lower lightness and IMF. However, it presented increased yellowness, Warner–Bratzler shear force, and protein content compared with those of stall-fed sheep ($p < 0.05$). Sheep grazing exclusively on pasture generally have reduced carcass yield and meat palatability but better overall meat quality; in contrast, pasture-fed sheep with feed supplements display similar carcass traits but improved meat color and health benefits. Meat from pasture-grazed lambs tends to have less color, tenderness, and IMF but higher protein levels. Supplementing pasture grazing improves meat color and protein content, although tenderness and IMF remain lower than those in stall-fed lambs. Compared with lambs fed indoors, pasture-grazed lambs usually have a lower ADG, SLW, hot carcass weight (HCW), cold carcass weight (CCW), and dressing percentage. They also have a reduced IMF, which is considered more beneficial for health. Supplementing pasture grazing yields SLW, HCW, CCW, dressing percentage, and meat quality similar to those of unsupplemented pasture grazing. Wang *et al.* (2015) reported that pasture-grazed sheep have ADG and HCW comparable to those of indoor-fed sheep but lower IMF; adding concentrate to pastures improved ADG and HCW without affecting IMF (Wang *et al.*, 2015). Lambs supplemented with lucerne show better growth, tenderness, juiciness, fat, and flavor (Hamdi *et al.*, 2016). Conversely, lambs grazed on *Brachiaria* with concentrate supplements present carcass and meat qualities similar to those fed only concentrate (De Brito, Ponnampalam and Hopkins, 2017).

The production of lambs under extensive feeding systems lowers input costs, benefits the environment and animal welfare, and produces "healthier" meat for human consumption. A forage-based diet can generate lean lambs with low-fat content, but the use of high-value forages can increase growth, increase carcass weight, and produce even "healthier" meat. Adding supplements rich in crude protein and energy promotes faster weight gain and better carcass quality. Meat from animals fed forage diets often has a greater proportion of PUFAs, a lower omega-6:omega-3 ratio, and sometimes more natural antioxidants, which can help reduce oxidation. Factors such as forage species and cultivar, feeding duration, climate, forage management, supplementation, physical activity, diet choices, breed, genetics, and other elements affect meat quality. Their interactions can lead to incorrect interpretations (De Brito, Ponnampalam and Hopkins, 2017).

The qualitative traits of meat, such as color, are important during the purchase process and directly affect how consumers perceive its quality. Compared with lamb fed concentrated diets, those fed forage-based diets produce meat with lower muscle glycogen levels, resulting in a higher final pH and darker color. Tenderness is also a key factor in meat choice. Typically, meat from forage-fed lambs is seen as less tender than that from lambs fed concentrates (Perlo *et al.*, 2008). Flavor also plays a crucial role in meat palatability and is the primary sensory trait influencing customer preference, especially when tenderness is similar (Díaz *et al.*, 2011). Additionally, flavor should be considered when evaluating lambs fed various types of fodder.

Lamb raised in feedlots or with supplemental feeding in extensive systems grow faster, reach target weights more quickly, and produce heavier carcasses than those subjected to grazing. However, research shows that lamb raised on high-quality pasture can achieve satisfactory growth rates while maintaining carcass and meat quality. Recently, consumer interest in healthy products that emphasize animal welfare and environmental sustainability has increased, making extensive lamb production more attractive.

Lambs on pasture can meet many of these expectations. Additionally, lambs fed high-quality green pasture tend to produce meat richer in omega-3 FAs, such as EPA and DHA, than lambs raised on feedlot pellets, grains, or dry pasture/straw (De Brito, Ponnampalam and Hopkins, 2017). Animals raised in extensive systems typically tend to be smaller, with less body fat and higher levels of SFAs, omega-3 FAs (ω-3 FAs), rumenic acid (RA, C18:2 *cis*-9, *trans*-11, also called CLA), and *trans*-vaccenic acid (TVA, C18:1 *trans*-11). In contrast, animals in intensive or semi-intensive systems fed grain-based concentrates generally grow larger, weigh more, and accumulate more body fat, along with higher levels of oleic acid and ω-6 FAs and a greater ω-6/ω-3 ratio (Ponnampalam *et al.*, 2022).

6.3.2.2 Grass- and Grain-Fed Meat Quality

The increasing popularity of grass-fed beef among consumers has raised questions about how it compares nutritionally to grain-fed beef. Over 30 years of research have shown that grass-based diets can significantly improve the FA profile and antioxidant levels of beef, although the effects on taste vary. These diets increase total conjugated linoleic acid (CLA) isomers, *trans*-vaccenic acid (TVA), a precursor to CLA, and omega-3 FAs (Whetsell and Rayburn, 2003). Several studies have also shown that, compared with grain-fed diets, grass-fed diets increase the number of precursors for vitamins A and E and increase the activity of antioxidants, including glutathione (GT) and superoxide dismutase (SOD) (Descalzo *et al.*, 2007). Additionally, grass-finished beef may have a yellowish fat tone due to higher carotenoid levels, which are precursors to vitamin A (Raes, De Smet and Demeyer, 2004). These differences in FA content give grass-fed beef a unique flavor and cooking qualities, which are important to consider when transitioning from grain-fed beef. To maximize the health benefits of lipids and antioxidants, animals should be fed 100% grass- or pasture-based diets. Consumers who eat grain-fed beef can still achieve similar levels of omega-3 and CLA by selecting higher-fat cuts, which also tend to offer better flavor and palatability. Notably, grass-finished beef contains more stearic acid (C18:0), a saturated FA with a neutral effect on serum cholesterol.

The benefit of grain-feeding lies in its ability to promote faster growth, allowing cattle to reach higher carcass weights and fat cover levels at a younger age. Consequently, grain feeding is likely to influence meat quality characteristics, such as tenderness and meat color, which are affected by age. It may also alter the composition of FAs and meat volatiles; however, its effect on flavor remains undetectable by sensory panels. Nogoy *et al.* (2022) reported that beef cattle fed a grass-based diet presented a lower fat content than those fed a grain-based diet. This reduction affected the FA profile of beef intended for human consumption. Compared with the grain-fed beef, the grass-fed beef contained 2,773 mg less total SFAs per 100 g. It also had a more favorable saturated FA profile, with lower levels of cholesterol-raising fats (C12:0 to C16:0) and less cholesterol-lowering C18:0 FA. Moreover, grass-fed calves had higher levels of total omega-3 FAs, long-chain n-3 PUFAs, and TVA, which are beneficial for health. The increases in long-chain n-3 PUFAs (EPA, DPA, and DHA) were notable in grass-fed beef. Conversely, grain-fed Hanwoo beef had higher EPA and DHA levels than grass-fed Hanwoo beef. The higher n-3 PUFA content in grass-fed beef also lowered the n-6 to n-3 ratio, which is advantageous. Owing to its lower total fat content, grass-fed beef had higher n-3 PUFA and lower MUFA levels. Overall, grass-fed beef enhances healthy lipids, such as omega-3 PUFAs, and reduces harmful SFAs, potentially offering health benefits, such as reduced risks of cancer and cardiovascular disease. Although grain-fed beef contains fewer long-chain n-3 PUFA, consuming it in large amounts can still meet omega-3 needs. Notably, grain-fed beef has increased total MUFAs, which may help lower cardiovascular risk (Nogoy *et al.*, 2022).

The levels of functional lipids and FAs in beef depend on two feeding systems: grain-feeding, which involves grains and formulated feedlot diets, and grass-feeding, which reduces or eliminates grains. Recognizing the beneficial FA content in beef is important because of growing consumer interest in healthier options. The health risks associated with beef fat should be considered in terms of both specific FAs and their synergistic effects within related groups. Although grass-fed beef often has increased SFAs, such as myristic (C14:0), palmitic (C16:0), and stearic (C18:0) acids, it also shows improvements in omega-3 FAs, total CLA (C18:2) isomers, and *trans*-vaccenic acid (TVA, C18:1 t11) in grass-based diets (Daley *et al.*, 2010). Both US grass-fed and grain-finished beef provide omega-3 FAs, mainly ALA. Lean beef from either feeding method can modestly help meet n-3 LCPUFA intake goals while contributing

only a small amount of total fat to the diet (Van Elswyk and McNeill, 2014). In contrast, four studies in the United States demonstrated that feeding cattle grass or forage significantly reduces overall fat levels compared with those of grain-finished beef. As cattle age and muscle growth decelerates, a grain-finishing diet generally increases fat content because it provides more net energy and glucose for fat deposition.

6.3.2.3 Precision Feeding Technologies

Precision feeding in animal production involves the delivery of highly tailored diets that meet the specific nutritional needs of animals (Broom, Galindo and Murgueitio, 2013). This practice, which involves customizing diets to meet individual requirements, has become a promising approach in animal farming. It significantly reduces the environmental impact by decreasing feed waste and nutrient excretion. As a key component of modern animal production, it offers multiple benefits, including ecological advantages, improved animal welfare, and improved nutritional efficiency (Sonea *et al*., 2023). Precision feeding involves customizing nutrition for individuals within a group via advanced feeding technologies such as sensors and feeders to deliver the right amount, content, and timing of feed, whether to groups or individual animals (Pomar *et al*., 2009). Predictive models such as InraPorc estimate nutrient needs and excretion, helping optimize feeding strategies by adjusting the nutrient supply daily for each animal. These models can be improved further by enhancing sensor accuracy or by incorporating factors such as ambient temperature and physical activity, which also affect energy use and the feed conversion ratio (Gaillard, Brossard and Dourmad, 2020).

Precision feeding systems use advanced technologies such as radio-frequency identification (RFID) and sensors to automate data collection, processing, and real-time decision-making. RFID tags identify animals at feeders, recording visits, duration, and intake. Typically, only sows are recognized individually owing to cost constraints, but the technology allows for customized diets, particularly for gestating sows, on the basis of body composition analyzed through imaging, video, or ultrasound. Precision pig feeding involves the accurate and timely delivery of feed with the correct composition for each pig, requiring an understanding of individual variability in behavior, physiology, and response. It aims for automatic management, providing diets that meet daily nutrient needs, lowering costs by over 4.6%, and reducing nitrogen and phosphorus excretion by more than 38% (Pomar *et al*., 2009). Proper diet formulation, nutrient density, and environmental control improve feed efficiency (Gaillard, Brossard and Dourmad, 2020). Using synthetic amino acids allows for lower crude protein levels, decreasing nitrogen waste and environmental impact (Remus, 2018). Precision feeding enhances amino acid utilization; decreases intake by 17–27%; and reduces nutrient, odor, and gas emissions, with potential environmental benefits, including greater than 12% feed cost-savings, greater than 60% excretion reduction, and greater than 12% GHG emissions (Pomar and Remus, 2019).

Artificial intelligence (AI) and ML play crucial roles in data analysis and interpretation, enabling personalized feeding strategies. Diets are typically customized to meet each animal's specific nutritional requirements. Precision feeding can increase resource efficiency, reduce environmental impact, and promote sustainability in animal production. Accurately matching the nutrient supply to individual needs minimizes feed waste and nutrient excretion, lowering the environmental footprint of livestock farming. Additionally, it supports tailored dietary plans that improve animal health and product quality.

New feeding strategies emphasize individual variation, aiming to feed animals closer to their needs. Precision feeding delivers the correct ratio at the right time, and models could be enhanced by incorporating environmental and behavioral data that influence intake. An automated system can identify issues early, saving farmers' time and reducing stress. Dourmad *et al.* (2017) created a decision-support tool for precision feeding of gestating sows on the basis of InraPorc. It calculates the optimal daily intake for each sow using a factorial approach that considers factors such as genotype, parity, and gestation stage. The energy needs are determined to achieve the target BW and BT at farrowing (Gaillard *et al*., 2019). Simulations comparing daily individual mixing of two feeds with different lysine levels to standard fixed mixing revealed that precision feeding could reduce the total SID Lys supply by 27–32% across farms and reduce instances of under- or overfeeding sows (Gaillard, Brossard and Dourmad, 2020). Adjusting feeding strategies throughout gestation to better match changing nutrient requirements holds promise for

lowering N and P excretion and feed costs. Using a mixture of two feeds, one more expensive for higher needs and one cheaper for lower requirements, could also offer economic benefits by allowing ongoing nutrient adjustments.

6.3.3 Effects of Housing Density and System Type: Free Range, Intensive

Housing system (HS) and housing density (HD) are among the most common management variables influencing poultry welfare, physiological resilience, growth performance, and ultimately meat quality and sustainability (Attia *et al*., 2021a, 2021b). Meat consumption from free-range animals increased by approximately 250% in Europe from 2009 to 2019, due in part to consumers' perception that animals with access to the outdoors have better welfare (Martelli, 2009; Willer, Trávníček and Schlatter, 2024). The shift toward outdoor access for birds has also led to renewed scientific interest in how different housing systems, from free-range systems to systems with controlled microenvironments, affect the behavioral expression of animals, physiological homeostasis, and carcass quality.

6.3.3.1 Behavioral Expression and Welfare in Free-Range Systems

Free-range systems offer outdoor access, allowing birds to engage in natural behaviors, especially locomotion, which is observed up to 91 times more often than under conventional intensive housing (Ahmad *et al*., 2021). The percentage of birds in the range spans 4–50%. Birds are influenced by climate, topography, and design (Fanatico *et al*., 2016; Taylor *et al*., 2017), but once defined, individual birds demonstrate consistent range use over time, suggesting a changeable yet consistent "personality" trait that may be a trait underpinned by genetics (Bonnefous *et al*., 2023; Carere and Maestripieri, 2013).

Welfare benefits of access to free-range systems regarding increased behavioral enrichment create both metabolic and environmental variability. Studies indicate the potential of increased outdoor activity to increase bone strength and mineralization; however, the welfare impact remains context-based. Hock burns and pododermatitis—a key welfare assessment—demonstrate no clear differences in incidence between birds with high ranges and birds with low ranges (Marchewka *et al*., 2020; Stadig *et al*., 2016; Taylor *et al*., 2018), indicating that general leg health is independent of range use if ground conditions are well managed. An assessment revealed that increased pododermatitis occurred under muddy ground conditions at the doorways of the houses. Notably, it is essential to appreciate the influence of climate and management on range use to understand potential responses.

6.3.3.1.1 Growth Performance and Economic Trade-Offs

The interaction between range access and housing density influences the efficiency of growth. For broiler strains that reach market weight quickly, birds that utilize this range have reduced BW gain compared with birds housed indoors (Durali *et al*., 2014; Taylor *et al*., 2018). For birds from slow-growing genotypes, birds housed indoors gained approximately 4–5% more weight at slaughter than birds that had access to outdoors (Stadig *et al*., 2016). On the other hand, other genotypes have opposite relationships, where birds with higher usage of the outdoor range had a higher BW at the end of the study (Marchewka *et al*., 2020). These inconsistencies demonstrate the importance of genotype–environment interactions and the energetic cost associated with locomotion and thermoregulation.

Research conducted in controlled-environment settings has also revealed that feed intake, BW gain, and feed conversion efficiency decline as HD increases, especially beyond 90 birds/m^2 (Goo *et al*., 2019; Jhetam *et al*., 2022; Kaya and Fidan, 2023; Weimer *et al*., 2020). An optimal breed performance within ranges of 30–60 birds/m^2 coincides with birds efficiently converting feed while assuming minimal welfare stress (Nawarathne, Kumari and Nayananjalie, 2020). The impacts of high density include diminished feeder and drinker access caused by overcrowding (Franco-Rosselló *et al*., 2022). As also reported by Goo *et al.* (2019), elevated densities impact gut integrity, increase permeability, and increase nutrient absorption sensitivity (Li *et al*., 2019). Older birds appear to demonstrate more substantial negative outcomes related to cumulative density stress (Nawarathne, Kumari and Nayananjalie, 2020). Mortality subsequently increases under greater HD as well, supporting the original assumption that HD is a welfare and production issue.

6.3.3.1.2 Meat Quality and Metabolic Outcomes

Housing in free-range systems leads to changes in muscle biochemistry characterized by increased physical activity and a dietary focus on carotenoid-rich forage. The behavior of high-ranger birds frequently leads to a systemic increase in ultimate pH levels and darker breast meat, generally in alignment with altered glycolytic flux and delayed postmortem acidification (Fanatico *et al*., 2005; Stadig *et al*., 2016). In the JA757 strain, increased outdoor activity increased the pHu as well as the amount of yellow color in the breast meat, which may have been affected by access to grass and clover that contain carotenoids (Dal Bosco *et al*., 2014; Mattioli *et al*., 2022). While their compositions differ, drip loss, cooking loss, and tenderness are typically not affected by hen rearing or selection for increased outdoor activity. Finally, high rangers do exhibit increased concentrations of ALA (C18:3 n-3) in the thigh muscle, which is evidence of improved nutrition through the consumption of omega-3 FAs. Finally, the different relationships between range use and color intensity indicate that genotypes may respond differently and highlight strain differences in metabolic processes (O'reilly and Eckersall, 2014; Stadig *et al*., 2016).

6.3.3.1.3 Physiological and Biochemical Adaptations

Housing conditions influence systemic physiology through changes in inflammation, oxidation, and lipid homeostasis. Fast- and intermediate-growing strains of high-range birds (JA757, S757N) generally present lower lysozyme and haptoglobin-like activity, suggesting diminished chronic inflammation (Castellini *et al*., 2016; Franciosini *et al*., 2011; O'reilly and Eckersall, 2014). On the other hand, increased locomotion can increase oxidative buildup; for example, when the concentrations of total antioxidant status and tocopherol decrease, the increase in hydrogen peroxide levels results in a shift away from a redox balance due to activity (Mattioli *et al*., 2017, 2021). Blood lipids shift with diet, as we observed a decrease in the n-6/n-3 ratio and higher omega-3 levels in the S757N strain. An observed reduction in the n-6/n-3 ratio is due to these birds foraging on pasture (Dal Bosco *et al*., 2012). Moreover, White Bresse chickens presented increased total antioxidant status and triglyceride levels in high-elevation individuals, suggesting that these chickens can utilize metabolism in strain-specific ways.

6.3.3.1.4 Advances in Controlled-Environment Housing

Although free-range systems can improve welfare and product differentiation, they also create environmental and performance variability. In contrast, automated systems with controlled microenvironments—such as the multitier model designed by the Innovative Control System Company (Bethlehem, PA)—provide better precision and sanitation. Multiple conveyor belts prevent manure from remaining in the barn, whereas positive pressure multiduct ventilation maintains a more consistent air velocity through the barn to minimize the spread of pathogens and maintain a more stable thermal environment for the chicks. Automated systems maintain a high level of precision and sanitation, which can be particularly beneficial during the brooding period of the chick, as chicks at this stage lack adequate thermoregulatory and immune system components (Munonye and Munonye, 2022; Son *et al*., 2022). Keep in mind that the initial trials of the semiautomated system demonstrated a diminished growth rate and feed intake during that phase because high airspeeds were involved in controlled ventilation, which further indicates that methods used to control the microenvironment must be balanced (May, Lott and Simmons, 2000). Adjusting the air velocity improved performance and further balanced the microclimate and comfort.

6.3.3.1.5 Integrated Perspective: Balancing Welfare, Quality, and Sustainability

Both free-range and intensive housing systems result in different benefits and burdens. Free-range systems have the potential to improve natural behavior, bone strength, and quality and help develop a "nutritional profile" of the meat, but growth performance and antioxidant activity are often reduced. Intensive housing systems can optimize efficiency and biosecurity but restrict behavioral expression and potentially increase chronic stress. Housing density will interact with systems, as it affects physiological, metabolic, and welfare outcomes.

To achieve a sustainable poultry production system, future approaches should focus on optimizing the "genotype–environment–housing" interaction in the production system, integrating precision farming

technologies, and establishing a system that combines behavior–phenotyping individualized management. The need is not to define "free-range" and "intensive", but to combine environmental enrichment, microclimate monitoring, and dietary modulation into a hybrid system that achieves both economic viability and ethical standards.

6.3.3.2 Stress Physiology and Its Impact on Meat pH and Tenderness

Preslaughter handling, loading, transport, and feed withdrawal are known stressors that can significantly impact animal welfare and muscle biochemistry postmortem (Bórnez, Linares and Vergara, 2009; Broom, 2000; Kannan *et al*., 2002). As part of the preslaughter management system, the lairage phase plays an essential role in relieving an animal's physiological stress load from transport while also providing an added operational handling layer for the slaughter plant. If a lairage facility is adequately managed, it will improve the welfare of animals before slaughter. However, operational practices may exacerbate stress responses, affecting welfare and meat quality. Several lairage conditions can create stress responses, such as social mixing of unfamiliar conspecifics, improperly timed fasting, handling, and excessive short or long lairage times (LTs) (Goumon and Faucitano, 2017; Warriss, 2003).

Studies have shown that lairage duration has an important effect on the physiological state of pigs, carcass characteristics, and the development of meat defects. For example, short lairage periods of less than 3 hours are positively correlated with pale, soft, and exudative (PSE) meat compared with lairage periods greater than 14 hours (Dokmanovic *et al*., 2014, 2017). Conversely, longer overnight lairage periods can decrease carcass weight and BT and increase the risk of DFD meat, skin lesions, gastric ulceration, and elevated cortisol concentrations (Gottardo *et al*., 2017). Therefore, determining an optimal resting time during lairage is important for balancing animal recovery and the establishment of the physiological state, which is related to increased meat quality outcomes (Dokmanović *et al*., 2014).

In pigs, stress responses are modulated by a network of neuroendocrine systems, including the HPA axis and the sympathetic–adrenal medullary (SAM) system. Serotonin and dopamine generally act as neurotransmitters involved in behavioral and emotional responses to stress, fear, and reward (Arroyo *et al*., 2016). At the same time, catecholamines (epinephrine and norepinephrine) and cortisol are released in response to activation of the SAM and HPA axes, respectively, to induce physiological adaptations for self-defense (Einarsson *et al*., 2008; Padgett and Glaser, 2003). The importance of animal welfare has thus underlined the reliable associations between HPA axis activation and the psychological and physiological stress experienced by pigs while in lairage (Einarsson *et al*., 2008).

The objective of the stress response is to achieve homeostasis, which is achieved by mobilizing energy reserves and altering metabolic processes (De Kloet, Joëls and Holsboer, 2005; McEwen, 2007; Mora *et al*., 2012). With the increase in cortisol and catecholamines, glycogenolysis in skeletal muscle is stimulated, resulting in rapid postmortem accumulation of lactic acid and a subsequent reduction in muscle pH (Fernandez and Tornberg, 1991; Foury *et al*., 2005). Rapid acidification of muscle pH contributes to the formation of PSE meat through the loss of muscle fiber integrity and a reduction in water-holding capacity. HSPs, specifically HSP70, act as molecular chaperones to maintain the homeostasis of intracellular proteins during stress (Basu *et al*., 2001; Sun *et al*., 2000). Cortisol and norepinephrine (Meng *et al*., 1996) have been shown to increase the expression of HSP70, which provides a potential defense mechanism in the cellular response to stress. Owing to the high-stress susceptibility of pigs, it is essential to evaluate many stress factors, both hormonally and intramuscularly, to assess welfare accurately (Dokmanovic *et al*., 2017).

The intricate interplay between the endocrine and metabolic systems underscores the need to evaluate preslaughter stress using a combination of physiological, behavioral, and biochemical markers. Many studies have investigated individual indicators; however, few have conducted quantitative analyses of the causal relationships between lairage time and physiological response via statistical frameworks. To address this known gap in temporal studies, the Animal and Plant Quarantine Agency of Korea stipulate a maximum lairage time (i.e., handling and waiting) of 12 hours, with a typical average for commercial businesses of 5–6 hours. Recent studies have investigated the mechanistic pathway and how lairage time impacts stress-related hormones and intramuscular metabolism during the preslaughter period. Path analysis and other multivariate methodologies have suggested that longer lairage times directly

increase cortisol concentrations, which also increase epinephrine due to phenylethanolamine-*N*-methyltransferase (PNMT), even with transfer impact, highlighting the physiological cross talk between the HPA and SAM axes (Mittal *et al*., 2017; Xie *et al*., 2023). Furthermore, muscle glycogen depletion and the accumulation of lactic acid compounds associated with increased lairage times affect meat pH and quality (Zhen *et al*., 2013). In addition, psychosocial stressors, such as mixing pigs or creating a crowded situation, are complex neuroendocrine adaptations (Cornale *et al*., 2015; Proudfoot and Habing, 2015).

Broilers are warm-blooded animals whose body temperature is relatively constant through both behavioral and physiological means. If the surrounding temperature exceeds the birds' ability to disperse heat, they will suffer HS (He *et al*., 2018; Lu *et al*., 2019; Yan *et al*., 2020). Body surface temperature (BST) is a physiological indicator of HS and was used in this study to validate a model for HS. Chronic HS in broilers results in decreased growth performance due to detrimental effects on gut integrity, feed intake, and feed conversion (Lu, Wen and Zhang, 2007; Lu *et al*., 2018). Consistent with previous research, the results of the present study revealed that heat-stressed birds presented a decreased ADG, increased feed-to-gain (F:G) ratio, and impaired meat quality, resulting in greater drip loss, cooking loss, and shear force, as well as reduced pH 24 *h* and *a** values of the pectoralis major (PM) muscle (Abudabos *et al*., 2021).

In the analysis of the PM muscle transcriptome, 1,239 DEGs were successfully identified from the HS versus NC and HS versus PF comparisons. The DEGs were associated mainly with metabolic processes, response to stimulus, catalytic activity, cell growth and death, HIF-1 signaling, lysosomes, regulation of the actin cytoskeleton, and sphingolipid metabolism (Lingwood and Simons, 2010; Lu *et al*., 2017). DEGs associated with muscle structural components (e.g., actin, myosin, and troponin) were identified, which provided evidence of an alteration to the sarcomere that would lead to differences in texture, tenderness, and WHC (Ertbjerg and Puolanne, 2017; Squire, 2019; Tobacman, 2021). Chronic heat altered oxidative stress, in part, by increasing the expression of cytochrome P450 genes (CYP1C1, CYP2J21, CYP2J23, CYP39A1, and CYP4A22) (Liu *et al*., 2022b) and by increasing ROS production. Lipid metabolism was altered through the expression of DEGs such as ACACA, GPAT3, PPARG, and CPT1, which, on the basis of the gene expression profile, led to increased deposition of IMF and a subsequent decrease in β-oxidation (Ma *et al*., 2019; Zhao *et al*., 2018). Additionally, the homeostasis of energy metabolism is disrupted, resulting in the downregulation of gene expression for the TCA cycle (IDH3B) and glycogen synthesis (GYS1) and the upregulation of glucose transporters (Gholamreza *et al*., 2018; Ma *et al*., 2019), which reduces ATP production and increases compensatory glucose uptake. HS induces apoptosis, with examples of increased gene expression of TNFRSF, TGFB1, MYC, JAK1, and PDCD1; however, histological analysis of muscle injury revealed vacuolation and degradation of muscle fibers (Liu *et al*., 2022b).

6.3.3.3 Practice: Transport, Lairage, Stunning, and Slaughter Techniques

The handling of animals before slaughter, loading, transportation, lairage, stunning, and slaughter is one of the most critical steps affecting animal welfare and meat quality. Good management of this part of the process affects carcass integrity, sensory properties, and ultimately the sustainability of livestock production systems (da Cunha Leme *et al*., 2012).

6.3.3.3.1 Transport and Welfare Implications

The importance of road transport as a preslaughter stressor influencing beef quality and sustainability cannot be overlooked, as it is driven by a number of physical and environmental factors, such as the loading density of animals, vehicle layout, duration of travel, ambient temperature, and handling practices during loading and unloading (Xing *et al*., 2019). When transport is poorly managed or continues for a prolonged period, a DFD product with compromised tenderness, juiciness, and color quality is produced (Alma *et al*., 2020; Mendonça *et al*., 2017). As a result, product acceptability is diminished, as are carcass-grading scores and economic value.

Acknowledging these relationships, legislation such as the European Commission Regulation (EC, 2005) and, more recently, EFSA (2022) have introduced species-specific guidelines regarding maximum travel periods and required rests and recovery (Romero *et al*., 2013). The introduction of animal welfare

standards into practice has resulted in reduced mortality and improved consistency of meat products. Furthermore, the Meat Standards Australia (MSA) system provides a framework that accounts for pre-slaughter stress indicators in an integrated model predicting postmortem eating quality; such indicators include MARB, muscle cut, and carcass temperature (Mpakama, Chulayo and Muchenje, 2014).

Breed-specific variations can also influence transport-related stress responses. For example, Limousin cattle have been shown to exhibit greater sensitivity to handling and transport stimuli than do Nellore or Angus cattle, highlighting breed-specific genotype–environment interactions for stress physiology and muscle metabolism (Grandin, 2015; Lyles and Calvo-Lorenzo, 2014). Therefore, transport strategies should also consider genetic robustness practices to meet welfare requirements and ensure meat quality.

6.3.3.4 Lairage Management and Recovery Dynamics

After transport, lairage is intended to provide animals with the opportunity to rest, rehydrate, and reestablish homeostasis prior to slaughter. The welfare outcomes during lairage, however, depend on the duration of lairage, stocking density, access to food and water, and mixing (Silva *et al.*, 2022a). A brief duration of lairage may not provide sufficient time for recovery to take place, whereas an extended duration of lairage with an unfavorable environment may worsen fatigue, dehydration, or aggression (Broom and Kirkden, 2004).

Behaviors are useful indicators of agitation and the welfare state of animals; they include head-butting, mounting, and chasing. In cattle specifically, these behaviors are observed shortly after arrival, particularly after the short distance of transport, and are attributed to acute stress and social reorganization (Jorquera-Chavez *et al.*, 2019; Silva *et al.*, 2023). Cattle demonstrate a decrease in aggressive activity and an increase in calm behaviors (e.g., rumination) over time, indicating recovery and adaptation. Therefore, providing an appropriate duration of rest and minimizing the stress of regrouping are key aspects of animal welfare and meat quality.

From a physical standpoint, an increased respiratory rate (RR) during lairage (>30 breaths/min) suggests that sufficient recovery has not occurred and correlates with higher postslaughter pHu and DFD risk indices (Hänninen and Pastell, 2009). Zebu male animals presented a relatively high response rate due to relatively high release rates of cortisol and catecholamine, indicating that glycolytic activity decreases and that the pH decreases, resulting in tougher, darker meat (Coimbra, Machado Filho and Hötzel, 2012; Pastell, 2016). Competitive behaviors and aggression among animals in crowded lairage pens also contribute to bruised carcasses, and bruised tissue causes economic loss resulting from carcass downgrading due to elevated creatine kinase activity (Bran Agudelo, Ferreira de Quadros and Pinheiro Machado Filho, 2013).

6.3.3.4.1 Neuroendocrine Stress Pathways and Pig Lairage Studies

In pigs, lairage provides respite from transport-related stress while preparing for slaughter (Bórnez, Linares and Vergara, 2009; Broom, 2000). The length of the lairage period and the social context of lairage have implications for stress response physiology, which activates SAM and HPA axes (Goumon and Faucitano, 2017; Kannan *et al.*, 2002; Warriss, 2003). These systems secrete catecholamines (epinephrine and norepinephrine) and cortisol to free energy stores and modify muscle biochemistry prior to slaughter (Dokmanović *et al.*, 2014). Excessive stress can lead to PSE meat when the lairage time is too short (<3 hours) or to DFD meat when the lairage time is too long (>14–20 hours) (Dokmanovic *et al.*, 2017).

The expression of HSP70 increases in response to long-term stress, and HSP70 functions as a molecular chaperone to ensure protein stability (Gottardo *et al.*, 2017). HSP70 levels increase in combination with the release of cortisol, indicating a physiological mechanism to adapt to a stressor; however, chronic elevations in HSP70 or cortisol with little or no glycogen can lead to the degradation of meat quality, such as meat tenderness and WHC (Arroyo *et al.*, 2016). Behavioral factors, such as mixing strange pigs or overcrowding, can also exacerbate hormonal responses to stress, making the management of lairage time and space a critical consideration (De Kloet, Joëls and Holsboer, 2005; Einarsson *et al.*, 2008; Padgett and Glaser, 2003).

Research conducted in commercial abattoirs in Korea revealed that pigs lairaged for 6–8 hours had the best recovery from stress, lower cortisol levels, and better carcass yield than pigs prepped immediately or lairaged for 12 or more hours. In particular, greater lairage times in combination with overcrowding increase fatigue, aggression, and physiological stress (McEwen, 2007; Mora *et al.*, 2012). Overall, the best management method for achieving both welfare and quality is a moderate resting time while minimizing mixing when possible.

6.3.3.4.2 Stunning, Slaughter, and Sustainability Integration

The conscious stunning and slaughter process should cause loss of consciousness as soon as possible and minimize distress to safeguard both animal welfare and meat quality. If stunning is ineffective, the animal will be inadequately insensitive to pain, altering the physiology of the muscles and the underlying muscle biochemistry and meat quality due to the metabolic effects of stress (Feitosa and Leydson, 2008; Foury *et al.*, 2005; Silva *et al.*, 2022b). Proper training of slaughter plant staff, effective stunning equipment, and adherence to welfare standards are paramount to avoid suffering preslaughter and to ensure a humane slaughter process.

In terms of sustainability, welfare-based handling and the use of quality prediction models such as the MSA system and the new Guaranteed Global Grading (3G) framework encourage efficiency and ethical compliance (Costa *et al.*, 2006). These systems facilitate a data-driven approach to predict eating quality across genetics, breeds, and environments, which could promote a transparent and welfare-conscious beef and pork industry.

6.3.3.4.3 Synthesis and Implications

Evidence from both studies in cattle and pigs clearly shows that transportation, lairage (preslaughter periods during which the animal awaits slaughter), and handling at slaughter are interacting variables of both meat quality and meat sustainability. Physiological imbalances that can be induced by stress, measured physiologically by cortisol, catecholamine, and glycogen, lead to measurable quality defects in beef, including DFD, or in pork, including PSE. The development of protocols for animals, optimizing the lairage period, preventing overcrowding, and improving stockperson behavior are necessary to reduce the effects of stress. Future research with molecular biomarkers (i.e., HSP70, cortisol) used for research-based grading of meat (i.e., MSA, 3G) will further develop an integrated scientific approach for welfare and meat quality–based assurance, leading to a more sustainable framework in the animal sector globally (Lee, Kang and Shim, 2023).

6.3.4 Health, Immunity, and Disease Control

6.3.4.1 Preventive Health Management and Biosecurity

The role that biosecurity and preventive health management play in sustainable livestock production, high meat quality, and animal welfare is critical. In Ethiopia, where the poultry production sector is expanding as a result of population growth and increased protein demands (Ebsa, Harpal and Negia, 2019; Milkias, 2016), preventive health management and biosecurity are necessary to minimize disease burdens and increase productivity. The poultry sector is important for food and nutrition security because it grows rapidly, has good feed conversion rates, and uses little land (Belay and Oljira, 2019). However, 57 million chickens, which comprise 78.9% indigenous, 12% exotic, and 9.1% hybrid chickens, are underperforming in terms of productivity because of high disease prevalence and inadequate management (Asfaw *et al.*, 2021; Habte *et al.*, 2017)

Proficient biosecurity involves evidence-based strategies that block the introduction and transmission of pathogens within and among flocks (Carr and Howells, 2018; Waktole *et al.*, 2023). The central elements of biosecurity include segregation, sanitation, disinfection, limited farm access, vaccination, and quarantining newly introduced or sick animals (Waktole *et al.*, 2023). These biosecurity methods help lower mortality rates, decrease antibiotic usage, and promote high-quality, drug-free meat, in turn assisting in the development of sustainable production systems (Gelaude *et al.*, 2014; Siekkinen *et al.*, 2012). Although biosecurity is paramount, biosecurity practices in Ethiopia still show variability, especially at

commercial poultry farms in the central area (Alemu *et al*., 2008; Mtui, 2012). The majority of poultry farms used deep litter housing, with 47%, 55%, and 99% of poultry farms in Addis Ababa, Bishoftu, and West Shaggar, respectively ($\chi^2 = 19.91$; $p < 0.001$). Deep litter housing (poultry) promotes the accumulation of ammonia and pathogens that negatively affect bird health and meat quality (Eze *et al*., 2017; Iyiola-Tunji *et al*., 2013). Furthermore, inadequate access to the quarantine act of bird entry is notable; 73.2%, 82.9%, and 98% of farms did not have individual delivery sections for new birds (Laanen *et al*., 2014; Ornelas-Eusebio *et al*., 2020; Tanquilut *et al*., 2020). The risk factors for feed contamination include poorly sealed feed storage units, which increase the risk of pathogen sharing and decrease feed efficiency (Robertson, 2020).

The aspects of waste disposal and movement control are also inadequate. According to this study, 82.1% of farms in Addis Ababa and 77.1% of farms in Bishoftu do not have waste disposal systems. Furthermore, waste handling is performed with minimal protective gear, which can increase biosecurity and zoonotic transmission risks. While vaccination programs exist on 71.4%, 95.7%, and 55% of farms in Addis Ababa, Bishoftu, and West Shaggar, respectively, the lack of continuous health monitoring and veterinarian access impacts disease prevention strategies (Asfaw *et al*., 2021). Furthermore, death (mortality) management systems are inadequate, as more than 50% of farms lack a separate disposal system for dead birds, facilitating disease spread. While the use of footbaths is essential to minimize pathogens from visitors and vehicles entering the production area, there are no footbaths in 58.9% of farms in Addis Ababa or 71% of farms in western Shaggar, whereas every farm in Bishoftu has full access to footbaths.

The mean biosecurity ranking in Central Ethiopia is 43.1, which is significantly lower than the global average of 64.3 (Tanquilut *et al*., 2020). The external and internal biosecurity scores of 40.7 and 52.6 are also inadequate compared with the European standards of 68 and 76.6 (Van Limbergen *et al*., 2018). In Bishoftu, larger farms had higher biosecurity compliance than did smaller farms (Moredaa and Mesekel, 2016), reinforcing the importance of management capacity and access to resources. Low biosecurity leads to the overuse of antimicrobials, which contributes to antimicrobial resistance (AMR). In many low- and middle-income countries, antibiotics have been used for growth promotion and disease prevention due to weak regulations and a lack of awareness among farmers (Landers *et al*., 2012; Schar *et al*., 2018; Van Boeckel *et al*., 2015). The improper use of antimicrobials, combined with poor hygiene, a lack of quarantine, and minimal veterinary supervision, increases AMR and compromises meat safety (Essack *et al*., 2017; Ozturk *et al*., 2019). Overall, biosecurity and preventive health management are critical to improving meat quality, sustainability, and public health protection. The biosecurity measures within Ethiopia's poultry industry must include corresponding cleaning and disinfection protocols, vaccinations, quarantine measures, appropriate feed safety practices, responsible waste management, and movement control, all augmented by a national biosecurity framework, effective farmer education, and mechanisms for compliance. Such measures implemented on Ethiopian poultry farms are likely to reduce economic losses, antibiotic resistance, and improve animal welfare, while providing reliable, high-quality meat production.

6.3.4.2 Subclinical Diseases and Their Hidden Impacts

Subclinical diseases represent a major obstacle to flock health, productivity, and ultimately the sustainability of animal production systems. In contrast to simple clinical disease, subclinical infection and metabolic disease are more insidious but can also have significant detrimental impacts on growth, reproduction, lactation, meat quality, and farm profitability. In dairy cattle, subclinical mastitis (SCM) remains one of the greatest global challenges because it occurs silently and has lingering economic impacts (Cheng and Han, 2020; Hogeveen, Huijps and Lam, 2011). SCM is defined as an increased somatic cell count without any visible udder inflammation or abnormal milk, which makes diagnosis difficult (Cheng and Han, 2020). SCM is responsible for 70–80% of the economic losses associated with mastitis through decreased milk production, loss of specific milk quality, increased treatment costs, culling of affected animals, and reduced reproductive efficiency. The economic losses associated with SCM differ by country, with loss estimates of $38, $188, and $17.5 per cow per year in Ethiopia, Madagascar, and India, despite the most likely minimal reporting across countries owing to a lack of data and inconsistent diagnostic criteria (Motaung *et al*., 2017).

The California mastitis test is a popular rapid cow-side test for the detection of SCM but has limited value in detecting SCM in acute clinical conditions (Moroni *et al*., 2018). Pathogen prevalence is dependent on a variety of factors, including geography, breed, season, parity, stage of lactation, and management (Sumon *et al*., 2020; Tarekegn, 2022), with *Staphylococcus aureus*, *Streptococcus agalactiae*, *Streptococcus uberis*, *Streptococcus dysgalactiae*, *Escherichia coli*, and *Mycoplasma* spp. being the most reported etiological agents associated with SCM in the majority of reports (Cobirka, Tancin and Slama, 2020). In Africa, exotic breeds such as Holstein Friesian cattle and Jersey cattle are more predisposed to SCM due to their udder anatomy, teat morphology, and genetic predisposition, whereas indigenous zebu cattle demonstrate a lower prevalence of SCM when maintained in systems of extensive production (Girma and Tamir, 2022; Khasapane *et al*., 2023). Pathogen-specific measures, combined with good management practices, such as pre- and postmilking teat vaccination, dry cow therapy, selective culling, and follow-up, will assist with the effective management of SCM (Abebe *et al*., 2016; Schnitt and Tenhagen, 2020).

Subclinical hypocalcemia (SCHC) may be another significant underlying condition in high-yield periparturient dairy cows that has an impact on neuromuscular function, the immune system, and uterine function and increases the risk of postpartum complications such as retained placentas, endometritis, displaced abomasum, ketosis, and mastitis (Berean, Bogdan and Cimpean, 2025). Up to 50% of multiparous and one-third of primiparous cows may have SCHC, which demonstrates the high demand for calcium in the initial lactation period (Hernández-Castellano, Hernandez and Bruckmaier, 2020; McArt and Neves, 2020). Disordered calcium homeostasis results in more extended service periods, longer calving intervals, less successful conception, an increased number of insemination attempts, and increased clinical mastitis (Ghasemi *et al*., 2024; Tufarelli *et al*., 2024). The economic ramifications include higher veterinary costs, penalties for poor milk quality, losses in reproduction, and the culling of valuable animals; a recent estimate suggests an approximate 54 EUR per cow increase in cost for beef over the course of six months (Bahrami-Yekdangi *et al*., 2022; Esnaola, Neto and González, 2020). Preventative management strategies, such as dietary cation–anion difference (DCAD) management prepartum and controlled calcium supplementation postpartum, are essential for maintaining calcium homeostasis and productivity (Serrenho *et al*., 2021; Wilkens *et al*., 2020).

6.3.4.3 Veterinary Interventions and Residue-Free Production

Intensified livestock production systems, especially in the poultry and meat industries, have resulted in increased use of antimicrobial drugs (AMDs) for preventive treatments and to facilitate growth (Chattopadhyay, 2014; Kim *et al*., 2013; Page and Gautier, 2012). Veterinary use is essential to support animal health, but the inappropriate and medically unnecessary use of AMDs presents substantial safety, sustainability, and human health concerns through AMR and drug residues in edible tissues (Donoghue, 2003).

Highly important antibiotics, including gentamycin, erythromycin, and colistin, have been identified by the WHO as crucial in human medicine, and, consequently, stricter regulations on their use in farmed animals are recommended (Collignon *et al*., 2016). The antibiotics administered to poultry and ruminant systems include penicillins, fluoroquinolones, tetracyclines, aminoglycosides, macrolides, and polymyxins, which are often added to feed and/or water (Nhung *et al*., 2016). Consequently, regulations such as Vietnam's ban on antibiotic growth promoters (AGPs) (2018), the EU legislation (Regulation (EU) No. 37/2010), and the EU AMR Action Plan call for the production of residue-free meat and for consumer protection (Ministry of Agriculture and Rural Development in Vietnam 2016) (Lees *et al*., 2021). The application of maximum residue limits (MRLs) and drug withdrawal periods is a measure to ensure that meat is safe for consumption; however, adherence varies by region (Landoni and Albarellos, 2015). The frequent disparity between reported drug use and drug residues found in animal tissues indicates the need for more effective monitoring and analytical detection platforms, such as high-performance liquid chromatography and mass spectrometry (Jansen *et al*., 2017). This problem is significantly greater in developing countries, where farmers frequently lack knowledge about withdrawal periods and are complicating possible drug residue effects (Kurćubić *et al*., 2025). Investigations conducted in both Ethiopia and Nigeria revealed low compliance with withdrawal periods and limited knowledge of food

safety standards, highlighting the need for farmer education and the enforcement of regulations. In the Eurasian Economic Union, TR EAEU 051/2021 restricts antibiotic residues in meat or poultry (chloramphenicol <0.0003 mg/kg, tetracyclines <0.01 mg/kg, bacitracin <0.02 mg/kg) to bolster residue control and ensure consumer safety (OECD, 2021).

Excessive antibiotic use at the global level is a contributor to AMR, with the WHO stating that by 2050, deaths from resistant infections could surpass those from cancer (Zalewska *et al.*, 2021). Antibiotic residues can be found in meat even after cooking (Åkerfeldt *et al.*, 2021) or can be released and introduced into an ecosystem through manure, most notably by contaminating water and soil and contributing to the resistant growth of certain populations of microorganisms in the environment (Campagnolo *et al.*, 2002; Zalewska *et al.*, 2021). In the case of environmental emissions due to antibiotic use in China, barn emission estimates show that 84% of antibiotics are related to livestock production (Zhannara *et al.*, 2025). Tetracyclines, which are among the most commonly prescribed classes of veterinary drugs, are consistently found in animal husbandry sources (during live animal processing) and environmental matrices (e.g., water and soil) and are more closely associated with resistance development in microorganisms than any other class of antibiotics.

In light of these risks, veterinarians are moving toward antimicrobial stewardship to focus on disease prevention, an ethical way of treating animals, and meat production that is free of any antibiotic vegetative (Dela Cruz *et al.*, 2019; Singer *et al.*, 2019). To avoid the use of antibiotics, alternative methods, such as probiotics, herbal extracts, essential oils, organic acids, vaccines, enzymes, bacteriophages, nanoparticles, and a modified feeding regimen, are becoming more frequently used to determine whether these alternatives support health while also producing antibiotic residue-free meat (Ghasemi, Kasani and Taherpour, 2014; Giannenas *et al.*, 2012). Probiotics, such as *Enterococcus faecium*, *Streptomyces* spp., and/or *Bacillus* spp., have shown strong effects on improving the gut microbiota balance, nutrient absorption, and immune response and reducing pathogenic bacteria through competitive exclusion and bacteriocin production (Hassanein and Soliman, 2010; Levkut *et al.*, 2012; Pan and Yu, 2014). Probiotics not only increase growth performance (~4.4% change in BW) but also reduce ammonia and hydrogen sulfide emissions and affect meat quality by improving the water-holding capacity, color parameters, pH stability, FA profile, and sensory evaluation (Latha *et al.*, 2016; Mehdi *et al.*, 2018; Popova, 2017; Zhang, Cho and Kim, 2013).

6.3.5 Pre- and Postslaughter Interventions

Throughout the transition phase, which encompasses preslaughter management and postmortem biochemical changes, meat quality may vary significantly. Strategic interventions are needed to regulate rigor mortis and aging during this critical period, which ultimately optimizes softness, color fidelity, and longevity (Berry *et al.*, 2017). These strategic interventions are discussed in the following sections and summarized in Table 6.5.

6.3.5.1 Antemortem Management

The physiological condition of the animal before slaughter, which is significantly influenced by muscle glycogen levels, dictates the ultimate quality of the muscle tissue. Inadequate handling, extended transit times, or suboptimal lairage conditions can induce significant stress, leading to elevated cortisol secretion. This accelerates the breakdown of muscle glycogen (Carrasco-García *et al.*, 2020).

During the postmortem period, muscle pH decreases as glycogen is converted to lactic acid. The velocity and magnitude of this pH decline are crucial for inhibiting bacterial proliferation and achieving the appropriate color and texture of the meat (Carrasco-García *et al.*, 2020). To achieve proper acidification, the pH must decrease from its equilibrium level (approximately 7.0) to its target value (approximately 5.5) (Carrasco-García *et al.*, 2020). When an animal's glycogen reserves deplete due to prolonged or chronic stress, insufficient lactic acid is produced, inhibiting the requisite decrease in pH (Jacob and Hopkins, 2014). Properly caring for animals in their final days, including providing adequate feed and water, bathing, and shade during confinement, is crucial for optimizing glycogen storage and ensuring appropriate acidity postmortem (Carrasco-García *et al.*, 2020).

TABLE 6.5

Impact of Key Preslaughter and Postslaughter Practices on Meat pH, Color, Tenderness, and Microbial Stability

Practice	Actions	Meat Quality Impact	Indicators	Reference
Fasting	12–24 hour feed withdrawal	↓ Gut fill (hygiene) Excessive fasting → weight loss May ↑ ultimate pH (DFD)	Monitor live, HCW, glycogen level	Carrasco-García *et al.*, 2020
Transport/ handling	Journey length, mixing, roughness	Chronic stress (days) depletes glycogen → high pH DFD10 Acute stress (minutes) can cause rapid pH fall, PSE	Cortisol or lactate blood tests Behavior scores	Carrasco-García *et al.*, 2020
Stunning and slaughter	Captive bolt/ electric versus halal/Kosher (no-stun)	Stunning guarantees unconsciousness Exact ritual cuts correspond with bleed-out	Postslaughter blood splash marks Hemoglobin traces	Żurek *et al.*, 2021
Chilling	Cooling rate (e.g., to 4 °C)	Rapid chilling slows spoilage Too fast chilling can toughen meat Slow chilling can increase tenderness (accelerated proteolysis)	Carcass temperature profiles Microbial counts	Żurek *et al.*, 2021
Aging	Duration (days) and type (wet/ dry)	Prolonged aging ↑ tenderness and flavor Dry-aging adds characteristic flavor but incurs weight loss	Warner–Bratzler shear force Sensory panels	Żurek *et al.*, 2021
Packaging	Vacuum versus MAP versus active/smart	Vacuum packaging reduces oxygen → lowers oxidation, good for shelf life High-O_2 MAP maintains red color but may ↑ lipid oxidation Active packaging (e.g., O_2 scavengers, smart labels) can further preserve quality	Color stability, drip loss, oxidation markers, sensor readings	Cenci-Goga *et al.*, 2020

6.3.5.2 Etiology of Quality Deficits: DFD and PSE

Deficiencies in preslaughter stress management result in anticipated meat quality issues related to ultimate pH and its correlation with muscle temperature.

6.3.5.2.1 DFD Meat

DFD, often referred to as dark cutting beef, results from prolonged preslaughter stress that depletes muscle glycogen stores (Karabasil *et al.*, 2019). The absence of lactic acid accumulation results in a high ultimate pH (often ≥5.5) in beef, contingent upon local regulations (Carrasco-García *et al.*, 2020). The elevated pH produces a black hue, a dense texture, and increased water retention capacity, resulting in the meat appearing desiccated (Karabasil *et al.*, 2019). An elevated final pH significantly promotes bacterial growth, substantially diminishing the preservation characteristics and shelf life of the meat (Jacob and Hopkins, 2014). Moreover, meat with an elevated pH matures less efficiently than does meat within the usual pH range (Dashdorj *et al.*, 2016). The impaired marketability of the product indicates that inadequate animal welfare immediately leads to substantial processing deficiencies and financial losses.

6.3.5.2.2 PSE Meat

PSE meat is predominantly observed in pigs, although it can also manifest in beef (Karabasil *et al.*, 2019). This syndrome arises from acute, intense stress soon preceding slaughter, which prompts fast glycolysis. The abrupt and significant decrease in pH transpires while the muscle temperature remains elevated, resulting in the denaturation of muscle proteins (Jacob and Hopkins, 2014) Denatured proteins forfeit their ability to retain water, resulting in meat that appears pale, mushy, and "exudative" (expelling fluid) (Karabasil *et al.*, 2019).

6.3.5.3 Slaughter Techniques: Conventional Stunning and Religious Methods

Slaughter techniques must emphasize animal care by ensuring effective, rapid stunning while also addressing various conventional and religious market requirements. Traditional slaughter depends on efficient stunning methods (such as electrical or mechanical techniques) to put the animal immediately insensible prior to exsanguination, hence reducing stress (Żurek *et al.*, 2021).

Religious practices, including halal (Islamic) and Kosher (Jewish), necessitate a particular manner of ceremonial slaughter characterized by a swift, singular incision that severs the primary blood vessels and respiratory tracts (*shechita* or *dhabihah*) (Bir *et al.*, 2024). Significant differences are present: Kosher requires meticulous precision, as any mistake in a single stroke renders the meat unsuitable; this rigor is not universally applicable in halal (Żurek *et al.*, 2021). Postslaughter, Kosher processing entails salting and washing to eliminate leftover blood, a procedure deemed unnecessary for halal (Żurek *et al.*, 2021). Many Islamic authorities authorize reversible stunning procedures, such as nonpenetrating mechanical or electrical stunning, as long as the equipment is monitored and the procedure does not result in the death or permanent injury of the animal (Żurek *et al.*, 2021). Conventional Kosher slaughter typically prohibits stunning before the incision.

6.3.5.4 Postmortem Technologies for Quality Assurance: Chilling, Aging, and Electrical Stimulation

Regulating the dynamics of rigor mortis onset and a decrease in muscle temperature is essential for optimizing tenderness.

6.3.5.4.1 Electrical Stimulation (ES)

ES is an efficacious method for expediting postmortem glycolysis, leading to rapid ATP depletion and accelerating the onset and resolution of rigor mortis (Adeyemi and Sazili, 2014). The principal advantage is the inhibition of cold shortening, a notable toughening phenomenon that transpires when muscle fibers contract due to rapid cooling before the complete onset of rigor mortis (Adeyemi and Sazili, 2014). The expedited pH reduction at elevated muscle temperatures further amplifies the action of intrinsic proteolytic enzymes, hence enhancing eventual tenderness (Adeyemi and Sazili, 2014).

6.3.5.4.2 Controlled Chilling and Prevention of HTLP

Immediate and regulated chilling, such as blast or spray chilling, is essential for the fast extraction of heat from carcasses to prevent HTLP (Jacob and Hopkins, 2014). Nonetheless, carcass cooling must be regulated to avert high-temperature, low-pH (HTLP) conditions, characterized by a pH below 6.0 and a temperature above 35 °C in the deep muscles of substantial corpses (Jacob and Hopkins, 2014). HTLP induces protein denaturation, adversely impacting color and water retention capacity (Jacob and Hopkins, 2014). Effectively managing postmortem quality is a dynamic process in which interventions are interrelated. If accelerated chilling is employed to prevent HTLP, ES must be concurrently applied to mitigate the risk of cold shortening, thereby ensuring that both protein stability and optimal tenderness are attained (Jacob and Hopkins, 2014).

6.3.5.4.3 Aging

Postmortem aging involves maintaining meat under controlled conditions to facilitate the natural action of proteolytic enzymes, which degrade structural components (myofibrillar proteins) to increase softness (Dashdorj *et al.*, 2016). Aging is most effective in meat sourced from corpses, with an ultimate pH ranging from 5.4 to 5.7. Muscles that are cold-shortened or heat-shortened, typically due to insufficient chilling or improper ES, exhibit diminished aging efficacy, resulting in inferior quality outcomes (Dashdorj *et al.*, 2016).

6.3.6 Role of Technology in Meat Quality Enhancement

The livestock and meat processing industries are undergoing a swift digital transformation driven by sensor technologies and AI. These tools facilitate the transition from subjective, reactive quality control to objective, real-time, and predictive management across the supply chain (Prates, 2025).

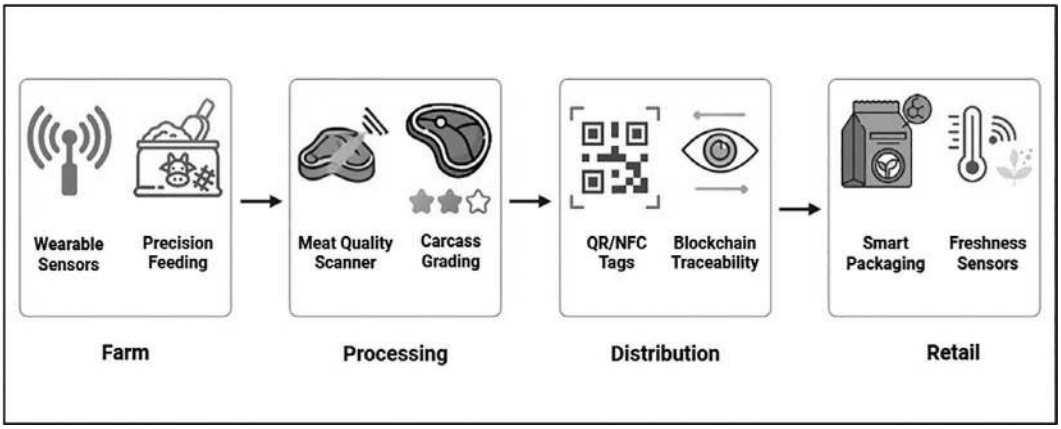

FIGURE 6.5 Schematic of technological innovations across the meat supply chain.

6.3.6.1 Integrating Sensors and PLF for Real-Time Monitoring

In the realm of meat quality, PLF devices deliver continuous, objective data that might impact management decisions aimed at optimizing final carcass characteristics (Kleen and Guatteo, 2023). Figure 6.5 provides a short overview of technological innovations across the meat supply chain to optimize carcass characteristics.

Sensors on farms provide precision feeding by assessing forage quality, water consumption, and overall nutritional equilibrium (Wongpiyabovorn *et al.*, 2025). Moreover, noninvasive phenotyping instruments offer significant insights into biological conditions before slaughter. Ultrasound and magnetic resonance spectroscopy (MRS) can be used to assess muscle architecture, alterations in tissue metabolites, and IMF levels (Alvarenga *et al.*, 2025). Digital infrared thermal imaging (DITI) provides an economical, noninvasive approach for assessing body temperature and physiological markers of heat tolerance and stress, correlating real-time welfare conditions with potential meat quality implications (Alvarenga *et al.*, 2025).

6.3.6.2 Assessment of Carcass Composition via Noninvasive Spectroscopy and Imaging

High-speed technology involves the use of manual methods for objective carcass grading at the processing level. Spectroscopic techniques, including near-infrared and Raman spectroscopy, exploit the interaction of light with molecular constituents to rapidly and nondestructively quantify essential intrinsic properties (Jeong *et al.*, 2025). These approaches can be used to evaluate elements associated with flavor, juiciness, and tenderness, specifically the IMF content and water dynamics (Anagnostou *et al.*, 2025).

Nuclear magnetic resonance technology is being investigated for its potential to noninvasively evaluate meat tenderness by analyzing water distribution and mobility within muscle tissue (Anagnostou *et al.*, 2025). Microwave sensor technology provides real-time, noninvasive detection of biomarkers such as glycogen, lactate, and muscle proteins, offering immediate insight into the biochemical condition of the muscle (Alvarenga *et al.*, 2025).

6.3.6.3 AI-Driven Predictive Modeling and Automated Carcass Grading Systems

AI and deep learning are the most important parts of the future generation of meat quality assessment. They go beyond simple grading to predictive modeling that works ahead of time (Jeong *et al.*, 2025). AI uses ML and computer vision to look at spectral and image data from corpses. It then makes very accurate predictions about the yield and quality grade of the carcasses (Lim and Song, 2025).

TABLE 6.6

Noninvasive Sensor Technologies for Real-Time Meat Quality Prediction

Technology	Principle	Targeted Quality Traits	Application Context	Key Advantages	Reference
Ultrasound Imaging	Sound wave reflection	Muscle structure, intramuscular fat	Live animal assessment (breeding, feeding)	Portable, relatively low cost, used in the field	Alvarenga *et al.*, 2025
Microwave sensor technology	Electromagnetic wave interaction	Glycogen, lactate, muscle proteins (biomarkers)	Perimortem/ postmortem processing	Real-time, noninvasive detection of chemical biomarkers	Alvarenga *et al.*, 2025
Raman spectroscopy	Molecular scattering analysis	IMF, tenderness (water content), molecular composition	Carcass grading/ retail cuts	Rapid, nondestructive, detailed molecular data	Alvarenga *et al.*, 2025; Jeong *et al.*, 2025
AI/deep learning (EfficientViT)	Computer vision/deep feature extraction	MARB, carcass yield, quality grade	Automated processing lines	High classification accuracy and fast inference speed	Lim and Song, 2025

Recent advancements emphasize highly efficient vision transformer topologies, such as EfficientViT, which exhibit superior classification accuracy and rapid inference speed, making them essential for real-time industrial applications in beef grading (Lim and Song, 2025). These advanced models can capture comprehensive contextual data, enhancing performance compared with ordinary convolutional neural networks (Lim and Song, 2025). The industrial implementation of these technologies is fundamentally linked to both precision and rapidity, as profitability depends on smooth, high-volume integration. The advancement of AI models includes interpretability features, such as Grad-CAM visualizations, to elucidate the model's decision-making process, thereby ensuring robustness and fostering essential trust in high-stakes contexts (Lim and Song, 2025). The application of these noninvasive sensors for real-time meat quality assessment is discussed in Table 6.6.

The amalgamation of these technologies establishes an uninterrupted forecasting cycle across the supply chain. Data acquired from PLF sensors on live animals (e.g., growth rate, feed efficiency, heat response), in conjunction with genomic information (Section 6.2.5), can be assimilated into AI models (Wongpiyabovorn *et al.*, 2025). This connection facilitates precise forecasts of final carcass grade and quality problems before slaughter, enabling producers and processors to proactively modify management plans, optimize slaughter scheduling, and conduct predictive sorting on the basis of expected meat quality results.

6.3.7 Environmental Sustainability

To make cattle production more environment-friendly, we need to develop specific plans to address the problems caused by climate change. These plans should focus mainly on lowering the carbon footprint, reducing CH_4 emissions, and encouraging regenerative land care. The plans are discussed in the following sections, and Table 6.7 shows a comparison of the environmental and production outcomes of sustainable livestock systems.

6.3.7.1 Climate Change Challenges for Livestock Systems

Livestock systems are significant contributors to global GHG emissions, primarily CH_4 from enteric fermentation and nitrous oxide (N_2O) from manure and fertilizers. Enteric CH_4 from cattle, sheep, and goats alone accounts for ~60% of agricultural CH_4 emissions (and >25% of all anthropogenic CH_4) (Hegde, 2025). Methane's GWP is approximately 80× CO_2 over a 20-year timespan (Hegde, 2025).

TABLE 6.7

Comparative Environmental and Production Outcomes of Sustainable Livestock Systems

Production System	Climate Adaptation (Resilience)	CH_4 Mitigation Strategy	SOC Sequestration Potential	Meat Quality Link	References
Conventional intensive	Low (high heat load risk)	Diet optimization (limited)	Minimal/negative	High risk of stress-induced quality defects (e.g., DFD, PSE)	Karabasil *et al.*, 2019
Silvopastoral system	High (shade reduces core temperature	Improved production efficiency Optimized forage	High (27–163% increase versus pasture)	Stable productivity Improved welfare Potential for grass-fed attributes	Ripamonti *et al.*, 2023; Sandoval *et al.*, 2023
Seaweed-supplemented grazing	System dependent (often pasture)	High (bromoform-based reduction up to 37.7%)	Moderate (if regenerative grazing is used)	Maintenance of animal performance and carcass traits during mitigation	Meo-Filho, Ramirez-Agudelo and Kebreab, 2024

In the United States, enteric CH_4 is estimated to constitute 56% of beef's carbon footprint (Honan *et al.*, 2021). Manure management adds another 6–10% of livestock GHGs (CH_4 and N_2O) to intensive systems (Montes *et al.*, 2013). In addition to GHGs, livestock also drives land-use change and water use, so sustainable practices must be addressed on multiple fronts.

6.3.7.2 Quantitative Assessment of the Environmental Footprint: Role of Life Cycle Assessment (LCA)

LCA is a systematic and comprehensive approach employed to measure the environmental impacts linked to a product over its full life cycle, from raw material acquisition to final disposal (Risner *et al.*, 2024). An LCA is essential for evaluating the environmental effects, including the GWP, of different livestock production methods.

In the cattle industry, a comprehensive LCA must encompass more than just measuring the environmental impact per unit of live animal weight. A thorough evaluation requires the inclusion of four critical components in the supply chain: (a) the environmental impact per unit of farm-gate output (liveweight); (b) the slaughter yield percentage; (c) the meat yield from the carcass; and (d) the nutritional composition of the resulting meat (McAuliffe, Takahashi and Lee, 2018). A conventional mass-based functional unit (e.g., a kilogram of deboned beef) facilitates fundamental comparisons; nevertheless, this methodology may unintentionally disadvantage high-quality, sustainable systems that have a greater environmental impact per mass unit owing to prolonged growth or specialized feeding practices. To synchronize LCA with meat quality objectives, the functional unit must adapt to include metrics of nutritional density (e.g., omega-3 levels or elevated protein production) (McAuliffe, Takahashi and Lee, 2018). This transition ensures that sustainable, quality-oriented methods are assessed equitably based on their nutritional contributions, thereby discouraging the discouragement of environmentally responsible management strategies.

6.3.7.3 Mitigating Methane Emissions and Manure Management

The enteric CH_4 generated by ruminants is a notable, ephemeral climate pollutant. Mitigation strategies focus on modifying the rumen microbiota through dietary changes and genetic interventions.

6.3.7.3.1 Nutritional Inhibitors

Highly successful nutritional therapies employ targeted feed additives to inhibit CH_4-producing microorganisms. The red macroalgae *Asparagopsis taxiformis* contains bromoform, which, when included in the

diet, has been shown to reduce enteric CH_4 emissions in grazing beef cattle (such as Wagyu and Angus crossbreeds) by an average of 37.7% (Meo-Filho, Ramirez-Agudelo and Kebreab, 2024). This reduction was accomplished without negatively affecting animal performance or carcass characteristics (Meo-Filho, Ramirez-Agudelo and Kebreab, 2024). The application of other inhibitors, such as 3-NOP, further illustrates the capacity to significantly reduce the carbon footprint of ruminant meat production by up to 50% without sacrificing carcass quality. For comprehensive industrial application, it is imperative that each mitigation strategy, whether nutritional or genetic, is subjected to rigorous validation to guarantee that environmental benefits are achieved while maintaining or improving the productivity and quality attributes essential for economic viability (Meo-Filho, Ramirez-Agudelo and Kebreab, 2024).

6.3.7.3.2 Manure Management

Stored liquid manure in pits or lagoons generates CH_4; dry manure emits less CH_4 but may emit N_2O when tilled into soil. Anaerobic digesters capture manure CH_4 and convert it into biogas for energy. The EPA reports that covered digesters can reduce manure CH_4 emissions by roughly half (and offset fossil fuels) (Montes *et al.*, 2013). Even simpler practices, such as frequent manure removal (dry/daily spreading) or composting, can reduce CH_4 by 50–100% (Chadwick *et al.*, 2011). For example, pasture-based or solid storage systems (exposed to oxygen) essentially prevent anaerobic CH_4 production (Chadwick *et al.*, 2011). Proper manure management also reduces nitrogen runoff and nitrous oxide (N_2O) emissions. Implementing digesters on dairy and swine farms reduces GHG emissions while generating sustainable energy (electricity or biogas) and producing stabilized fertilizer, completing a nutrient–energy cycle (McAllister *et al.*, 2025).

6.3.7.4 Regenerative Land Management and Circular Farming Approaches

Regenerative agriculture and grazing strategies offer systemic solutions to environmental challenges by focusing on increasing soil health, water retention, and carbon sequestration. Regenerative practices, which include agroforestry, cover cropping, and optimized animal integration, effectively increase the rate of soil organic carbon (SOC) sequestration in agricultural ecosystems (Villat and Nicholas, 2024). In particular, well-managed grazing supports climate change mitigation (Villat and Nicholas, 2024). By enhancing SOC sequestration, these land management practices improve overall soil properties, including nutrient uptake and water infiltration, stabilize forage availability, and increase the resilience of the production system to climate variability (Sandoval *et al.*, 2023). Although species-specific comparisons are still limited, evidence indicates that integrating animal grazing within a regenerative framework provides significant climate benefits (Clark *et al.*, 2025).

In addition to nutrient cycles, sustainability is associated with excellence. Livestock inherently converts crop waste and by-products into meat, while their dung can enrich fields or supply biogas facilities. Anaerobic digestion of manure reduces CH_4 emissions while producing biogas (a renewable energy source) and digested solids that increase soil fertility (McAllister *et al.*, 2025). By recycling nutrients on the farm, growers diminish their reliance on synthetic fertilizers and the accompanying CO_2 emissions (McAllister *et al.*, 2025). A new analysis emphasized that animals convert nonhuman food biomass (forage, residues, food industry waste) into high-quality protein, simultaneously returning manure nutrients to the land (McAllister *et al.*, 2025). This circular methodology also alleviates climate impacts by preventing waste and augmenting soil carbon. For example, composting or incorporating manure into fields helps with carbon sequestration and promotes the growth of beneficial bacteria. Overall, integrated crop–livestock systems where manure and by-products flow back into production can deliver lower net emissions and richer soil, all while producing the same (or better) meat yield (McAllister *et al.*, 2025).

6.3.7.5 Silvopastoral Systems

Silvopastoral systems (SPSs), the deliberate integration of trees, fodder, and livestock, constitute a comprehensive approach that automatically connects environmental sustainability with animal welfare and meat quality (Ripamonti *et al.*, 2023).

The arboreal element of SPS provides shade, effectively alleviating the detrimental impacts of HS on animal welfare (Ripamonti *et al*., 2023). Compared with those in traditional open pastures, animals foraging in silvopastures present diminished indicators of HS, as evidenced by lower core body temperatures (Clark *et al*., 2025; Ripamonti *et al*., 2023). By mitigating hyperthermia, SPS directly enhances animal welfare and stabilizes overall livestock productivity, hence safeguarding meat quality from heat-induced deterioration (Ripamonti *et al*., 2023).

SPS provides substantial environmental advantages, especially in the context of climate change mitigation. The incorporation of trees enhances net carbon storage (both above- and below-ground), leading to a 27–163% increase in carbon sequestration compared with that in treeless open pasture lands (Sandoval *et al*., 2023). Elevated carbon density improves the environmental sustainability of the resulting meat by reducing GHG emissions per unit of output (Sandoval *et al*., 2023). SPS enhances biodiversity and ecosystem resilience (aligned with SDGs 15 and 13) by establishing intricate habitats, optimizing soil nitrogen cycling, and stabilizing food availability through improved water infiltration (Sandoval *et al*., 2023). The ability of SPS to address climate mitigation (carbon sequestration), climate adaptation (cooling), and quality preservation (diminished HS impacts) concurrently positions it as a fundamental method for resilient, sustainable, and high-quality livestock production.

6.3.8 Economic Sustainability in Meat Production

6.3.8.1 Productivity versus Profitability Trade-Offs

Productivity is defined as output per unit of input, which in this case is weight increase per unit of feed, whereas profitability can be measured by the net profit and is influenced by costs, pricing, and productivity. Although higher feed intensity and genetically driven growth rates can increase output, they also increase input costs and pose health hazards. As a result, increased productivity does not always translate into increased profitability (McDonald *et al*., 2010). Cobanoglu *et al*. (2014) examined profitability differences between conventional and organic broiler production. Slow-growing broilers and fast-growing broilers in conventional and organic production systems were compared.

They concluded that broilers were more productive. However, organic broiler meat is more profitable in terms of profitability (Cobanoglu *et al*., 2014). Another study examined several factors limiting cattle productivity, including input costs, disease burden, and feed constraints. Productivity increases must be adjusted to prevent mortality and sickness to guarantee profitability (Kennady *et al*., 2023). According to Khan, Fouzder, and Sarkar (2023), farms with a mortality rate below 5% are more profitable than those with a rate above 10% (Khan, Fouzder and Sarkar, 2023). If the quality of the meat is higher, a larger output may also be less profitable than a smaller output. A perfect balance between quality and quantity is needed to optimize profitability. To address these issues, strategies for economic sustainability are given in Table 6.8.

6.3.8.2 Branding for Carbon-Neutral, Organic, and Grass-Fed Products Adds Value

The separation of meat products into several categories allows farmers to profit from higher prices. Branding with these qualities has many benefits. A study by Chen *et al*. (2024) examines how Chinese customers respond to carbon-neutral and grass-fed labeling. If these qualities are present, customers are prepared to pay higher rates (Chen *et al*., 2024). These qualities improve reputation and facilitate access to areas, such as the export market, that require sustainability and higher standards. These qualities also have limitations. The cost of certifications alone is relatively high. Additionally, there are several disadvantages, such as slower growth rates, more work, and pasture maintenance. The cost of producing broilers via organic methods is approximately 70–86% greater than that of conventional methods (both fixed and variable expenses) (Cobanoglu *et al*., 2014). The cost is also increased by branding, marketing, and various supply networks. Many businesses use these qualities as part of their marketing strategy. For example, the Australian organic grass-fed, free-range beef company Cleaver's Organic declared itself to be completely carbon neutral (Harrison *et al*., 2025).

TABLE 6.8

Strategies for Economic Sustainability

Approach	Impact on Economic Sustainability	Effect of Meat Quality on Sustainability	Reference
Marine supplements, agricultural by-products, and diets based on forage	Lowers feed costs and supports the circular economy	Lowers emissions and improves the FA profile	Salami *et al.*, 2019
AI, digitization, and PLF	Increases productivity and uses fewer resources	Reduces GHG emissions and enhances animal health	Kumar *et al.*, 2022
Host genetics and gut microbiota management	Lowers input costs and improves feed efficiency	Reduces CH_4 emissions and enhances the quality of meat	Mizoguchi, 2023
Increased grassland and better grazing management	Lowers land expansion and boosts production	Reduces GHG emissions and preserves pasture quality	Cardoso *et al.*, 2020
Feed efficiency through selective breeding	Reduces feed expenses and boosts earnings	Increase yield while lessening the impact on the environment	Terry *et al.*, 2020
Use of crops resistant to drought, such as millet and sorghum	Lowers feed expenses during climate stress	Keeps output high and promotes the bioeconomy	Ammann *et al.*, 2024
Stress reduction and advances in animal welfare	Minimizes losses, and increases marketability	Improves the quality of meat and satisfies consumer need	Ammann *et al.*, 2024
Innovative feed components (algae)	Reduces feed costs and promotes the circular economy	Increasing the nutritional value of beef, prolongs its shelf life	Prates, 2025
Recycling, waste management, and policy incentives	Reduces expenses and generates new sources of income	Lessens its environmental impact	Jiang *et al.*, 2020
Stakeholder cooperation, education, and digital expansion	Increases adoption and closes knowledge gaps	Encourages industry resilience and sustainable practices	Bist *et al.*, 2024

6.3.8.3 Government Policies and Incentive Functions

Instead of excessive regulation, government support can improve economic sustainability through the recognition of organic meat production, carbon emission reduction, and environmentally responsible operations. Regulations that restrict the use of contaminants, growth hormones, and antibiotics increase product credibility and public health outcomes while increasing costs (Van Boeckel *et al.*, 2015). The adoption of low-emission production systems has been shown to reduce environmental impact while maintaining productivity (Gerber *et al.*, 2013). Furthermore, legislative support for branding, market access, and exports can help local meat producers achieve long-term profitability (Capper, 2011).

Examples of how the government has improved the cattle and meat sector abound. The World Bank collaborated with the Kazakh government to promote sustainable livestock development. To promote sustainable, inclusive, and competitive beef production in Kazakhstan, they enforced a program (Nendissa *et al.*, 2023). Yang *et al.* examined the effects of providing subsidies to farmers and retailers for organic farming and demonstrated that these subsidies can encourage organic production by relieving them of the additional costs associated with the organic approach (Yang, Dai and Zhang, 2024). In terms of sustainability, this is also beneficial. However, the government also faces specific difficulties. Ensuring that funds are distributed appropriately is a challenging task. It is imperative that the people who are in need, not the large producers, receive subsidies. Maintaining the quality of approved items is a difficult but crucial responsibility for reputation. Numerous sustainable measures may require initial funding, which even the government may find burdensome.

6.3.8.4 Grading Models (MSAs)

Meat grading models serve primarily as standards for several aspects of meat quality, including carcass appearance, cuts, predicted yield, and eating quality. Meat can be classified and graded via a variety of grading models. The MSA is a widely used grading scheme. Meat & Livestock Australia founded it in 1998. Over 250,000 people from more than 13 countries completed 1.7 million consumer taste tests for this grade system. These methods consider every element that can influence the quality of food (Griffith *et al*., 2024).

MSA uses numerous parameters that could affect the final meat output. Breed, sex, age, ultimate pH, hump height, meat color, cooking method, and aging period are considered in addition to conventional methods. Rather than being efficient, the MSA technique is more likely to result in satisfied customers. This ensures that the MSA is highly accepted in the consumer market. In 2010, Thompson and Polkinghorne discussed how different cultures and demographic groups accept higher-quality meat. They demonstrated the compatibility of the MSA with all other countries' grading schemes. Higher-quality meat might command a higher price from consumers. Furthermore, manufacturers, distributors, and retailers in Australia have made significant profits because of the MSA (Polkinghorne and Thompson, 2010).

The grading system makes it possible to assess a product's worth on the basis of its quality rather than its quantity. Customers were pushed to pay more for quality. The industry benefits greatly from MSA grading, which is influenced by trust and willingness to pay (Stewart *et al*., 2024). Additionally, by lowering waste, the quality data from MSA assists producers in making critical production decisions that enhance meat quality and guarantee sustainability. Furthermore, this knowledge aids in maintaining supply and demand equilibrium (Zhang *et al*., 2023).

Grading schemes such as MSA encourage growers to prioritize both quality and quantity from a sustainability standpoint. Because higher-quality meat is produced when an animal is under less stress, this indirectly improves animal welfare. Furthermore, there is no denying MSA's influence on the global grading scheme. On the basis of muscle characteristics and intermuscular fat, nations such as the United States and Korea are creating prediction algorithms that follow the MSA path (Ardeshiri, Sampson and Swait, 2019; Cho *et al*., 2010). This demonstrates how the meat market can be impacted by grading systems through quality-driven distinctions.

6.3.9 Social and Ethical Sustainability

6.3.9.1 Perception and Demand among Consumers for Ethical Meat

The consumer demand for safe meat is increasing due to cultural beliefs, pricing, trust, environmental concerns, and animal welfare. This change has increased the demand for organic and sustainable farming methods that emphasize natural living conditions, low environmental impact, and the use of fewer antibiotics and hormones. Meat produced using such humane and environmentally responsible procedures is usually referred to as ethical meat. The major factors for ethical meat demand are discussed in the following sections.

6.3.9.1.1 Prioritizing the Welfare of Animals

Across Europe and other places, animal welfare is frequently prioritized over environmental sustainability as the most relevant ethical consideration in meat purchasing decisions, with people prepared to pay a premium for free-range and welfare-certified goods (Clark *et al*., 2016; Lagerkvist and Hess, 2011). Ethical meat production is founded on the "Five Freedoms", which provide independence from hunger, discomfort, pain, damage, and disease (FAWC, 2009). It also emphasizes appropriate housing and animals' ability to perform natural behaviors while reducing anxiety and stress (Fraser *et al*., 1997).

6.3.9.1.2 Environmental Sustainability

Decreased Carbon Footprint: Farms that prioritize sustainable agriculture and other methods to reduce their environmental impact are frequently the source of meat that is sourced ethically. *Biodiversity and Soil Health:* Techniques such as incorporating trees and wildflowers, minimizing tilling, and using natural fertilizers (manure, compost) rather than synthetic fertilizers all contribute to better soil health and biodiversity.

6.3.9.1.3 Human Welfare

Food Quality: Meat quality is closely linked to animal health and welfare, as reduced stress, proper nutrition, and humane handling improve meat safety, sensory attributes, and nutritional value (Broom, 2010).

Reduction of Pesticides and Chemicals: Lower reliance on synthetic fertilizers, pesticides, and chemical inputs in livestock production systems reduces chemical residues in meat and mitigates adverse impacts on human health and the environment (Pretty *et al.*, 2018).

6.3.9.1.4 Labeling and Trust

Informed Consumer Decisions: Ethical meat producers increasingly provide transparent information regarding animal welfare standards, feeding regimes, and production practices, enabling consumers to make informed purchasing decisions (Wu *et al.*, 2021).

6.3.9.1.5 Consumer Segmentation and Attitudes

Demographics show that younger consumers, women, and those with higher education levels are more likely to choose ethical and sustainable meat, whereas lower-income groups are still influenced by price sensitivity (Hoek *et al.*, 2011).

6.3.9.1.6 Difficulties and Opportunities

Many customers are confused about sustainable practices and the true environmental effects of meat production, but price, flavor, and health continue to be the most important drivers (Siegrist and Hartmann, 2020). Integrated messaging that includes ethical concerns (animal welfare) with environmental and naturalistic cues surpasses single-issue approaches in boosting consumer acceptability of ethical and alternative meat products (Bartels and Onwezen, 2014).

6.3.9.2 Animal Welfare Certification Schemes

According to several groups, animal welfare certification programs confirm that farms and companies adhere to strict guidelines for animal care, guaranteeing that animals are comfortable, healthy, and free to exhibit their natural behaviors. These independent programs, which frequently entail onsite audits and demand standards above and beyond the requirements of the law, increase consumer confidence, give farmers access to markets, and generally promote the welfare of animals (Clark *et al.*, 2017).

6.3.9.2.1 Examples of Schemes

Certification programs may be started by nongovernmental organizations, the government, or the business community. With differing degrees of welfare requirements, they range from fundamental quality assurance to particular animal welfare and organic programs. Higher welfare standards are frequently offered in the upper tiers of multitier schemes, which occasionally correspond with organic farming methods. GLOBALG.A.P., Certified Humane, and Animal Welfare Approved are a few examples, each with unique requirements and inspection procedures (Heinola *et al.*, 2021).

6.3.9.2.2 Principal Objectives

Animal welfare certification systems provide verifiable labels that inform consumers that basic welfare requirements are met throughout an animal's life, from breeding to slaughter. These programs encourage continuous advancement by establishing management systems that assure humane treatment, adequate housing, nourishment, health care, and monitoring in accordance with scientific guidelines. They also raise awareness by educating producers and consumers, which builds trust and increases animal welfare in public conversation. Furthermore, certification helps decrease unnecessary animal suffering while increasing farmers' market access, branding, and economic prospects (Lagerkvist and Hess, 2011).

6.3.9.2.3 Effectiveness, Consumer Perception, and Market Impact

Certification programs can increase adherence to animal welfare laws and potentially improve welfare results, particularly when evidence-based practices and ongoing improvements are used (Souza and Molento, 2015). In general, consumers appreciate and are willing to pay more for goods with reliable

welfare certifications; however, trust depends on openness, independent verification, and unambiguous labeling. In specific markets, skepticism occurs because of varying standards and a perceived lack of rigor (de Castro Júnior *et al.*, 2025).

6.3.9.3 Sociocultural Significance of Sustainable Livestock Systems

The sociocultural significance of sustainable livestock systems includes reinforcing community bonds and identity, supporting religious and ceremonial practices, providing food security and economic stability, and influencing cultural values and traditions. Sustainable systems also require integrating traditional and modern knowledge to ensure ongoing acceptance and adaptation by local communities, recognizing that cultural sustainability is context dependent and involves societal perceptions, not just expert views.

6.3.9.3.1 Security and Social Perceptions

Livestock contribute to the overall economic well-being of many rural communities by providing a reliable source of food, resources, and income. By supplying wholesome, reasonably priced food and promoting resilience in the face of economic and environmental shocks, sustainable systems help ensure food security. Because the idea of sociocultural sustainability depends on context, people's and cultures' priorities and perceptions can vary greatly.

6.3.9.3.2 Combining Traditional and Modern Knowledge

To integrate community viewpoints and local knowledge into contemporary farming systems, social scientists and practitioners must work together to achieve sustainable transformations. Social values, experiences, and concerns influence public acceptance and understanding, which are essential for the success of sustainable livestock systems. Maintaining culturally significant landscapes, sustaining rural livelihoods, and upholding traditions all are facilitated by sustainable livestock systems. Citizens consider numerous sociocultural elements, including farming practices, animal care, landscape beauty, and national culture, essential for future generations. The majority of their value is related to more general cultural and social roles; only a small portion is directly related to food (Dumont *et al.*, 2019).

6.3.10 Integrating Sustainability with Meat Quality

Livestock production, especially beef production, has a major impact on the environment. The environmental impacts vary according to beef system. Understanding these differences will help mitigate the effects of beef production (de Vries, van Middelaar and de Boer, 2015). This type of assessment needs to quantify resource utilization and emissions to air, water, and soil throughout the product's entire life cycle. An increasingly used technique for calculating environmental impacts, such as net GHG emissions throughout a beef production system, such as from cradle to farm gate or cradle to consumption, is life cycle assessment. To determine how much a specific management change might reduce GHG emissions in a given region, comparative LCAs that compare improved versus conventional beef management in surrounding systems are helpful. According to some recent studies, with better management of temperate ecosystem grazed lands, beef GHG emissions can be lowered to net zero or even negative emissions (i.e., net C sequestration) (Herrero *et al.*, 2016; Paustian *et al.*, 2016; Rowntree *et al.*, 2016; Stanley *et al.*, 2018; Teague *et al.*, 2016). Several studies have used LCA to assess the environmental impact of beef production. In a beef life cycle assessment, resource consumption and emissions from every stage of production, as shown in Figure 6.6, are measured, assigned to environmental effect categories, and connected to the system's primary output, such as 1 kg of live weight, slaughter weight, or edible beef. LCAs of animal-source food environmental effects include the use of fossil fuels, land, water, GWP, acidification potential, and eutrophication potential (De Vries and de Boer, 2010). Two types of LCA are usually performed in the livestock sector: consequential LCA and attributional LCA. Consequential LCA studies aim at quantifying the environmental consequences of a change in a production system or a change in

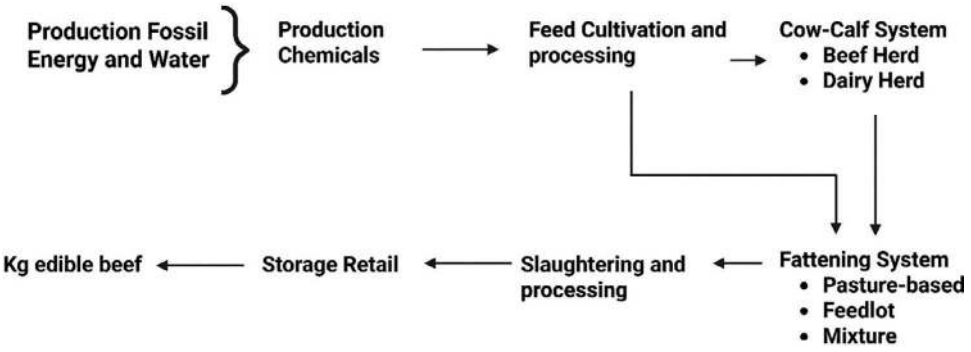

FIGURE 6.6 Stages in the beef production system.

product demand. Attributional LCA studies aim at the environmental effects of the main product (such as beef), assuming a status quo situation (Thomassen *et al.*, 2008). The environmental impacts can be calculated when the system and diet remain the same.

6.3.10.1 Balancing Efficiency with Meat Quality Outcomes

Management changes were generally targeted at reducing total beef GHG emissions in several LCA studies. Since the improved-versus-conventional comparison was locally defined, studies differ somewhat in which specific management changes were identified as "improved". Some of the categories are listed in Table 6.9.

Cusack *et al.* (2021) reported that 73% of studies reported significant reductions in beef GHG emissions, indicating that there is broad potential for improving beef climate impact across regions and producers. Among all the management strategies, integrated field management for C sequestration significantly reduced beef emissions, lowering GHG emissions per unit of beef by 62±9%. Compared with the extensive grazing system, intensive rotational grazing had the second most significant reduction in GHG emissions per unit of beef, accounting for 37±7%. These two management changes constitute strategies for land-based carbon sequestration to reduce beef GHG emissions.

TABLE 6.9

Management Change Strategies with Examples

Management Strategy Types	Treatment Examples
Breed comparison	• Crossbreeding to reduce the calving interval, age at first calving, and increase beef yield per animal • Selection for low inbreeding, which allows for animals with better growth and efficiency
Conventional versus organic beef production	• Eliminating the use of chemical fertilizers, pesticides, antibiotics, feed additives, growth hormones, and genetically engineered breeding
Feedlots versus grazing finished	• Conducting the finishing phase of cattle production in a pasture or rangeland, rather than a feedlot, to quickly fatten cattle
Fertilizer use change	• Reduction of mineral N fertilization to reduce GHG emissions from soil • Increase in mineral N fertilization to increase plant growth and nutrient content
Cattle life cycle management	• Weaning cows earlier so that they can spend additional time in the finishing phase as a means of more efficiently converting feed to weight gain • Younger age at slaughter
Integrated field management	• Integrating trees and/or organic soil amendments and/or inorganic nutrients to enhance plant and soil C sequestration in degraded pasture and/or rangeland

6.3.10.2 Strategies to Improve Production Efficiency

Breed changes significantly reduced GHG emissions per unit of beef by 30±14%. Overall, changes in life cycle management did not lead to a significant decrease in beef GHG emissions per unit of beef or per unit of land (Cusack *et al.*, 2021). Improved efficiency reduced GHG emissions per unit of beef by 8%, with most of the reductions driven by breed change, which alone reduced beef GHG emissions by 30%, a smaller contribution from improved feed, and no change from life cycle management. This finding contradicts earlier worldwide estimates that suggested that improved feed might reduce CO_2 emissions by approximately three times as much as breed changes and life cycle management combined (Griscom *et al.*, 2017). Using dairy-bred beef calves from dual-purpose cattle or from dairy cows crossed with beef breeds can further reduce environmental impacts while increasing the feed efficiency and growth performance of dairy-bred beef cattle (Hietala, Bouquet and Juga, 2014). Although efficiency improvements offer a significant opportunity to mitigate climate change, it is unlikely that greater efficiency alone can reduce net world beef production GHG emissions to a level compatible with increasing demand (Springmann *et al.*, 2018). To conclude, according to the findings above, beef production systems may be able to significantly reduce GHG emissions through both enhanced efficiency and land-based carbon sequestration.

6.3.11 Innovations and Future Outlook

6.3.11.1 Digital Agriculture and Big Data Analytics

Digital technologies are revolutionizing livestock production by shifting management from a reactive system to a predictive system. PLF combines networked sensors, imaging systems, automated weighing systems, and decision-support algorithms to optimize growth, behavior, health, and carcass characteristics in real time and thus allows individuals to diagnose disease or stress earlier and more accurately regulate feeding and housing factors (Neethirajan, 2020). Big data analytics can also explain the relationships between genotype, environment, and management practices that affect intramuscular fat deposition, pH, color stability, and carcass yield when high-frequency data produced by such systems are aggregated, leading to better resource efficiency and product uniformity (Wolfert *et al.*, 2017).

Traceability and value-based marketing have the same digital base. By allowing information to be captured at the lot or carcass level through farms, transport, slaughter, or retail and linking it together in interoperable databases or blockchain platforms, it will be possible to record the origin, welfare status, and carbon footprint, thereby enhancing consumer trust and differentiated brand positioning (Astill *et al.*, 2019). The combination of sensor-based phenotypes with genomic analyses further improves selection decisions because enriched information can be utilized beyond conventional records; therefore, genetic gain around complex traits, such as robustness, behavior, and resilience, is achieved faster, and sustainability reports requested by regulators and markets are met (Hayes, Lewin and Goddard, 2013; Neethirajan, 2020).

6.3.11.2 Breeding Climate-Resilient Animals

Rising temperatures, frequent heatwave events, and changing disease dynamics require that breeding objectives be specifically defined with climate resilience, growth, and meat quality indicators (Shukla *et al.*, 2019). GS enables the identification of animals with desirable carcass structure and greater heat tolerance, disease resistance, and reproductive performance under stressful conditions via dense SNP panels and reference populations to approximate the breeding values of resilience (Hayes, Lewin and Goddard, 2013; Hoffmann *et al.*, 2015). FAO evaluations also focus on the preservation and production of locally adapted breeds, which, in most cases, have inherited resistance to heat, parasites, and low-quality forage and are thus important resources for climate change adaptation and meat quality under extreme conditions (Gerber *et al.*, 2013).

In the future, low-emission and climate-resilient animals have the potential to contribute to national mitigation objectives, as judged by selection. Empirical and modeling studies have shown that permanent, cumulative herd GHG emissions can be achieved through breeding to reduce CH_4 production when better methods of feeding and managing manure are used (Hayes, Lewin and Goddard, 2013; Limmeechokchai *et al.*, 2023). New biotechnologies, such as gene editing, are under evaluation as an

addition to elite lines to add alleles to confer thermotolerance or disease resistance, but their regular use will require regulatory acceptance and societal acceptance (Hoffmann *et al.*, 2015). Practically, climatic intelligent breeding of meat systems will require the use of selection indices that combine marbling, tenderness, robustness, fertility, and the ecological footprint jointly and can be updated as climatic conditions, market needs, and social anticipations change (Limmeechokchai *et al.*, 2023).

6.3.11.3 Policy Frameworks and Alignment with Global Sustainability Goals

Advancements in breeding and management will not transform the industry independently without integrated policy frameworks that align farm-level choices with global sustainability objectives. Sustainable development goals directly relate livestock to zero hunger, good health, responsible consumption and production, climate action, and life on land, and the FAO now calls upon the member states to make livestock policies that approach productivity, livelihood, welfare, and environmental performance holistically, not separately (Gerber *et al.*, 2013). Mitigation and adaptation strategies related to livestock have already been included in the list of Nationally Determined Contributions of many countries under the Paris Agreement, providing incentives and financial incentives to mitigate CH_4 and lessen feeding and better handling of manure in meat systems (Shukla *et al.*, 2019).

International standard organizations reinforce these guidelines through health, welfare, and antimicrobial policies. In support of the concept of sustainable meat production, safe trade, and a One Health approach to address zoonotic risk, the World Organization for Animal Health offers science-based advice on animal health, welfare, and biosecurity, known as the Terrestrial Animal Health Code (Donachie, Ewann and Poudevigne, 2023). The World Health Organization recommends that the utilization of medically necessary antimicrobials in food-producing animals should be based on the gradual elimination of the everyday utilization of antibiotics to promote growth and prevent nonveterinary illnesses, in line with livestock management and the international action plan for AMR (Aidara-Kane *et al.*, 2018). When combined, the frameworks of the FAO, IPCC, WHO, and WOAH create a policy framework that aligns genetic enhancement, management intervention, and value-based marketing, thereby enhancing meat quality, animal welfare, farm profitability, and environmental integrity simultaneously.

6.4 Case Studies

To illustrate the principles of genetic selection, management, and economic integration discussed in the preceding sections, this chapter presents five distinct case studies. Each case has been selected to provide a real-world example of how these strategies are being applied in different species and production systems to improve meat quality and sustainability. The thematic alignment and specific contribution of each case study to the chapter's overarching narrative are summarized in Table 6.10.

TABLE 6.10

Thematic Alignment and Significance of the Case Studies

Case Study	Core Thematic Link	Key Takeaway and Contribution	Reference
Low-CH_4 sheep selection in New Zealand	Applied genetics for environmental mitigation	Selective breeding heritably reduces CH_4 without hurting production	Hickey *et al.*, 2022
Feeding 3-NOP to feedlot cattle	Nutritional interventions for emissions reduction	3-NOP feeding minimizes CH_4 while keeping production efficiency	Araújo *et al.*, 2023
Silvopastoral cattle systems	Agroecological systems for climate resilience and welfare	Agroecological systems promote resilience, welfare, and consistent production	Ripamonti *et al.*, 2025
Halothane genotype and pork quality	Molecular genetics of meat quality	Genetic removal of a deleterious allele improves pork quality	Miller *et al.*, 2000
MSA-aligned beef supply chain	Value chain integration and economic models	Value-based models align supply chain, improving quality consistency	Polkinghorne *et al.*, 2008

6.4.1 Low-Methane Sheep Selection in New Zealand

The New Zealand sheep farming industry has been integrating different genetic tools to address GHG emissions. A study analyzed more than 9,000 respiration chamber records collected over ten years from over 2,200 sheep, supplemented with maternal and health data from more than 8,000 of their female relatives (Hickey *et al*., 2022). The heritability of CH_4 output was shown, supporting the possibility of continuous genetic improvement. Among the two assessed indicators, CH_4 output in relation to total gas emissions ($CH_4/(CH_4+CO_2)$) was more heritable (0.21) than CH_4 per unit of DMI (CH_4/DMI) (0.12). Critically, genetic correlations with key maternal traits such as fertility, fecundity, lamb survival, and parasite resistance are neutral, indicating that selection for CH_4 reduction should not compromise reproductive performance (Hickey *et al*., 2022).

Some trade-offs were also noted: low-CH_4-yield animals tend to have lighter BWs and lower body condition scores, and fleece weight was negatively correlated with CH_4 yield. Physiological mechanisms include smaller rumen volumes, altered fermentation, and a higher propionate-to-butyrate ratio (Gleason, Beckett and White, 2022). These changes reflect fundamental differences in rumen function and energy use. This case shows that incorporating CH_4 traits into national breeding programs provides a cumulative, cost-effective, and permanent mitigation strategy (de Haas *et al*., 2021). The use of genomic prediction tools and portable accumulation chambers has enabled large-scale implementation, which can be extended to other ruminant systems worldwide (O'Connor *et al*., 2024).

6.4.2 Feeding 3-Nitrooxypropanol (3-NOP) to Feedlot Cattle under Tropical Conditions

Chemical inhibitors of methanogenesis have been studied for decades, yet few have consistently reduced emissions without harming productivity. 3-Nitrooxypropanol (3-NOP; Bovaer, DSM) has been the first compound to achieve sustained reduction across various production environments. Araújo *et al*. (2023) tested 3-NOP in feedlot Nellore (*Bos indicus*) bulls in Brazil. In a 96-day trial with 138 animals, supplementation with 3-NOP at 100 or 150 mg/kg diet dry matter did not affect feed intake, daily gain, feed efficiency, or standard carcass traits; the dressing percentage tended to be greater with supplementation. A companion study in 24 bulls measured CH_4 via the sulfur hexafluoride tracer technique and revealed reductions of approximately 49% in absolute emissions, 41% in CH_4 yield (per unit of feed), and 39% in CH_4 intensity (per unit of gain), with effects persisting across two measurement periods (Cunha, 2021). The share of gross energy lost as CH_4 fell by 43%. In addition to CH_4, total nitrogen excretion (urine + feces) decreased by 27%, whereas nitrogen retention efficiency was unchanged (Ahvenjärvi *et al*., 2024). Meat composition shifted slightly more protein at the 100 mg/kg dose and lower IMF at both doses, without changes in tenderness; meat color during retail display was largely unaffected, aside from a small decrease in instrumental fat at the 150 mg/kg dose (Ismail and Huda, 2024). The mode of action is the inhibition of methyl-coenzyme M reductase, which suppresses CH_4 formation and redirects hydrogen away from methanogenesis (Araújo *et al*., 2023). Confirming its effectiveness in Zebu cattle on tropical, high-grain finishing diets broadens the global use of 3-NOP, as both doses achieve similar CH_4 reductions without performance penalties (Pepeta, Hassen and Tesfamariam, 2024). Selecting 100 mg/kg can be considered a practical possibility where cost and simplicity are priorities, although the study did not evaluate cost-effectiveness (Luo *et al*., 2025).

6.4.3 Silvopastoral Cattle Systems in Mediterranean Climates

HS is a major constraint for beef production in the Mediterranean and other semiarid regions (Leite *et al*., 2021). SPSs, pastures integrated with tree cover, reduce solar heat gain and create cooler microclimates, offering a practical adaptation strategy while supporting grazing-based production (Ghahramani *et al*., 2019). A two-year on-farm study in southern Tuscany compared Maremmana cattle reared in open pastures with those managed in silvopastoral areas. The ADG, hair cortisol (a chronic stress indicator), blood glucose, and heat load (Black Globe Humidity Index—BGHI) were monitored (Ripamonti *et al*., 2025). In spring, when forage was abundant and the BGHI values were lower, open pastures yielded

greater gains (≈1.49 versus 1.25 kg/day in 2021; ≈1.24 versus 1.17 kg/day in 2022, open pasture versus silvopastoral). As summer heat intensifies and the BGHI increases, silvopastoral cattle support greater or steadier ADG and present smaller increases in hair cortisol (e.g., 35.04 versus 26.62 pg/mg in 2021 and 46.56 versus 42.94 pg/mg in 2022, open pasture versus silvopastoral), showing reduced chronic HS. Blood glucose decreases more in open-pasture cattle during peak heat, suggesting a less stable energy balance (Ramirez *et al*., 2024).

The final BW differences were limited, but SPS clearly mitigated HS and stabilized performance. The trees reduced the radiant heat load and provided shade, supporting their welfare and productivity (Elsadek *et al*., 2024). Management also influenced outcomes: higher spring stocking rates on open pastures improved gains when conditions were mild, whereas tree cover provided advantages as the thermal load increased (Tölgyesi *et al*., 2023). Ultimately, integrating shade into grazing landscapes enhances resilience to seasonal heat without sacrificing production goals (Gomez-Casanovas *et al*., 2021).

6.4.4 Halothane Genotype, Sire Line, and Pork Quality in Pigs

To study the effects of genetics on pork quality, Miller *et al*. (2000) conducted a controlled comparison of three commercial sires mated with a common halothane-negative dam line. Their evaluation focused on growth, carcass traits, meat quality, and curing yields under standardized housing, feeding, and slaughter conditions. With NN dams, sire line A (reactor, nn) produced all Nn (carrier) progeny; line C (NN) produced all NN progeny; and line B (Nn) produced both Nn (BNn) and NN (BNN) progeny within the same litters, enabling within-line genotype contrasts.

The growth performance differed by line. Line A pigs had a lower ADG (885 g/day) and feed intake (2.37 kg/day) than did the other classifications (1,049–1,082 g/day; 2.72–2.82 kg/day), while the gain:feed ratio was similar across groups (Tolosa Russi, 2022). The dressing percentages were comparable for A, BNn, and BNN (77.0–77.6%) but lower for line C (75.3%). Linear carcass measures and lean yield indices showed only minor differences among the groups after adjustment for slaughter weight (Lei *et al*., 2023). Meat quality outcomes separated lines and genotypes more clearly. The shear force was greater for line A than for BNN, BNn, and C, and the sensory panels scored line A and BNn lower for tenderness and juiciness than did BNN and C (Razmaitė, Šveistienė and Šiukščius, 2024). The early postmortem pH (45 minutes) was lower in carriers than in negative carriers, which is consistent with a faster glycolytic rate. While the pH (24 hours) was not significantly different among the groups, the authors noted that the value for line C was numerically lower (5.47 versus 5.68–5.70), potentially reflecting the influence of another major gene, such as the Rendement Napole (RN) gene. The objective color, drip loss, and Minolta L^*, a^*, and b^* values showed limited divergence between BNn and BNN under the handling and chilling conditions used (Mohammed, Munir and Aljabr, 2022).

Processing traits were largely conserved across groups. The Ham curing yields did not differ according to the halothane status at the modest pump level applied, whereas the belly curing yield was lower in line C than in line A (Schiavon *et al*., 2024). The authors noted that growth differences in line A likely reflected line ancestry (e.g., Pietrain influence) rather than the halothane locus per se and discussed the possibility that variation in eating quality in the negative lines could involve added loci such as the RN.

6.4.5 MSA-Aligned Value-Based Beef Supply Chain

In a study chronicling the commercial implementation of a predictive beef-eating quality model, the development of an integrated supply chain based on the MSA program was described (Polkinghorne *et al*., 2008). The MSA model turned consumer sensory data into a framework that estimates a composite palatability score (MQ4) for individual muscles under specified aging and cooking conditions, with retail grades assigned as 3 stars, 4 stars, or 5 stars. A commercial pilot translated this into "grade-by-cook" retailing: products were merchandised by a predicted outcome (e.g., 4-star grill; 3-star roast), with a higher entry threshold of 3 stars (52 MQ4 points versus the standard 46) to minimize the probability of unsatisfactory meals. Pricing differentials were set by grade, not cut, and products below the smallest threshold were withheld from sale (Saenz-de-Miera *et al*., 2025).

Implementation requires coordinated changes across the chain. Carcasses are processed with a tenderstretch suspension, controlled stimulation, and a decrease in pH–temperature (Kaić *et al*., 2024). Fabrication shifted from a traditional cut-based practice to separation by muscle, enabling uniform, predicted quality within each retail unit. Inventory and point-of-sale systems were integrated with MSA data to track MQ4 by muscle and days of age, enabling dynamic allocation to the highest-performing cooking category. To maintain carcass balance, secondary muscles were redirected to formats that maximized predicted performance (e.g., thin-slice, stir-fry, cooked meals) (Sun *et al*., 2025). In contrast, premium categories were supplied from multiple muscles meeting identical grade-by-cook criteria.

Production, supply, and incentives were aligned with consumer outcomes. Cattle were sourced to defined specifications, and payments were indexed to fabrication returns, linking on-farm decisions to downstream value (Samper, 2024). Detailed feedback reported carcass traits (e.g., ossification, MARB, fat depth, and ultimately pH) alongside the distribution of 3-, 4-, and 5-star outputs and realized value. The variation in returns within apparently uniform lots highlights the economic impact of small shifts in carcass attributes and compliance; grade failure associated with high ultimate pH, excessive fatness, or advanced ossification reduces value (Neethling *et al*., 2017). In contrast, tenderstretch and heifer carcasses delivered consistent value gains of $0.27/kg and $0.12/kg, respectively, through palatability effects independent of yield.

Outcomes at retail included sustained sales growth while achieving whole carcass use without resorting to discounting oversupplied cuts (Sundrum, 2024). The shift from cut names to grade-by-cook descriptors simplified choice, standardized quality assurance, and supported transparent pricing. Fabrication, traceability, and optimization software enables selection and aging strategies that increase the realized value (Cui, Hu and Liu, 2023). At the farm level, the feedback and payment structure provided clear signals for genetic and management adjustments to improve palatability-linked traits (Brito *et al*., 2021). Collectively, the program proves that a consumer-focused grading model can be embedded commercially to coordinate practices, reduce quality risk, and link payments to delivered eating quality across the beef supply chain (Amuno, 2020).

6.5 Conclusions

The increasing demand for animal protein is associated with stronger expectations for nutritional quality and animal welfare and lower environmental impacts. The core message of this chapter is that animal selection and management cannot be treated as separate topics. Together, these factors shape carcass composition, animal welfare, and sustainable livestock systems. Genetic selection has now progressed beyond simple growth measures to include complex traits of tenderness and resistance to disease, with the development of breeding approaches for heat tolerance and low-CH_4 emissions offering much needed adjustments to the changing climate. These innovations still rely on better on-farm management, where there is a need to reduce physiological stress through improved housing and handling, as a moral and practical requirement to avoid quality flaws such as dark, firm, and dry meat. Cross-species studies of cattle, sheep, goats, pigs, and poultry show that much of the biological regulation of muscle growth and fat deposition is conserved, meaning breeding goals in one species can be informed by findings in another. GS is enabled by high-throughput phenotypes generated with precision livestock technologies, such as imaging, spectroscopy, and automated behavior and welfare monitoring, and can be used to make real-time management decisions on farms. The most important issue is the use of these tools to establish and apply breeding objectives and management principles that directly combine meat quality, animal welfare, the environmental footprint, and farm profitability. This task will require more immediate cooperation between geneticists, meat scientists, veterinarians, welfare scientists, environmental experts, and producers. When selection indices, welfare protocols, and precision livestock technologies are aligned, livestock systems can move beyond a narrow focus on kilograms of product toward a more valuable outcome: meat that consistently meets consumer expectations, maintains animal welfare, and uses land, water, and feed resources sustainably for future generations.

Author Contributions

Md Jisan Ahmed and Delower Hossain conceptualized the chapter, surveyed the literature, drafted, reviewed, and edited the original manuscript, and structured the original outline. Md Jisan Ahmed, Delower Hossain, and S. M. Sertaz Islam supervised the project. S. M. Sertaz Islam, Saiful Islam, and Mamunur Rahman drafted, reviewed, and edited the original manuscript. Nahida Akter, Abdullah Al Noman, and Md Abdur Rahman contributed to manuscript writing, figure visualization, and table preparation. Md Piar Rahaman Shihab contributed to writing the manuscript. Saiful Islam, Mamunur Rahman, Abdur Rahman, and the remaining authors were involved in the critical editing and proofreading of the final manuscript. All the authors read and approved the final version of the chapter and agreed to be accountable for its content.

Abbreviations and Acronyms

3-NOP	3-nitrooxypropanol
ACACA	acetyl-CoA carboxylase alpha
ADG	average daily gain
AFABP/FABP4	adipocyte fatty acid binding protein/fatty acid binding protein 4
AI	artificial intelligence
ALA	alpha-linolenic acid
AMPK	AMP-activated protein kinase
ATP	adenosine triphosphate
BCFA	branched-chain fatty acid
BGHI	Black Globe Humidity Index
BMP2	bone morphogenetic protein 2
BST	body surface temperature
BT	backfat thickness
BTA1	bovine chromosome 1
BW	body weight
C	carbon (used in "C sequestration")
CAPN1	calpain 1
CAST	calpastatin
CBIA	Chew-Bite Intelligent Algorithm
CCW	cold carcass weight
ceRNA	competing endogenous RNA
CH_4	methane
circRNA	circular RNA
CLA	conjugated linoleic acid
CO	carbon monoxide
CO_2	carbon dioxide
CPT1	carnitine palmitoyltransferase 1
Cry1	cryptochrome circadian regulator 1
CYP	cytochrome P450
DEG	differentially expressed gene
DFD	dark, firm, and dry
DGAT1	diacylglycerol *O*-acyltransferase 1
DHA	docosahexaenoic acid
DITI	digital infrared thermal imaging
DL24/DL48	drip loss at 24 or 48 hours
DMI	dry matter intake
DPA	docosapentaenoic acid
DSM	Dutch state mines

DT	decision tree
EOA	ethyloctanoic acid
EPA	eicosapentaenoic acid
ES	electrical stimulation
EU	European Union
EX-FABP	extracellular fatty acid binding protein
F:G	feed-to-gain ratio
F1	first-generation offspring
FA	fatty acid
FAO	Food and Agriculture Organization
FDPS	farnesyl diphosphate synthase
GDF8	growth differentiation factor 8 (myostatin)
GH1	growth hormone 1
GHG	greenhouse gas
GPS	Global Positioning System
GS	genomic selection
GT	glutathione
GWAS	genome-wide association studies
GWP	global warming potential
Gx	gravitational acceleration on the *x*-axis
GZB	Guizhou White goat breed
HCW	hot carcass weight
HD	housing density
HFABP/FABP3	heart-type fatty acid binding protein/fatty acid binding protein 3
HIF-1	hypoxia-inducible factor 1
HMGA1	high-mobility group protein A1
HMGCS1	3-hydroxy-3-methylglutaryl-CoA synthase 1
HPA	hypothalamic–pituitary–adrenal (axis)
HS	heat stress
HSFA	heat shock factor
HSP	heat shock protein
HSP70	heat shock protein 70
HTLP	high temperature, low pH
ICDH	isocitrate dehydrogenase
ICT	Information and Communication Technology
IGA	intentional genomic alteration
IGF1	insulin-like growth factor 1
IGF2	insulin-like growth factor 2
IMF	intramuscular fat
JAK1	Janus kinase 1
KNN	*k*-nearest neighbors
L*	lightness value in meat color (CIELAB color space)
LCA	life cycle assessment
LCPUFA	long-chain polyunsaturated fatty acids
LEPR	leptin receptor
L-FABP	liver fatty acid binding protein
lncRNA	long non-coding RNA
LPIN1	lipin 1
lrWGS	long-read whole-genome sequencing
LT	lairage time
MAPA	Spanish Ministry of Agriculture
MARB	marbling
MAS	marker-assisted selection

MC4R melanocortin-4 receptor
MeC methane concentration
MeP methane production
miRNA microRNA
ML machine learning
MNA 4-methylnonanoic acid
MOA 4-methyloctanoic acid
MQ4 MSA composite palatability score
MRS magnetic resonance spectroscopy
MSA Meat Standards Australia
MSTN myostatin gene
MUFA monounsaturated fatty acid
MyHC myosin heavy chain
N nitrogen (in "mineral N fertilization")
NC normal control
ncRNA noncoding RNA
NF-κB nuclear factor kappa-light-chain-enhancer of activated B cells
Nrf2 nuclear factor erythroid 2–related factor 2
P/S ratio polyunsaturated/saturated fatty acid ratio
PDCD1 programmed cell death protein 1
PDGFRα platelet-derived growth factor receptor alpha
PF pair fed
pH 24LL pH of the longissimus lumborum (loin) muscle at 24 hours postmortem
PLF precision livestock farming
PM pectoralis major
PNMT phenylethanolamine-*N*-methyltransferase
PPARD peroxisome proliferator-activated receptor delta
PPARG peroxisome proliferator-activated receptor gamma
PRKAG3 protein kinase AMP-activated non-catalytic subunit gamma 3
PRLR prolactin receptor gene
PSE pale, soft, and exudative
PUFA polyunsaturated fatty acid
QTLs quantitative trait loci
R630/R580 ratio of reflectance at 630–580 nm (meat redness index)
RA rumenic acid
RFI residual feed intake
RFID Radio-frequency identification
RN *Rendement Napoléon* gene
RNA-seq RNA sequencing
ROS reactive oxygen species
Rx rotation rate on the *x*-axis
SAM sympathetic–adrenal medullary
SC365 scrotal circumference at 365 days
SCM subclinical mastitis
SF5 shear force measured at five days postmortem
SF_6 sulfur hexafluoride
SFA saturated fatty acid
SGA sweat gland area
SID Lys standardized ileal digestible lysine
SLW slaughter live weight
SNP single-nucleotide polymorphism
SOC soil organic carbon
SOD superoxide dismutase

SPS	silvopastoral systems
srWGS	short-read whole-genome sequencing
SV	structural variant
SVM	support vector machine
TCA	tricarboxylic acid (cycle)
TMR	total mixed ration
TNFRSF	tumor necrosis factor receptor superfamily
TSS	thermoregulatory efficiency
TVA	*trans*-vaccenic acid
USD	the United States dollar
WB	wooden breast
WGS	whole-genome sequencing
WN	Wagyu-by-Angus
WS	white striping
Wy	Wagyu
YBG	Yunnan black goat
ω-3 (n-3)	omega-3 fatty acids
ω-6 (n-6)	omega-6 fatty acids

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Part II

Meat Products and By-Products: Processing, Utilization, and Sustainable Innovation

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7

Application of HACCP and ISO22000:2018 in Meat and Meat Products (Salami) and Comparison with BRC and IFS in Conjunction with Other Risk Assessment Tools

Theodoros Varzakas

7.1 Introduction

According to the Organisation for Economic Cooperation and Development (OECD) and FAO, world meat production by 2023 will increase by 19% (57.7 million tons) (FAO, 2021; FAO-OECD, 2021).

The Hazard Analysis and Critical Control Points (HACCP) system appears as a solid and effective system for identification, evaluation, and control of food safety hazards throughout the production process (FAO-WHO, 2023; Arvanitoyannis, Varzakas and Tserkezou, 2009; Chavan, Paul and Nikhil, 2024).

The presence of environmental hazards creates significant obstacles in the establishment of comprehensive food safety systems. Environmental contaminants, including heavy metals, forever chemicals, radionuclides, and pesticide residues, make the monitoring and control of food safety risks very difficult (Baikadamova *et al.*, 2024; Moldagazyyeva *et al.*, 2022; Polivkina *et al.*, 2021).

Following Fukushima nuclear disaster in Japan, Bai, Yuan and Wang (2023) reported that local food industries utilized HACCP and achieved compliance with international safety standards in order to systematically monitor and control contamination risks in seafood and agricultural products.

Njoagwuani *et al.* (2023) suggested that implementation of HACCP could help address food safety challenges faced by vulnerable populations, such as children and the elderly.

The importance of the HACCP system in ensuring food safety and quality has been outlined in many studies, even in areas with ecological issues (Kvenberg *et al.*, 2000; Okpala and Korzeniowska, 2021; Reilly and Kaferstein, 1997). The effectiveness of HACCP in reducing foodborne illness outbreaks and improving product quality in various settings has been demonstrated (Awuchi, 2023; Kafetzopoulos, Psomas and Kafetzopoulos, 2013; Panisello *et al.*, 2000; Singha *et al.*, 2022).

At an international level, food standards, guidelines, and codes of practice are developed by the Codex Alimentarius[1] for an international food code recognized by the World Trade Organization (WTO). Australia, as a member of the WTO, is required, whenever feasible, to align its domestic standards with the Codex standards (Food Standards Australia New Zealand, 2024a, 2024b). Food safety risk management principles should be incorporated into relevant processing control to meet meat safety and suitability for consumption as reported by the International Code of Hygiene Practice for Meat (FAO-WHO, 2005).

A systematic science-based approach by a company needs to include a food safety plan and a comprehensive risk assessment and management tool needs to be included to identify biological, chemical,

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physical hazards, including allergens, and establish appropriate control measures for these hazards along the food chain system to ensure safe food production (FAO-WHO, 2020, 2023).

Seven principles comprise the HACCP system incorporating identification of reasonable hazards in each processing step in the verified process flow diagram for a product and effective control measures management for prevention or reduction and elimination of hazards to a safe level. Prerequisite programs (PRPs) or operational prerequisite programs (OPRPs), like good manufacturing practice (GMP) and good hygiene practice, can effectively control most of the hazards (Doménech, Amorós and Pérez-Gonzalvo, 2011); however, significant hazards require systematic management, as defined by the HACCP Plan.

Classification of the identified hazards is based on their significance according to a modified hazard risk assessment matrix that is based on the WorkSafe Risk Assessment Matrix (WorkSafe Victoria, 2022) and the Codex Alimentarius Commission principles of food risk analysis (FAO-WHO, 2023). Risk assessment is based on hazards evaluation by estimation of the likelihood of occurrence and the severity of potential consequences. However, the European Commission refers to Commission Notice 2016/C 278/01 on the implementation of food safety management systems covering prerequisite programs (PRPs) and procedures based on the HACCP principles, including the facilitation/flexibility of the implementation in certain food businesses.

There is a more recent notice also—2022/C 355/01—on the implementation of food safety management systems covering good hygiene practices and procedures based on the HACCP principles, including the facilitation/flexibility of the implementation in certain food businesses.

Historical incidents that have occurred in meat processing industries, as well as product recalls in global contexts, supplemented by scientific knowledge of the processes and meat products involved aid in the analysis of the likelihood of hazard occurrence (Pearson and Dutson, 2012). Mild discomfort to acute reactions or even fatal outcomes resulting from unsafe products are some of the adverse health effects on consumers (FAO-WHO, 2003). A risk score calculated by multiplying the likelihood and severity to indicate a significant hazard is the outcome of the process (Buchanan, 1997).

A successful HACCP strategy lies in the implementation of essential prerequisite programs (PrPs and OPrPs), adherence to GMPs, and the establishment of standard operating procedures (SOPs) (Hasnan *et al.*, 2022; Lee *et al.*, 2021, 2023).

7.2 Slaughterhouses

Adequate equipment or a plan for monitoring the temperatures applied in these processes is required for the heat treatment of viscera such as stomachs and small and large intestines, otherwise this might lead to a possible high bacterial load (Solanilla-Duque, Morales-Velasco and Salazar-Sánchez, 2024). The stages of elimination of legs, skin, and viscera, in the scalding process and in the quartering operations, show a high transmission of pathogenic agents and a higher frequency of microbiological contamination compared to chemical contamination, due to the high microbial load and inadequate handling (Buess *et al.*, 2019; Törmä, Fredriksson-Ahomaa and Lundén, 2019).

Other processing steps such as deboning and cutting might be contaminated if the environment in the operating areas is not suitable and unhygienic. *Salmonella* cases in slaughter plants in Switzerland and the United States show a strict control and it is the responsibility of food regulators in each country since foodborne illness outbreaks are derived from noncompliance with regulations. The risks of microbiological contamination, as observed in *Salmonella* outbreaks associated with poor practices in slaughter plants in Switzerland and the United States, increase following noncompliance with sanitation and quality control plans (Buess *et al.*, 2019; Li *et al.*, 2019; Muluneh and Kibret, 2015). Lack of compliance affects the shelf life of meat products and increases the risk of antimicrobial resistance (Ferri *et al.*, 2023; Waldman *et al.*, 2020).

The inadequate wastewater management in public animal slaughtering facilities (PASFs) allows the identification of a potential *Salmonella* outbreak. Thus, cases of meningitis, related to *Streptococcus*

suis in pork, outbreaks of salmonellosis and gastroenteritis, associated with *Salmonella* spp. in beef and chicken, can occur in PASFs, generating public health risks (Mohammed, Salih and Suliman, 2019; Kataria and Morey, 2020; Zwirzitz *et al*., 2019).

The EU reported 60,050 cases in 2021, primarily associated with pig products.

Foodborne pathogens persist, and their impact needs to be reduced by more coordinated efforts by governments and companies (Fasanmi *et al*., 2018; Wilhelm *et al*., 2011). In Thailand, a lower *Salmonella* contamination rate in pork (12.8%) was reported for HACCP-compliant slaughterhouses compared to noncompliant ones (36.7%) (Wu *et al*., 2019). Infected pigs might contribute to contamination at various slaughter stages with *Salmonella* being the culprit without symptoms (Muller *et al*., 2012). Fecal contamination and inadequate sanitation during evisceration contribute negatively (De Busser *et al*., 2013; Wheatley, Giotis and McKevitt, 2014).

Pork in HACCP-certified slaughterhouses had significantly reduced *Salmonella* contamination and antimicrobial resistance (AMR) compared to in non-HACCP facilities as reported by Saenkankam *et al.* (2025).

However, both types of slaughterhouses still experienced *Salmonella* contamination during the slaughtering process, not knowing enough on contamination sources and critical steps. The current study compared *Salmonella* distribution and AMR profiles in two Thai pig slaughterhouses, one of which implemented HACCP.

7.3 Case Study Meat Pate

Figure 7.1 shows the flow diagram for meat pâté "Phirmennyi" with the addition of meat and bone paste (MBP) from beef rib bones, covering each stage from raw material acceptance to the final storage of the product. The product also contains blanched pork fat, blanched beef liver, wheat flour, skimmed milk powder, chicken eggs, and spices.

7.4 Case Study 3D Printing Beef Pure

3D printing technology for meat processing has been widely employed recently. Novel meat products are being generated through food structure design. For example, minced meat and fat to mimic sensorial attributes of beefsteak have been used in crafting restructured meat products (Park, Lee and Kim, 2023). Other strategies include modification of mechanical and rheological structure of beef (Dick, Bhandari and Prakash, 2021b) and pork (Dick, Bhandari and Dong, 2020; Xu, Fan and Liu, 2023) products for textural changes in addressing special dietary needs, and enhanced nutritional composition of customized chicken products (Bulut and Candoğan, 2022; Dick and Yong, 2025; Wilson, Anukiruthika and Moses, 2021).

Dick, Bhandari, and Prakash (2021a) reported on the formulation of 3D-printed beef puree intended for dysphagia patients. Preparation of 1 kg of meat puree consists of 60 g of minced beef and 40 g of water for every 100 g of the mixture and dry ingredients (xanthan gum and salt, based on the ratio of meat and water mixture).

The process flow diagram (PFD) of a 3D-printed beef puree as described by Dick and Yong (2025) outlines the sequence from receiving raw materials to storage of finished products. The critical control points (CCPs) are indicated. The process starts from receiving raw materials, followed by storage of xanthan gum and salt at ambient temperature and minced meat in a cold room below 5 °C to inhibit microbial growth. Preparation of raw ingredients follows, including weighing and mixing all ingredients referring to the 1 kg of meat puree formulation. Pressure cooking at 80 kPa (12 psi) and 117 °C for 1 hour, cooling to less than 5 °C within 1 hour (step 4.2), and blending into a puree (all CCPs since temperature control, time, and pressure apply) then follow. Filling of the cooked beef puree into a stainless-steel cartridge for 3D printing (another CCP) is then carried out followed by freezing of the 3D-printed structures below −18 °C to preserve the shape before packaging (could also be considered a CCP). Vacuum-packaging of the frozen 3D-printed meat products follows, accompanied

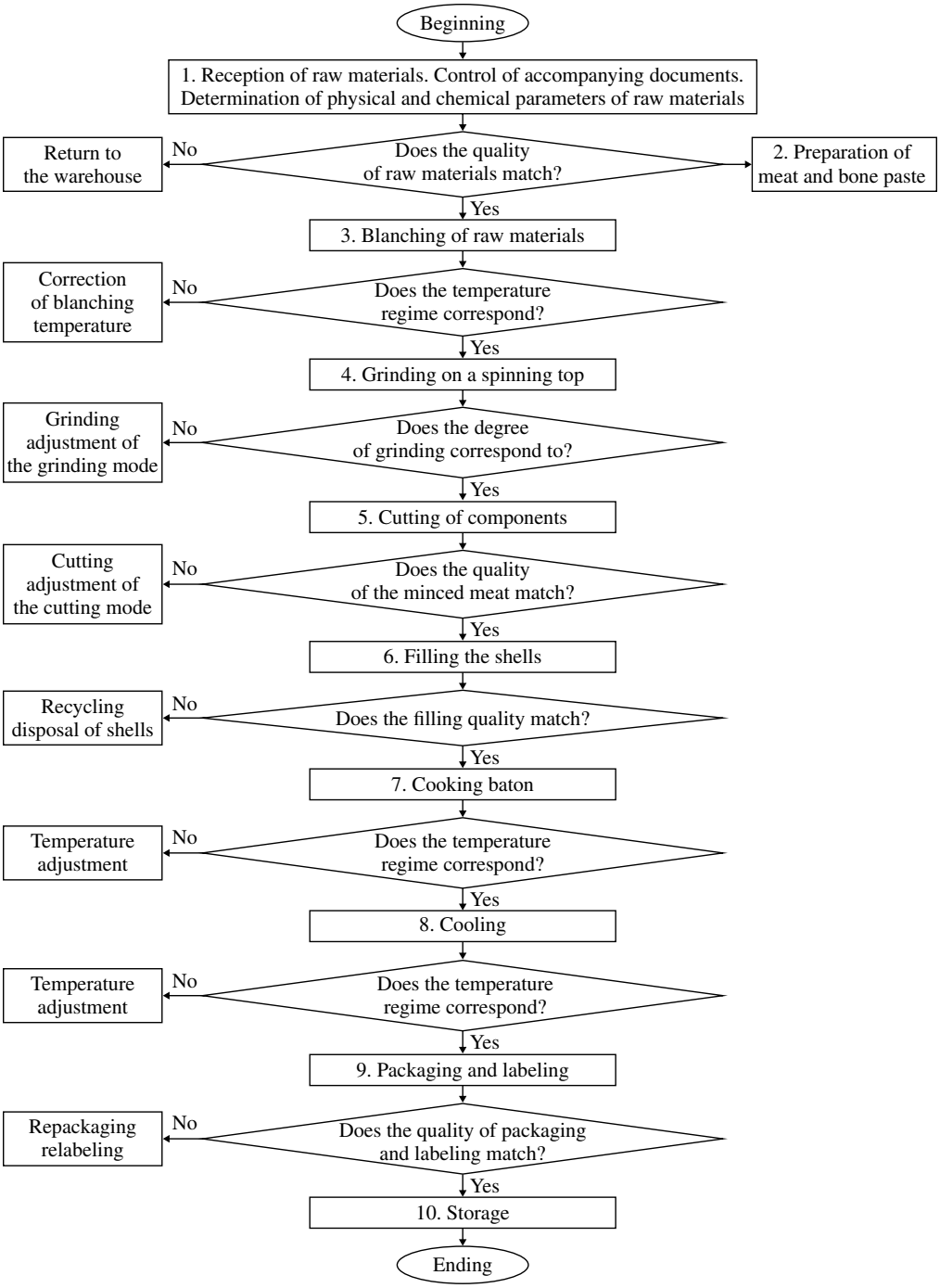

FIGURE 7.1 Flow diagram of meat pâté. (Baikadamova *et al.*, 2024.)

by metal detection, and labeling with ingredient list, storage conditions, and user instruction procedures. Metal detection and labeling are considered CCPs since metal fragments (a physical danger) can be detected. Removal of the products is carried out, and declaration of "may contain allergens" is shown. Finally, another CCP or OPrP might be the storage of the packed 3D-printed meat products below −18 °C.

7.5 Cultivated Meat

Cell culture technology produces cultivated meat, replicating the sensory and nutritional profile of conventionally produced meat, seafood, or organ meat (Powell *et al.*, 2025). Cell culture, stem cell biology, tissue engineering, fermentation, and bioprocess engineering are technologies encompassing cultivated meat (Specht *et al.*, 2018). Environmental parameters such as significantly lower land use, air pollution, and greenhouse gas emissions are those distinguishing cultivated meat production compared to conventional meat production (Sinke, Vergeer and Odegard, 2021, 2023; Tuomisto, 2019; Tuomisto, Allan and Ellis, 2022).

As reported by Sant'Ana *et al.* (2023), most cultivated meat manufacturers acquire cells from a healthy animal, and select them to develop a high-performing cell line. Cell lines are then grown into flasks and/or bioreactors to reach sufficient numbers to seed into large-scale bioreactors. At the same time, basic nutrients such as amino acids, glucose, salts, and vitamins are being added to a cell culture medium. Transformation of these cells into mature cells such as fat and skeletal muscle is then carried out. Then harvesting of these mature cells is being carried out followed by formulation, processing, and packaging (Sinke *et al.*, 2023).

Cultivated meat can be contaminated from animal-derived pathogens such as enteric zoonotic bacteria (e.g., pathogenic *Escherichia coli*, *Salmonella*, *Campylobacter*) leading to common foodborne illnesses. This compared to conventional meat production where European Food Safety Authority (EFSA) data indicate that conventional meat, seafood, and meat-based products were responsible for 24.4% of foodborne disease cases according to EU countries reports in 2017 (EFSA and ECDC, 2018).

Bioengineering Tools for Next-Generation Cellular Agriculture (CELLAG) project jointly funded by Singapore and Israel (Abdullah and Klein, 2023) reports on microbial contamination detection and novel antimicrobial compounds specifically for cultivated meat applications by sensors.

Similarly, in biopharmaceutical manufacturing, the use of sensors such as those for pH or other metabolites has been reported to achieve aseptic conditions through the design of bioreactors and operation under positive pressure (Ali *et al.*, 2020; Djisalov *et al.*, 2021).

Good meat specializing in this technology of cultivated meat production reports on particulate air (HEPA) filters of high efficiency, and differential air pressure similar to conditions of biopharmaceutical industry for controlled air quality and clean room processes (Licari, 2022).

7.6 Dry-Cured Meat

During maturation of dry-cured meat products ochratoxin A, a mycotoxin produced by *Penicillium nordicum* can grow at temperatures higher than 10 °C and a water activity (aw) of around 0.90 (Rodríguez *et al.*, 2024).

Legislation is the Commission Regulation (EU) 2023/915 of April 25, 2023, on maximum levels for certain contaminants in food and repealing Regulation (EC) No. 1881/2006 (European Commission, 2023), although OTA is not reported in meat products yet and is only reported in wine.

It is found in dry-cured ham (Bailly *et al.*, 2005) and fermented sausages as reported in studies with *P. nordicum* on dry-fermented sausages during their industrial ripening by Delgado *et al.* (2021).

The production processes of two smoked dry-cured hams and one unsmoked Norwegian specialty called *Fenalår* (dry-cured leg of lamb) were considered by Asefa *et al.* (2011). The only difference between the hams and *fenalår* production processes are the use of thawed meat and the absence of smoking in the latter case. According to the authors, the pressed meat are dipped in a brine solution (excess salt (NaCl and treated with curing salts like sodium nitrate ($NaNO_3$) at refrigeration temperature) before they go through smoking (cold smoking (20–30 °C), drying, washing, drying-ripening, sorting, and packing production processes, respectively.

In our flow diagram for curing and dry salting, whole muscle product (bone in or out) is evenly covered with salt. During curing, product is placed covered in the chiller ≤5 °C for designated period of time.

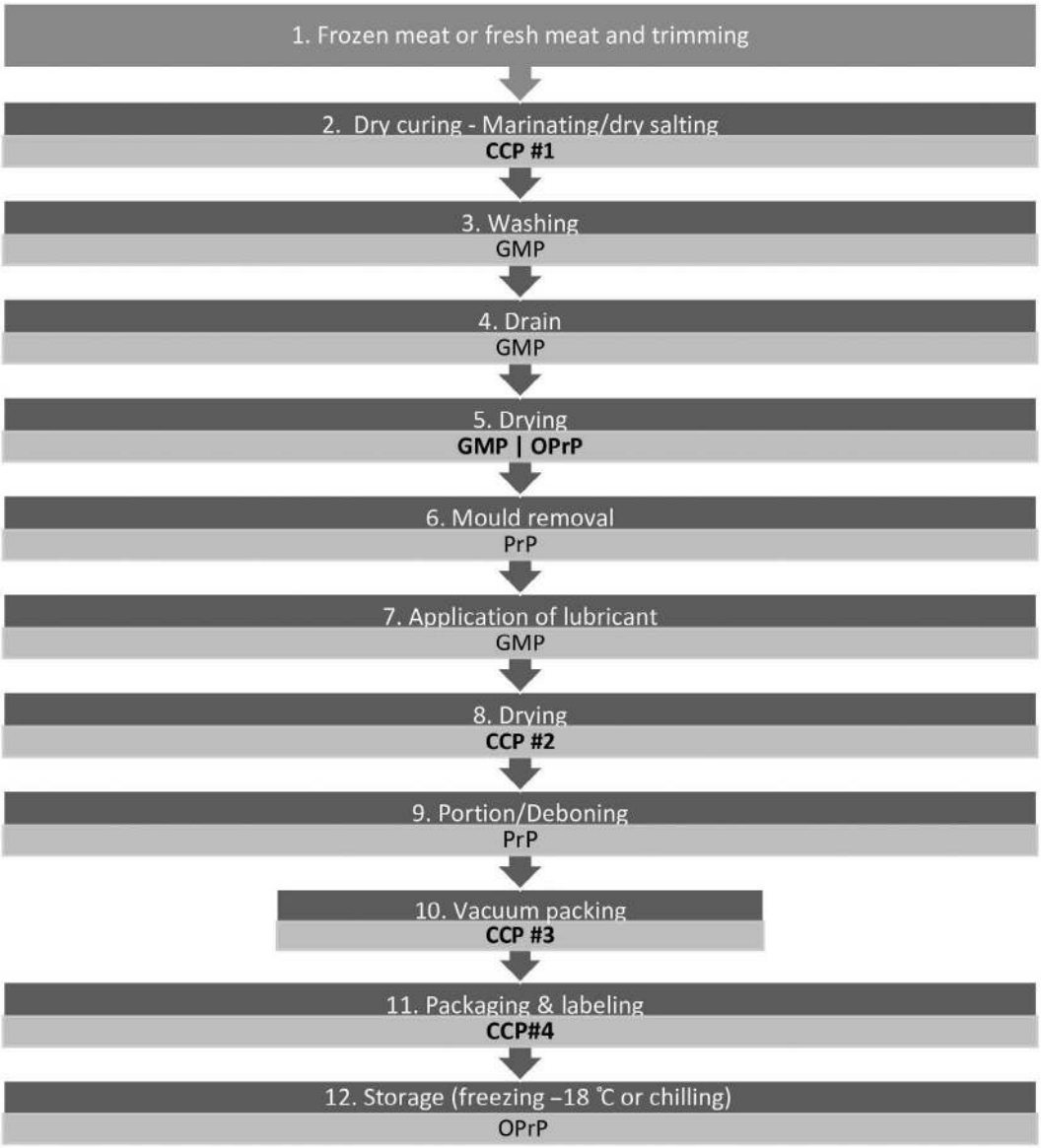

FIGURE 7.2 Flow diagram of dry-cured meat.

Product is vacuum packed when >40% weight loss from original weight is achieved (meeting required water activity limit of <0.92).

Drying is a critical step in ensuring product safety as it affects the microbiological and chemical aspect of the product.

The meat undergoes a carefully controlled and monitored surface drying process using air. Ripening process starts immediately after drying, but interrupted only by washing. During ripening process, dehydrating process continues while lipolysis and proteolysis are initiated responsible for sensory qualities (Toldra, 2002) of the products. The drying and ripening rooms at the production facility have a temperature range of 12–16 °C and a relative humidity of 70–80%.

Figure 7.2 shows a flow diagram of dry-cured meat.

Figure 7.3 shows the decision tree to identify CCPs.

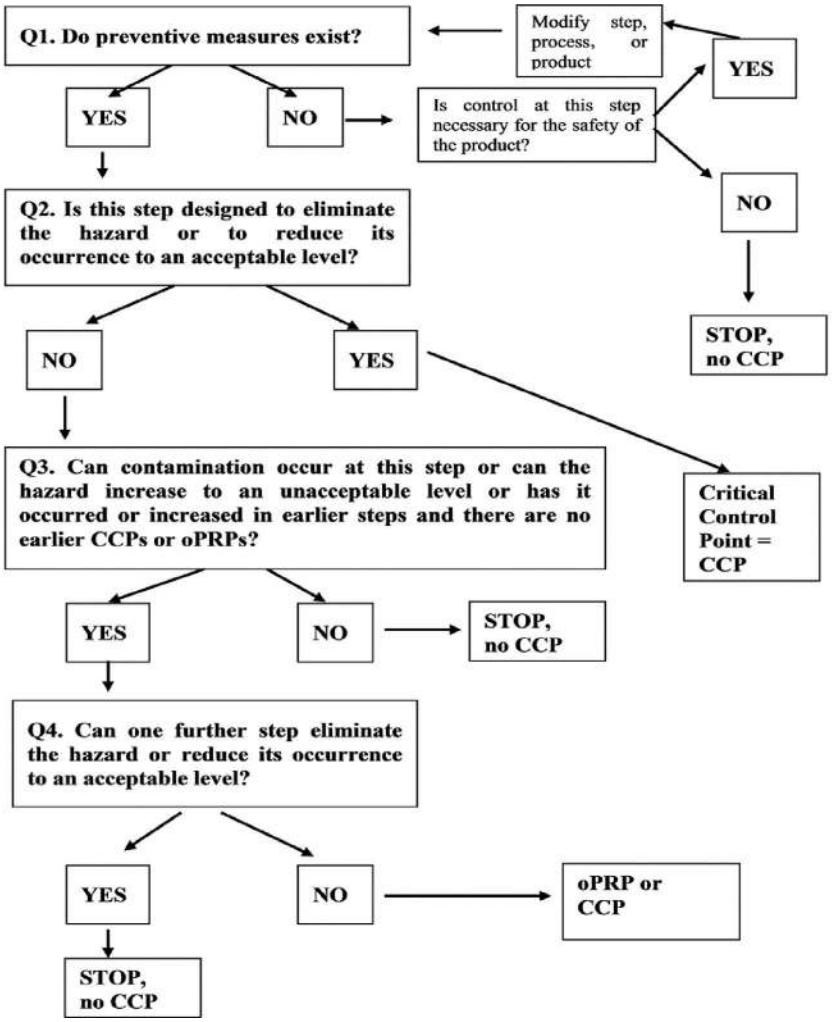

FIGURE 7.3 Decision tree to identify CCPs as shown in Appendix 3A Commission Notice on the implementation of food safety management systems covering prerequisite programs (PRPs) and procedures based on the HACCP principles, including the facilitation/flexibility of the implementation in certain food businesses (Official Journal of the European Union 2016/C 278/01).

Tables 7.1 and 7.2 depict hazard analysis and HACCP plan.
However, Table 7.3 to be taken into account refers to allergens.
A product description is always present (Table 7.4).

7.6.1 Validation of Control Measures

The hazard control–HACCP team must provide or ask for evidence that selected control measures are capable of achieving the intended control over the hazards identified beforehand.

The hazard control–HACCP team leader shall provide answers to the following questions:

- Have potential hazards been correctly identified as significant or not?
- Are applied control measures capable of reducing the significant hazards to acceptable levels?
- Are the critical limits correct and appropriate?
- Will the corrections/corrective actions restore product safety control?

TABLE 7.1

Hazard Analysis

Process Step	Hazard	Cause	Q1	Q2	Q3	Q4	Control Measures	CCP | OPrP	GMP | Support Program
1. Receiving of meats	Biological, chemical, and physical		Y	Y			Sampling and preventative control	CCP	✓
2. Curing	B: Pathogens (salt-tolerant *S. aureus*) at point of microbiological concern (surface)	Bacterial growth if salt is not evenly distributed or is at too low a level	Y	Y		–	• Apply correct amounts of salt and ensure it is evenly distributed over all meat surfaces while curing. • Product maintained ≤5°C under active refrigeration	CCP	
3. Washing	B: Microbiological contamination	Contaminated water used for washing Cross-contamination from unhygienic handling of product	Y	N	Y	Y	• Potable water source used for washing. • Use of PPE and or good hand sanitation when handling products. Keep raw and RTE products and equipment separate	**PrP**	✓
	P: Foreign matter	Foreign objects	Y	N	Y	Y	• Construction of wash area	**PrP**	✓
4. Draining	B: Growth of microorganisms	Bacterial growth if temperature and time allow Cross-contamination from unhygienic handling of product	Y	N	Y	Y	• Monitoring of temperature of meat during processing and time for no multiplication of microorganisms. • Use of PPE and/or good hand sanitation when handling products. Keep raw and RTE products and equipment separate.	PrP	✓
	P: Foreign matter	Foreign objects	Y	N	Y	Y	Construction of draining area	PrP	✓
Process Step	**Hazard**	**Cause**	**Q1**	**Q2**	**Q3**	**Q4**	**Hazard Control Measure**	**CCP | CP**	**GMP | Support Program**
5. Drying	B: Pathogens (salt-tolerant *S. aureus*)	*S. aureus* are potentially able to grow if moisture content remains high	Y	N	Y	Y	Ensure the environment is controlled for temperature and relative humidity	PrP	✓
7. Mold removal	B: Growth of microorganisms	Bacterial growth if temperature and time allow	Y	N	Y	Y	Monitor temperature of meat during processing and time in process does not allow multiplication of microorganisms	PrP	✓

8. Lubricant addition to cut surface	B: Microbiological contamination	Bacterial growth if temperature and time allow Cross-contamination from unhygienic handling of product	Y	N	Y	Y	• Monitor temperature of meat during processing and time in process does not allow multiplication of pathogens • Use of PPE and or good hand sanitation when handling products. Keep raw and RTE products and equipment separate.	PrP	✓
	C: Cross-contamination	Operator error with cleaning chemicals	Y	N	Y	Y	Suitable chemical storage and control and appropriate training for staff handling chemicals	PrP	✓
	P: Contamination	Foreign objects	Y	N	Y	Y	Compliant chiller construction	PrP	✓
9. Drying	B: Pathogens (salt-tolerant *S. aureus*)	*S. aureus* are potentially able to grow if moisture content remains high	Y	Y			• Ensure the environment is controlled for temperature and relative humidity. • Reduction of water activity and elimination of some pathogens and inhibition of others.	CCP	
10. Vacuum packaging	B: Growth of microbiological pathogen (*L. monocytogenes*) under vacuum packaging	Pathogen *L. mono* growth if product vacuum-packed water activity remains >0.92	Y	Y			Reduction of water activity to a level of (<0.92) which will inhibit growth of *L. monocytogenes.* Continue drying to achieve a water activity level of the finished product <0.92	CCP	
	B: Growth of microorganisms	Bacterial growth if temperature and time allow Cross-contamination from unhygienic handling of product Insufficient seal or vacuum	Y	Y			• Monitoring of temperature of meat during processing and time for no multiplication of microorganisms. • Use of PPE and/or good hand sanitation when handling products. Keep raw and RTE products and equipment separate. • Check seal and vacuum for sufficient application.		✓
11. Packaging and labeling	C: All ingredients, date marking, or warning statements not listed on packaging	Inadequate traceability and labeling of finished product	Y	N	Y	N	Mandatory information included on labels as per FSANZ Food Standards Code Section 1.2 Labeling and other information requirements	CCP/OPrP	
12. Storage	B: Cross-contamination	Cross-contamination from unhygienic handling and storage of product	Y	N	Y	N	Designated storage in segregated area protected from cross-contamination	OPrP	✓

Source: Adapted from PIRSA (2024).
Note: Hazard types—B: biological; C: chemical; P: physical.

TABLE 7.2

HACCP Plan

Step	Hazard	Critical Limit	Monitoring	Corrective Action	Records
Receiving	B, C, P	Regulations	Quality control in every batch-suppliers specifications	Return to suppliers if out of regulatory limits and out of agreed in-house specifications	
Curing CCP 1	B: Pathogens (salt-tolerant *S. aureus*)	Every surface coated in salt throughout curing Curing to occur under controlled environment at <5 °C	*What:* Surface salt coverage and room temperature *How:* Visual and refrigeration unit gauge *When:* Every batch *Who:* Trained operator	• Salt replacement at intervals during curing to ensure coverage and distribution. • Assess temperature of meat. If greater than 5 °C, move to another cold storage location if available. • Adjust room temperature setting for product to achieve ≤5 °C. Discard product if unable to maintain product temperature ≤5 °C. • Repair or replace refrigeration unit	Dry-cured meat processing record
Drying CCP 2	B: Growth of pathogenic bacteria	Controlled environment (Example: 10–15 °C and RH 75%)	*What:* Product *How:* Temperature and RH monitoring *When:* Every batch *Who:* Trained operator	• Failure in temperature or relative humidity, product placed on hold and assessed as per Work Instruction. • Assessment may include verification via product analysis for water activity. • Where the safety of the product is jeopardized or unable to be confirmed, the product is disposed off.	Dry-cured meat processing record
Vacuum packaging CCP 3	B: Growth of pathogen (*L. mono*) under vacuum packaging	Product is vacuum-packed when water activity of <0.92 is achieved—monitored by weight loss % from original weight (e.g. >40%) to achieve required water activity limit of <0.92. Weight loss requirement is determined via validated relationship between weight loss and water activity	*What:* Product weight loss % calculation *How:* Test piece weight using calibrated scales *When:* Every batch *Who:* Trained operator	• Do not vacuum-pack product. • Continuing drying product until weight loss % requirements are met to achieve water activity limit of <0.92	Dry-cured meat processing record
Labeling CCP 4	C: All ingredients, date marking or warning statements not listed on packaging	Correct mandatory labeling, including date marking, applied to finished products	*What:* Label applied to product	• Hold of product with incorrect labels. Removal of labels where labeling details are incorrect or inaccurate. • Discard of incorrect labels, application of correct details to product. • Inspection of all previous products from the batch for compliance and corrective action taken if found to be incorrect/inaccurate. • Disposal of all noncomplying and used packaging and not reuse. • Release product for dispatch once correct labels have been applied and verified	Dry-cured meat processing record

Source: Adapted from PIRSA (2024).

TABLE 7.3

Hazardous Agents, Including Allergens and Class of Hazard

A. Hazardous Agents	B. Hazard Class
Biological (pathogenic microorganisms, vegetative or spores, depending on circumstances)	B
Chemical (residues from cleaning chemicals, non-food-grade lubricants, oils and greases, and chemical residues)	C
Physical (foreign material, including metal, wood, plastic, or other foreign bodies)	P
Allergens (milk, soy, wheat, eggs, fish, shellfish, tree nuts, peanuts)	A

TABLE 7.4

Product Description for Dry-Cured Meat

Product Description	
Product and ingredient description	
Dry-cured meat	
End product characteristics	
Name (product, product group, line)	
Composition	
Type (e.g., raw, cooked, ready to eat)	
Key chemical, biological, and physical characteristics	
Key processing steps (e.g., drying, heat treatments, freezing)	Salting/curing, drying
Other	
Specifications and regulatory requirements (food safety related)	
Product specifications	
Product-specific regulatory requirements	
Filling and packing	
Packaging description (e.g., size)	
Packaging system (e.g., modified atmosphere)	Plastic covering as primary packaging Clean cartons as secondary packaging
Claims and label information	Labels to include: • Product name • Accredited business • Business address and contact details • Directions for use and storage conditions • Packaging date • Use by date (may include batch identification) • Advisory statement/warning (e.g., allergens) • Ingredient information (as per recipe) • Nutrition information • Country of origin
Instructions for use by consumers (including use or storage after opening)	
Statements for safe use (e.g., allergen information, special instructions for safe handling)	
Other	

(Continued)

TABLE 7.4 ***(Continued)***

Product Description for Dry-Cured Meat

Product Description	
Distribution/storage/description	
Distribution instructions (ambient, chilled, frozen, and so on)	
Storage instructions (ambient, chilled, frozen, and so on)	
Shelf life conditions	
Other	
Use by consumers	Ready to eat (RTE), further processing not required prior to consumption
Intended use	
Target group of users and special consumer considerations (e.g., infants, the elderly)	
Reasonably expected mishandling and misuse	
Incoming material characteristics	
Name of raw materials, ingredients	
Composition	
High-risk ingredients	
Key chemical, biological, and physical characteristics	
Supplier	
Processing: Main steps and conditions (production method)	
Packaging and transportation containers	
Storage conditions and shelf life	
Preparation or processing before use	
Acceptance criteria related to safety	
Other (e.g., preservatives, processing aids, services)	

7.7 Dry-Cured Pastrami or Pasturma

According to the Egyptian recipe described by El-Mougy *et al.* (2023), dry-cured pastrami consists of the following ingredients: meat cut (*Longissimus dorsi* muscle of frozen beef meat cuts), additives (table salt [7%]; sodium nitrite [100 ppm], ascorbic acid [550 ppm]; spices; brown sugar; molasses), seasoning paste constituents (Fenugreek [*Trigonella foenum graecum*]; garlic; hot and sweet pepper puree; rosemary and nutmeg extract; spices; water for mixing).

Dry-cured pastrami manufacturing steps have been implemented according to Aksu, Dogan and Sirkecioglu (2017) and Kaban (2013), involving dry-curing mixture addition: two rounds of drying, pressing, and covering with seasoning paste and final drying achieved at <15 °C, 70% RH for 2 days, <18 °C, 65% RH for 2 days, <20 °C, 60% RH for 4–5 days.

7.8 Low-Fat Meat Patties

Microbial threats like *Salmonella* spp. and *E. coli* constitute significant risks in meat products, including low-fat meat patties, leading to severe foodborne illnesses (Atambayeva *et al.*, 2022; Bantawa *et al.*, 2018; Pratiwi *et al.*, 2023; Rana *et al.*, 2019).

Low-fat meat patties are manufactured as below.

Veal and rabbit meats undergo slicing, deboning, and trimming, while rabbit liver is thoroughly being cleansed. Mincing of the prepared patty meat then follows using a meat grinder, to which milk thistle

meal and mélange are introduced. Finely diced white onion, milk, salt, and pepper are added to the mixture and mixed thoroughly. The patty mixture is then shaped into round, flattened forms and coated in breadcrumbs to produce the final product. Finally, freezing at –30 °C is the last stage before storage at –18 °C (Spanova *et al.*, 2025).

The temperature of the minced meat should not exceed 12 °C. Mixing, forming, and freezing conditions should include monitoring of temperature control and hygiene practices, for prevention of contamination and assurance of product's integrity. During processing, temperature of the meat should be maintained as low as possible to inhibit bacterial growth, and freezing should be rapid for texture and nutritional value preservation. The precision in measuring spice quantities and their freshness and quality affects the safety and sensory attributes of the final product. Moreover, mincing rapidly disperses any surface contaminants throughout the entire mass of meat, hence handling cutting are particularly critical. It also leads to a rise in temperature, facilitating rapid bacterial proliferation (Qiu *et al.*, 2022).

7.9 Salami

The transportation of raw materials (meat, dry ingredients, starter cultures, water, salt, cases, clips, etc.) used in the production process must be carried out with special vehicles that meet all the specifications for the transportation of food. They must be completely sterile and special care must be taken to ensure that there is no contamination from other materials that may be transported at the same time. The quality manager checks the necessary quality and analysis certificates of suppliers, the integrity of the packaging, and the temperature at which the materials are received, especially perishable materials (e.g., pork and pork fat).

The materials are stored in both dry cargo areas (ambient temperature) and at freezing temperature, and the risk of the development of microorganisms from storage at high temperatures is high.

- Meat temperature: –18 °C
- Store immediately in the freezer at the same or lower temperature
- Slaughterhouse pH control (5.8 < pH <6.2)

As for the fat:

- Low content of unsaturated fatty acids (skinless lard)
- During receipt and processing: –12 °C, –13 °C

When mixing the ingredients, the staff must be careful both in following the recipe and in applying the general principles of hygiene as defined in the requirements of GMPs.

- *Dry ingredients*: sterilized in aseptic packaging
- *Spices*: certified for sterilization that they have undergone
- Black pepper, cumin, and dried garlic that give desired flavor and aroma
- *Nitrates—Nitrites*: Certified for 99% purity, are preservatives, which participate in fermentation and drying, giving the attractive red color. In addition, ascorbic acid and sugars could be added.
- *Starter cultures*: Lyophilized form with reconstitution taking place before use
- *Water*: Chlorinated tap water
- *Salt*: Certified for high purity and free of heavy metal salts

Cases: Sterilized in aseptic packaging and must allow moisture to be removed during drying and could be natural.

7.9.1 Storage-Thawing

- *Meat, fat*: At a temperature of –18 °C
- *Meat thawing*: With continuous water flow until its temperature reaches –3 °C, –2 °C in a refrigerated area

Quick freezing is one of the most critical points in the production process. The freezing of the product must be done in a short period of time so that the temperature in the center of the product is less than –15 °C. During packaging, it is possible for the product to be contaminated by pathogenic microorganisms. This can be avoided by hermetically sealing the products so that the contents do not come into contact with the outside environment. The materials used for packaging must be suitable for contact with food and the suppliers must, as in the case of the raw materials, be certified. Also, the packaging boxes must be suitable for freezing.

7.9.2 Cutting and Grinding

Meat and fat: Grinding into small pieces (rice size).

To avoid emulsion formation, the meat is ground first and then the fat

Weighing–mixing of ingredients is the next stage where weighing of meat and other ingredients and gentle mixing of the mixture is carried out to avoid protein extraction and emulsion formation.

Mixing of ingredients is affected by the uniformity of temperature.

Casing follows by adding the mixture in sterile cases with a special machine that places plastic clips to separate each piece.

7.9.3 Product Immersion in Sanitizing Liquid

The "sticks" are immersed in a potassium sorbate solution (preservative) to prevent the growth of fungi on the outer surface.

7.9.4 Hanging/Fermentation/Wet Smoking

The pieces are transferred to a room with controlled temperature and relative humidity

Temperature: 22 °C, RH: ~95%

In three days: pH <5

Wet smoking is applied on the third day of fermentation.

7.9.5 Fermentation

The microbial phenomenon in which starter cultures convert sugars into lactic acid, resulting in a decrease in pH (pH <5.3).

7.9.6 Starter Cultures

Lactobacilli, *Pediococci*, and *Micrococci*

They perform proteolysis and the metabolism contributes to the good taste.

7.9.7 Maturation/Drying

During maturation, the room must have a temperature of

10–15 °C and RH: 68%–72%

Stage 1

Stay in the maturation chamber for 7 days → gradual decrease of humidity and T

Stage 2

The goal is aw <0.90

Shelf-stable → complete maturation

The next stage is the existence of a metal detector, which is required because it is one of the main means of controlling the product that will be made available to the customer and gives us the opportunity to eliminate some risks (e.g., metal objects) from previous stages.

7.9.8 Packaging

Vacuum Air

Removal of air and creation of negative pressure → vacuum

Prevention or slowing down the growth of aerobic microbes

The storage of the final product on pallets is done in a refrigerated environment at a temperature of 2–4 °C, where it remains until loading into special refrigerated vehicles and transporting it to the points of sale. During its transport, the temperature is continuously recorded.

Figure 7.4 describes the flow diagram process of salami production. Start and end of the process are ellipsoid, whereas metal detection has a decision process represented by a diamond shape.

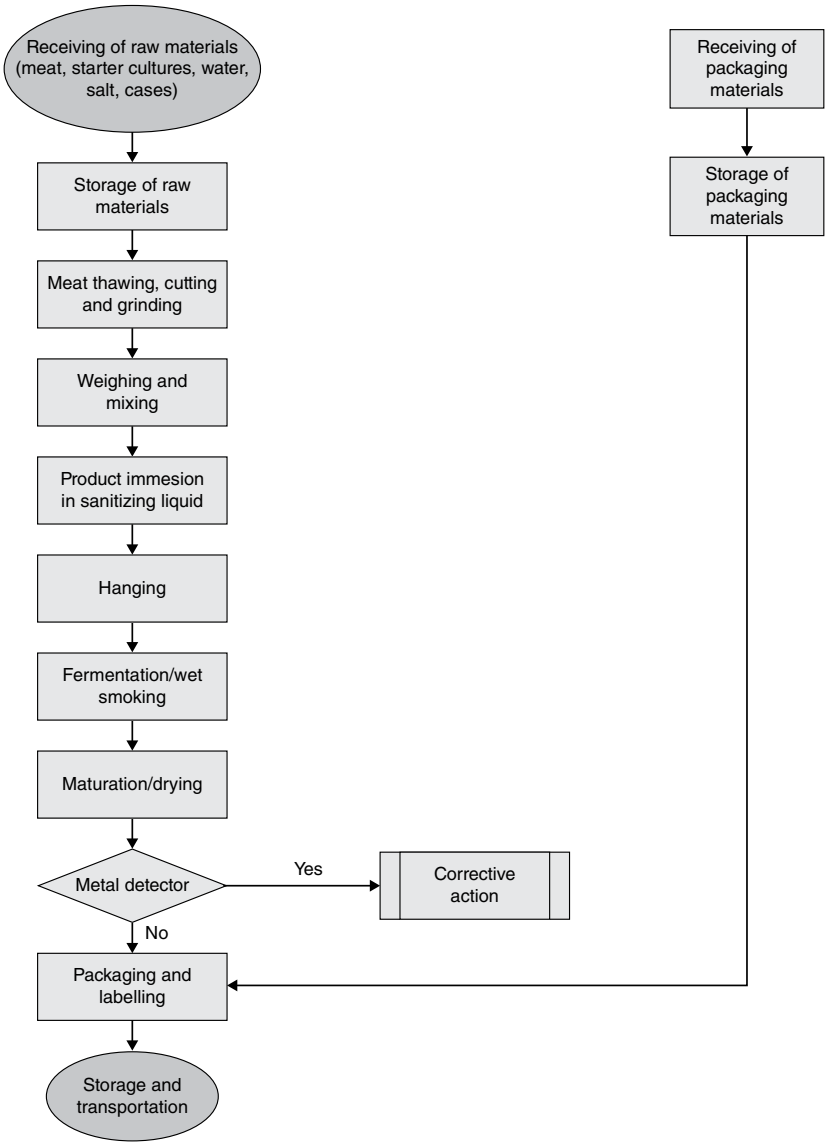

FIGURE 7.4 Flow diagram of salami processing.

TABLE 7.5

HACCP Plan (Hazard Identification and Control Measures) for Salami Manufacturing

No.	Processing Stage	Hazards	Control Measures
1	Receiving of raw materials	• Foreign bodies (P) • Contamination with pathogens due to damaged packaging (B) • Contamination with chemicals due to damaged packaging (C)	• Agreed specifications/list of approved suppliers • Organoleptic control • Visual inspection (product, means of transport) • Product/means of transport temperature control • Expiry date control
2	Storage under freezing	• Pathogen growth due to inappropriate temperature and/or poor stock management (expiry date has passed) (B)	• Time and temperature control • Refrigeration systems maintenance
3 and 4	Weighing-mixing	• Contamination with pathogens from personnel • Contamination with pathogens from equipment • Contamination with *C. botulinum* due to lack of nitrates • Introduction of foreign bodies from the environment/equipment/personnel	• GMP • adherence to equipment cleaning/disinfection schedule • Adherence to equipment cleaning/disinfection schedule • Adherence to good practice for foreign bodies (glass, metal, plastics, etc.)
5	Casing	• Introduction of foreign bodies from the environment/equipment (plastic clips)/personnel • Contamination with pathogens from nonsterile cases	• GMPs • Maintaining an equipment cleaning/disinfection schedule
6	Immersion in sanitizing liquid	• Chemical contamination with excess potassium sorbate	• Control of the correct amount of sorbates
7	Fermentation-wet smoking	Pathogen growth due to insufficient pH drop in the required time	*T*: 22 °C, RH: ~95% In three days: pH <5 –
8	Maturation-drying	Insufficient drop in aw leads to growth of pathogens	*First stage:* Stay in the maturation chamber for seven days → gradual decrease in humidity and temperature *Second stage*: Target a_w <0.90 –
9	Metal detector	Nonrecognition of metal objects by the detector	GMPs calibration
10	Packaging–labeling	• Contamination with pathogens from staff • Contamination with pathogens from equipment • Chemical contamination with residues of cleaning/disinfection materials due to inadequate cleaning/disinfection process of equipment • Introduction of foreign bodies from the environment/equipment/personnel	• Compliance with good hygiene practices for staff • Compliance with equipment cleaning/disinfection program • Compliance with good practices for foreign bodies (glass, metal, plastics, etc.)
11	Storage under chilling	Chemical contamination with cleaning/disinfecting material residues due to inadequate equipment cleaning/disinfection process	Checking temperature recorders Maintaining equipment cleaning/disinfection schedule

Table 7.5 shows a HACCP plan (hazard identification and control measures) for salami manufacturing.

Table 7.6 also shows traditional meat processing referring to CCPs, hazards, storage temperature, and packaging.

Table 7.7 also refers to risk assessment according to Commission Notice on the implementation of food safety management systems covering prerequisite programs (PRPs) and procedures based on the HACCP principles.

TABLE 7.6

Traditional Meat Processing

Product	Packaging	Storage Temperature	CCP	Hazards	References
Raw, nonintact beef (e.g., ground beef, beef patties, jalapeno cheddar burgers, tenderized steaks, and cubed (tenderized) steaks	Plastic chubs, tray packages, vacuum sealed packages or in butcher paper	Refrigeration (≤4 °C) or freezing (≤12 °C)	organic acid application and product temperature)	Presence and outgrowth of pathogens	U.S. Department of Agriculture (2020, 2021)
Cooked and cured sausages	Stuffed in collagen casings and packed under vacuum or in modified atmosphere	Keep refrigerated (≤4 °C)	Heat processing and cooling down	Presence, survival, and thermotolerant bacteria or spores growth	Arvanitoyannis and Varzakas, 2009; Metaxopoulos, Kritikos and Drosinos, 2003
Cooked and cured meat products (e.g., cooked ham and cooked bacon	Stuffed in casings or nets and packed under vacuum or in modified atmosphere	Refrigeration (≤4 °C)	Thawing, heat processing, and cooling	Proliferation, presence, survival, and growth of thermotolerant bacteria or spores potentially present	Metaxopoulos *et al.*, 2003

A comparison between IFS and BRC has been outlined in Tables 7.8 and 7.9.

Another risk assessment process is that of threat assessment and TACCP (threat assessment critical control point) (Figure 7.5). Evaluation of threats, identification of vulnerabilities, and implementation of controls with respect to materials and products, purchasing, processes, premises, distribution networks, and business systems are carried out for the systematic management of risk with the aim to implement changes in procedures.

Process outline for assessing threats, vulnerabilities, and risk, plus risk assessment rating system need to be shown. Moreover, categories of threats relevant to the site with examples need to be presented.

One of the major guiding documents of TACCP is the PAS 96: 2014, originally developed in 2008 by the Centre for the Protection of National Infrastructure, in consultation with Heinz, Kellogg, and Kraft as well as the Food Standards Agency, the National Farmers Union, and the Food and Drink Federation, and retailers such as Sainsbury's, Tesco, and Marks & Spencer. At the 2013 Global Food Safety Initiative (GFSI) conference in Barcelona, the Food Standards Agency discussed the identification of future food safety risks referring to TACCP, PAS 96, and the need to look for threat points, hazard points, and value points in the process and demand of safe and quality food.

More specifically, some other definitions need to be mentioned.

Food defense refers to adopted procedures for assurance of safety and security of food and drink and associated supply chains from malicious and ideologically motivated attack leading to contamination or supply disruption.

Food fraud involves deliberately placing food on the market, for financial gain, with the intention of deceiving consumers. There are many sorts of food fraud, but the main types are as follows;

a. Selling food that is unfit and potentially harmful
b. Recycling animal by-products back into the food chain
c. Packing and selling beef and poultry of unknown origin
d. Knowingly selling goods that are past their "use by" date.

TABLE 7.7

Risk Assessment According to Commission Notice on the Implementation of Food Safety Management Systems Covering Prerequisite Programs (PRPs) and Procedures Based on the HACCP Principles, Including the Facilitation/Flexibility of the Implementation in Certain Food Businesses (2016/C 278/01) Applying Probability and Severity Values as Described in Appendix 2

Αρ.	Processing Stage	Danger	Probability	Explanation for Probability	Effect or Severity	Explanation for Severity	Risk Level	Significance	Control Measures	Initial Categorization	Final Categorization	Final Categorization
1	Receiving of raw materials (meat, fat)	Microbiological growth of pathogenic microorganisms (*E. coli*, *Salmonella*, *S. aureus, L. monocytogenes*, *C. botulinum*) -Multiplication from wrong temperature Contamination from personnel	3	PROBAB_3—The ineffectiveness or lack of specific control measure does not imply the systematic presence of the hazard in the final product, however, the hazard may be present in a certain percentage of the final product in the corresponding batch	3	SEVERITY_3—Serious injuries and/or serious symptoms are not caused or are only caused after exposure to extremely high levels of concentration over a long period of time	5	5	Raw material specifications within limits • Supplier suitability certificate • Raw material receipt control • Sporadic laboratory testing of the final product Temperature control—χρόνου (*E. coli*, *Salmonella*, *S. aureus*, *L. monocytogenes*) • Implementation of hygiene rules (*E. coli*, *Salmonella*, *S. aureus*, *L. monocytogenes*) • GMP (*E. coli*, *Salmonella*, *S. aureus*, *L. monocytogenes*) • Implementing a proper cleaning and disinfection program (*E. coli*, *S. aureus*, *L. monocytogenes*) • Visual inspection of foreign matter GMP, GHP	oPRP/CCP	Oprp/ccp	Raw material specifications, legislation/ bibliography

2	Receiving of nitrates–nitrites	Foreign matter	3	PROBAB_3—The ineffectiveness or lack of a specific control measure does not imply the systematic presence of the hazard in the final product; however, the hazard may be present in a certain percentage of the final product in the respective batch	3	SEVERITY_3—Clear health impact with short-term or long-term symptoms that rarely lead to death (e.g., gastroenteritis)	5	3	• Supplier Certificate of Conformity for 99% Purity • Visual Inspection, GMP, GHP	oPRP/CCP	oPRP	Raw material specifications, legislation / bibliography
3	Receiving of starter cultures	Chemical residues	1	PROBAB_1—This is followed by the next stage in the production process that will eliminate or reduce the risk to an acceptable level (e.g., pasteurization, fermentation)	2	SEVERITY_2—Serious injuries and/or symptoms are not caused or are only caused after exposure to extremely high levels of concentration over a long period of time	2	2	Raw material specifications within limits • Supplier qualification certificate • Raw material receipt control—Sporadic laboratory testing of the final product	PRP	PRP	Raw Material Specifications, Legislation / Bibliography
4	Receiving cases	Foreign materials	2	PROBAB_2—The probability of the risk appearing in the final product, due to ineffectiveness or absence of prerequisite programs, is very limited	3	SEVERITY_3—The risk has a long-term impact; the maximum dose is not known	4	4	• Supplier qualification certificate • Visual inspection, GMP, GHP	PRP/oPRP	oPRP	Raw material specifications, legislation / bibliography

(Continued)

TABLE 7.7 ***(Continued)***

Risk Assessment According to Commission Notice on the Implementation of Food Safety Management Systems Covering Prerequisite Programs (PRPs) and Procedures Based on the HACCP Principles, Including the Facilitation/Flexibility of the Implementation in Certain Food Businesses (2016/C 278/01) Applying Probability and Severity Values as Described in Appendix 2

Aρ.	Processing Stage	Danger	Probability	Explanation for Probability	Effect or Severity	Explanation for Severity	Risk Level	Significance	Control Measures	Initial Categorization	Final Categorization	Final Categorization
5	Water	Contamination	1	PROBAB_1—It is extremely limited and/or involves local infection	3	SEVERITY_3—The risk has a long-term impact; the maximum dose is not known (e.g., dioxins, pesticide residues, mycotoxins, etc.)	3	2	• Water quality analyses once a year	PRP/oPRP	PRP	Legislation / bibliography
6	Fermentation-cold smoking, ($T < 22$ °C)	Growth of pathogenic microorganisms (*E. coli*, *Salmonella*, *S. aureus*, *L. monocytogenes*) Contamination from poor handling by personnel Growth of microorganisms from incorrect product temperature	2	PROBAB_2—Pathogen growth due to insufficient pH drop in the required time)	2	SEVERITY_2—The risk can in no case reach dangerous levels (e.g., dyes, *S. aureus* in frozen foods, in which an increase in levels is very unlikely to occur or cannot occur due to storage and cooking conditions)	3	3	• Implementation of hygiene rules (*E. coli*, *Salmonella*, *S. aureus*, *L. monocytogenes*) • GMP (*E. coli*, *Salmonella*, *S. aureus*, *L. monocytogenes)* • Implementing a proper cleaning and disinfection program (*E. coli*, *L. monocytogenes)* • Control of fermentation chamber conditions (T °C and RH), measurement of vitality of starter cultures pH < 5 in 3 days	oPRP	oPRP	

7	Maturation-drying ($T < -15$ °C)	Growth of pathogenic microorganisms (*E. coli*, *Salmonella*, *S. aureus, L. monocytogenes*) Multiplication from incorrect room temperature Contamination from poor personnel handling	3	PROBAB_3—The ineffectiveness or lack of a specific control measure does not imply the systematic presence of the hazard in the final product, however the hazard may be present in a certain percentage of the final product in the respective batch.	2	SEVERITY_2—Serious injuries and/or serious symptoms are not caused or are only caused after exposure to extremely high levels of concentration over a long period of time.	4	4	• Time temperature control (*E. coli*, *Salmonella*, *S. aureus*, *L. monocytogenes*) • Hygienic control. (*E. coli*, *Salmonella*, *S. aureus*, *L. monocytogenes*) • GMP (*E. coli*, *Salmonella*, *S. aureus*, *L. monocytogenes*) • Implementing a proper cleaning and disinfection program (*E. coli*, *S. aureus*, *L. monocytogenes*)	oPRP	oPRP	
									• Visual inspection of foreign matter GMP, GHP *Stage A:* Stay in the maturation chamber for seven days leading to gradual drop in humidity and T *Stage B:* Target is aw <0.90. Control of drying chamber conditions (T °C and ERH) Monitoring the size of fat and meat particles during grinding			
8	Packaging	Growth of pathogenic microorganisms (*E. coli*, *Salmonella*, *S. aureus*, *L. monocytogenes*). Multiplication by incorrect temperature of product	2	PROBAB_2—The probability of the risk appearing in the final product, due to ineffectiveness or absence of prerequisite programs, is very limited.	1	SEVERITY_1—The risk can in no case reach dangerous levels (e.g., dyes, *S. aureus* in frozen foods, in which an increase in levels is very unlikely to occur or cannot occur due to storage and cooking conditions)	2	2	• Room/product temperature control (*E. coli*, *S. aureus*, *L. monocytogenes)* • Hygienic control. (*E. coli*, *Salmonella*, *S. aureus*, *L. monocytogenes*) • GMP (*E. coli*, *Salmonella*, *S. aureus*, *L. monocytogenes*) • Visual inspection for foreign matter • Label check GMP, GH	PRP	PRP	

(Continued)

TABLE 7.7 ***(Continued)***

Risk Assessment According to Commission Notice on the Implementation of Food Safety Management Systems Covering Prerequisite Programs (PRPs) and Procedures Based on the HACCP Principles, Including the Facilitation/Flexibility of the Implementation in Certain Food Businesses (2016/C 278/01) Applying Probability and Severity Values as Described in Appendix 2

Aρ.	Processing Stage	Danger	Probability	Explanation for Probability	Effect or Severity	Explanation for Severity	Risk Level	Significance	Control Measures	Initial Categorization	Final Categorization	Final Categorization
9	Metal detection	Metal residues in the final product due to damaged equipment or raw materials	3	PROBAB_3—The ineffectiveness or lack of specific control measure does not imply the systematic presence of the hazard in the final product, however, the hazard may be present in a certain percentage of the final product in the corresponding batch	3	SEVERITY_3—Clear health impact with short-term or long-term symptoms that rarely lead to death (e.g., gastroenteritis)	5	5	• Metal detector or X-ray detection, frequent periodic check of the detector's proper operation with standard pieces	CCP	CCP	1.5 mm ferrous, 2.0 mm nonferrous, 2.5 mm stainless steel
10	Storage, transportation/ distribution ($T < 4$ °C)	Growth of pathogenic microorganisms (*E. coli*, *Salmonella*, *S. aureus*, *L. monocytogenes*) Multiplication from incorrect room temperature	3	PROBAB_—The ineffectiveness or lack of specific control measure does not imply the systematic presence of the hazard in the final product; however, the hazard may be present in a certain percentage of the final product in the corresponding batch	3	SEVERITY_3—Clear health impact with short-term or long-term symptoms that rarely lead to death (e.g. gastroenteritis)	5	5	• Chamber temperature control (*L. monocytogenes*)	oPRP/CCP	oPRP or CCP	A critical limit can be set at which the temperature will be monitored

Categorization of control measures in PrPs, OPrPs, and CCPs.

TABLE 7.8

Similar Requirements for BRC, IFS

Similar Requirements
Documents
HACCP plan
HACCP team
Corrective actions
HACCP documentation and record keeping
Product development
Walls, floors, ceilings, windows, doors, lighting, air condition/ventilation
Air/gas
Waste
Transport
Process validation and control/calibration, control of measuring and monitoring devices
Deviations, nonconformities, corrections, and corrective actions

TABLE 7.9

Synoptic Table for Different Requirements of IFS and BRC

Chapter	IFS 8	BRC 9
Policy	Report on sustainability	
Food safety culture	No defined plan	Culture plan with specialized requirements reviewed at least annually
Objectives	No time defined	Four times per year
Structure	For any change of name of a legal entity or any change of production location, the organization is notified within three working days	Report on authenticity legality Substitute in the organization chart in case of absence
Management review meetings	Not exceeding 15 months	At least annually
Meetings of food safety team	Not reported	At least monthly
Food safety and quality management system	Not reported	Manual
Describe products	Not reported	Origin of ingredients
Flow diagram	Not reported	Certain requirements
Conduct hazard analysis	Not reported	Validation and verification of PrPs
Critical limits	Not reported	Measurable limits (where permitted) and if subjective, provide evidence, for example, photographs
Monitoring system for CCPs	Not reported	Monitoring records of CCP should be signed
Training	Trainer report	
Staff facilities	Not reported	Smoking facilities outside
Factory location, exterior, layout	Annual review	Production risk zones
Water	Risk-based sampling plan	Annual or according to regulation
Cleaning/disinfection	Risk based	
Foreign material and chemical risk mitigation	Metal and/or other foreign body detector maintenance at least once a year	More specific metal detector tests
Internal audits	Risk based	At least four during the year spread equally

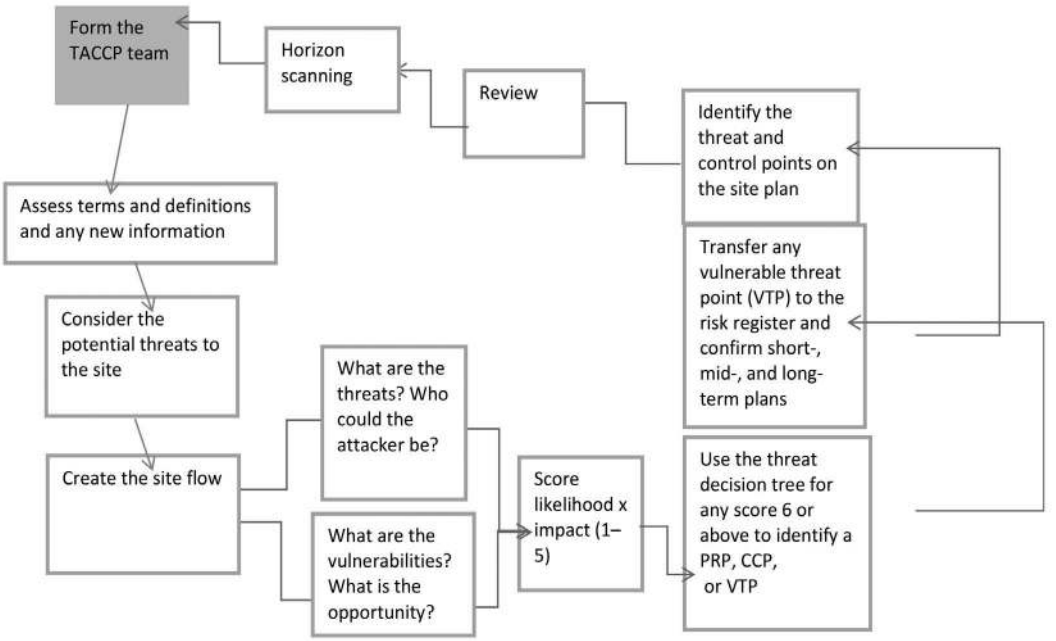

FIGURE 7.5 TACCP. (Adapted from BSI [British Standards Institution], 2014.)

The International Finance Corporation (IFC),[2] a World Bank Group member, addresses food fraud through its broader food safety and security programs by helping agribusinesses implement international standards, improve supply chain transparency, and reduce losses, thereby building resilience against adulteration and contamination, protecting consumers, and ensuring market access for companies.

Food fraud involves deliberately mislabeling food, such as by (a) substituting products with cheaper alternatives, for example, selling farmed salmon as wild salmon or selling basmati rice that has been adulterated with cheaper varieties, and (b) making false statements about the source of ingredients, that is, their geographical, plant, or animal origin.

Food fraud may also involve the sale of the meat from animals that have been stolen and/or illegally slaughtered, as well as wild game animals, such as deer, that may have been poached.

Types of threat might be adulteration (adding cheaper substances, diluting, or substituting ingredients) and economically motivated adulteration and misrepresentation (falsely claiming origin, quality, or composition, like selling frozen fish as fresh, malicious contamination, extortion—the motivation for extortion by an individual or a group is financial, to obtain money from the victim organization).[3]

Such activity is attractive to the criminal mind if the product, such as baby food, is sensitive or if the company is seen as rich. A small number of samples can be used to show the company that the attacker has the capability to attack, and is enough to cause public concern and media interest. The primary motivation of espionage is to seek commercial advantage by gaining access to intellectual property. Attackers may infiltrate using insiders to report, or they may attack remotely through information technology systems. Alternatively, organizations may try to entice executives to reveal confidential information or use covert recording to capture such material, or they may simply steal the material. The motivation of counterfeiting is financial gain by fraudulently passing off inferior goods as established and reputable brands. Moreover, besides copying the brand name, copying the packaging concept, recipe, processing method are also reported.[4]

Unapproved enhancement—adding unknown and undeclared materials to food products to enhance the quality attributes—is another threat or type of food fraud.

Both organized and petty crime can cause companies financial loss and harm to their reputation. In addition, sophisticated printing technologies can be employed to produce product labels that are indistinguishable from the genuine labels. Finally, cybercrime is the fraud where modern information and communication technologies provide new opportunities for malpractice. In the United Kingdom, for the year to February 2013, Action Fraud received 58,662 cyber-enabled fraud reports and 9,898 computer misuse crime reports, accounting for 41% of all of its reports, with an average loss of £3,689.16.

Notes

1. http://www.codexalimentarius.org/
2. https://www.ifc.org/en/insights-reports/2022/ifc-scan-guide
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8

Meat Production and Consumption: Global Trends and Future Outlook

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8.1 Introduction

The global meat sector is undergoing a profound transformation, shaped by the dual pressures of rising demand and intensifying sustainability challenges. As economic growth and dietary shifts in regions such as Asia, Africa, and Latin America drive increased meat consumption, the industry faces the complex task of scaling production amidst mounting environmental concerns (OECD/FAO, 2025). Concurrently, in many high-income countries, a counter-trend is emerging: a deliberate reduction in traditional meat intake, motivated by growing awareness of ecological impacts, animal welfare, and personal health, alongside a rising interest in plant-based and cultured protein alternatives (Jurcaga *et al.*, 2022).

This chapter examines divergent global patterns in meat production and consumption, analyzing the regional dynamics behind these patterns and the accelerating adoption of alternative proteins. It assesses the significant environmental footprint of conventional livestock farming, including its contributions to greenhouse gas emissions, land use change, and resource depletion. Furthermore, the chapter explores how technological innovations, from precision livestock farming to cellular agriculture, are reshaping production paradigms. It also considers the critical roles of policy frameworks, market forces, and the evolving bioeconomy in steering the industry toward greater resilience and sustainability. By synthesizing current research and emerging trends, this analysis aims to provide actionable insights and pathways to help balance global nutritional requirements with urgent environmental and ethical imperatives.

8.2 Global Landscape of Meat Production and Consumption

8.2.1 Regional Trends: Developed versus Developing Economies

Over the past few decades, global meat consumption has risen noticeably, particularly in Asia, Latin America, and Africa (Parlasca and Qaim, 2022). China and Southeast Asian countries, such as Vietnam, are major contributors to pork consumption growth, while the EU is projected to see a decline due to environmental concerns. Poultry remains the fastest-growing meat globally, driven by affordability, short production cycles, and fewer cultural restrictions, and is expected to account for 41% of global meat consumption by 2030 (Fanatico, Upadhyay and Bramall, 2025; OECD/FAO, 2021). Beef, mutton, goat, and other meats have also increased moderately. Beef production is projected to decline in Europe and India but rise in sub-Saharan Africa and parts of the Americas, while lamb production is expected to increase most in Africa and moderately in Oceania (OECD/FAO, 2021). Global production systems remain vulnerable to animal diseases, climate change, pandemics, and rising input costs (FAO, 2022).

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Global meat production and consumption are expected to shift significantly between 2025 and 2034. Consumption is projected to rise from 345 Mt in 2022–2024 to 382 Mt by 2034, with developed nations consuming 128 Mt and emerging nations 254 Mt. Per capita consumption averages 29.3 kg globally, led by North America (95.5 kg) and the EU (66.5 kg) (OECD/FAO, 2025).

Emerging countries will drive most of the growth as per capita consumption is approximately 55 kg in China, 75–85 kg in Brazil and Argentina, and 12 kg in sub-Saharan Africa. Poultry will account for 62% of additional consumption, followed by pork (130 Mt carcass weight equivalent [cwe]). Beef demand will rise modestly in Asia and the Middle East but decline in North America, Europe, and Oceania. Sheep meat demand remains strong in the Middle East and North Africa, reaching 19 Mt cwe (FAO, 2024; OECD/FAO, 2025; USDA, 2023).

By 2034, global production is projected to increase by 13% to 406 Mt cwe, with Asia accounting for over half of the growth. Latin America, led by Brazil, will continue expanding, while Africa will account for 6% of global meat production. Developing nations will drive most growth, whereas developed regions are expected to stabilize at 128–130 Mt (FAO, 2024; OECD/FAO, 2025; USDA, 2023).

8.2.2 Major Meat Producers and Consumers

In 2024, pork, chicken, and beef accounted for the majority of global production. Pork reached 116.45 Mt, chicken 103.72 Mt, and beef 61.66 Mt. Pork and poultry continue steady growth due to cost and demand, while beef growth is constrained by environmental and economic factors (USDA, 2025).

Leading beef producers include the United States (20%), Brazil (19%), China (13%), the EU (11%), and India (7%). Major poultry producers are the United States (21%), China (15%), Brazil (14%), and the EU (11%), followed by Russia, Mexico, Thailand, Turkey, Argentina, and Colombia (USDA, 2025).

Global meat consumption is projected to grow by 2034: poultry 21%, sheep meat 16%, beef 13%, and pork 5%. Upper-middle-income countries will account for 45% of the increase, driven by population and income growth. Africa's population growth, from 1.5 to 1.8 billion, will drive a 33% regional increase, while high-income regions, including Canada, the EU, Japan, and Switzerland, may see stagnation or decline. Beef demand will rise notably in the Middle East and Asia, while Latin America will see the largest increase in pork consumption (OECD/FAO, 2025). Table 8.1 provides a consolidated quantitative overview of these trends, projecting the evolution of global meat production and consumption from the 2024/25 baseline to 2034.

TABLE 8.1

Global Meat Production and Consumption Snapshot

Metric	2024/25 (Baseline)	2034 (Projection)	Key Trends
Total meat production	350 Mt (cwe)	406 Mt (cwe)	Global +13% growth; led by Asia and Latin America
Poultry production	104.20 Mt (RTC)	173.00 Mt (RTC)	Fastest-growing meat; 62% of global growth
Pork production	116.27 Mt (cwe)	130.00 Mt (cwe)	Growth slows to –4% per capita in high-income regions
Beef production	61.78 Mt (cwe)	84.00 Mt (cwe)	Growth in Asia and the Middle East; decline in North America and the EU
Sheep and goat production	19.00 Mt (cwe)	19.00 Mt (cwe)	Growth localized to the MENA region
Total meat consumption	345 Mt (cwe)	382 Mt (cwe)	Slower than production; growth led by upper-middle-income countries
Poultry consumption	103.50 Mt (RTC)	170.00 Mt (RTC)	Demand-led growth; affordability
Pork consumption	114.90 Mt (cwe)	128.00 Mt (cwe)	Stabilizing demand
Beef consumption	60.90 Mt (cwe)	82.00 Mt (cwe)	Asia and MENA driven
Sheep and goat consumption	18.80 Mt (cwe)	19.00 Mt (cwe)	Culturally concentrated

Source: 2024/25 Baseline and 2034 Projections.

Note: cwe, carcass weight equivalent; MENA, Middle East and North Africa; Mt, million metric tons; RTC, ready-to-cook.

8.2.3 Drivers of Demand: Income, Population, and Urbanization

Income strongly influences dietary choices, with variations between developed and developing regions (Muhammad *et al*., 2017). Low-income nations spend more of their budget on staples and are sensitive to income changes, whereas higher-income countries allocate more to high-value foods such as meat (Regmi *et al*., 2001; Smil, 2002). Popkin termed this shift the "nutrition transition" describing dietary changes prompted by economic growth (Drewnowski and Popkin, 1997).

Meat consumption rises with national wealth. Developing nations experience a "livestock revolution" where incomes above the poverty line rapidly increase animal product consumption (Delgado, 2003). Geography, culture, religion, urbanization, trade openness, and land availability also shape per capita meat intake (Cole and McCoskey, 2013; Drewnowski, 2018; Milford *et al*., 2019; Vranken *et al*., 2014).

Population growth further drives demand; for example, Africa's population is projected to grow from 1.5 billion to 1.8 billion by 2034, increasing regional meat consumption by 33%. Small per capita increases in populous countries such as China and India lead to substantial global shifts. By 2034, upper-middle-income nations will account for 45% of global growth in meat consumption, driven by rising incomes and population growth (OECD/FAO, 2025). The complex interplay of these demographic and economic drivers with the meat production system, and the resulting environmental and market pressures, is summarized conceptually in Figure 8.1.

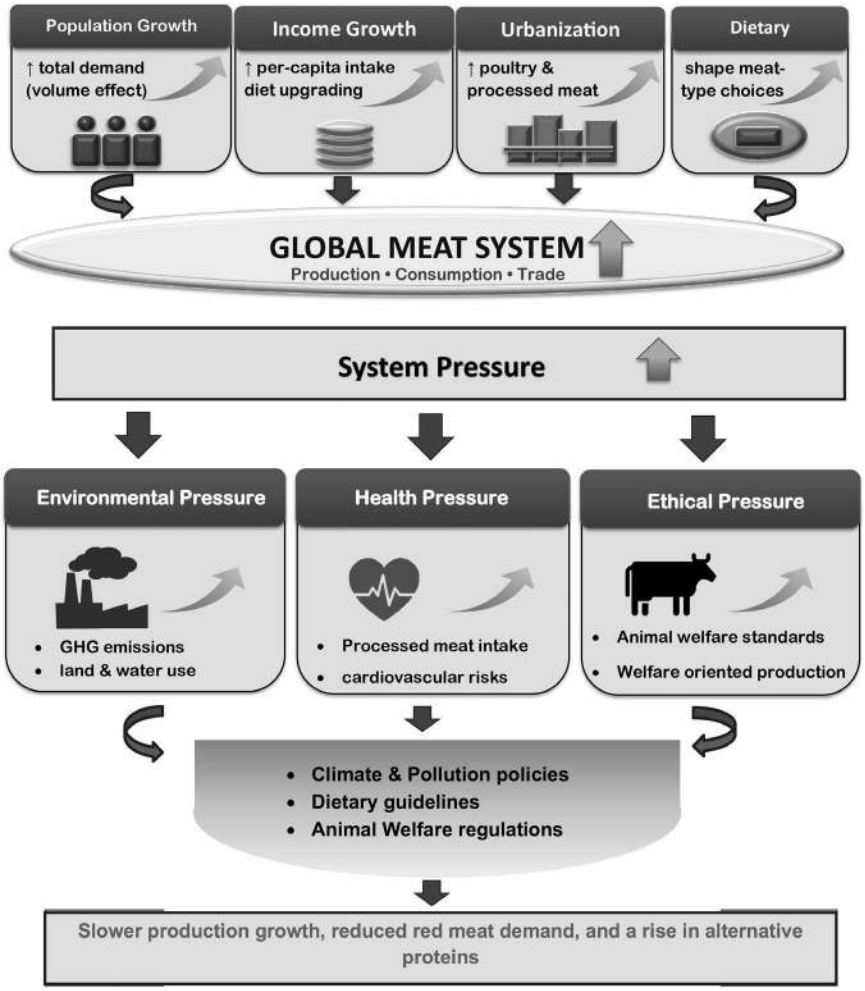

FIGURE 8.1 Global meat system: Interactions between drivers, pressures, and flows.

8.3 Shifting Consumer Preferences and Dietary Transitions

8.3.1 Rise of Ethical and Environmental Consciousness

Global meat consumption patterns are shifting as consumer awareness grows. Ethical concerns, especially regarding animal welfare, strongly influence purchasing decisions. Surveys indicate that around 73% of consumers consider animal well-being very or extremely important. Such concerns are driving reductions in meat intake and increasing interest in vegetarianism, veganism, and humane livestock practices, particularly in high-income countries. Younger generations show heightened concern for animal rights, further fueling the adoption of plant-based diets.

Environmental impacts of meat production are also shaping consumer behavior. Livestock farming contributes substantially to greenhouse gas emissions, land use, deforestation, and biodiversity loss. Food and Agriculture Organization (FAO) estimates that dairy and meat supply chains account for roughly 14–15% of global anthropogenic emissions (Grossi *et al.*, 2019). Livestock production occupies nearly 80% of agricultural land (Steinfeld *et al.*, 2006), contributing to ecosystem degradation, including Amazon deforestation for cattle grazing and feed crops (Barona *et al.*, 2010). Influential reports, such as the EAT-Lancet Commission's planetary health diet, advocate for substantial reductions in red meat consumption to meet climate and resource limits (Willett *et al.*, 2019b). Governments are responding; for example, China aims to cut meat consumption by 50% by 2030 to improve health and reduce emissions (Milman and Leavenworth, 2016). Sales of plant-based proteins are rising, especially in high-income nations where meat consumption has plateaued.

8.3.2 Health Perceptions and Meat Consumption

Health concerns are a major factor in dietary change. Epidemiological studies link high red and processed meat intake to obesity, cardiovascular disease, type 2 diabetes, and certain cancers. In 2015, IARC classified processed meat as carcinogenic to humans, particularly regarding colorectal cancer (Bouvard *et al.*, 2015). Other risks include coronary heart disease, stroke, and elevated all-cause mortality, associated with saturated fat, cholesterol, sodium, preservatives, heme iron, and compounds formed during high-temperature cooking (Hill *et al.*, 2024; Micha, Wallace and Mozaffarian, 2010).

These risks are prompting consumers to shift toward perceived healthier protein sources, such as poultry, fish, and plant-based alternatives, contributing to measurable changes in meat consumption patterns across populations. Current disparities in per capita consumption, reflecting these health trends alongside income and cultural factors, are detailed in Table 8.2.

TABLE 8.2

Per Capita Meat Consumption by Type and Country (2025)

Country	Sheep Meat (kg/capita)	Poultry Meat (kg/capita)	Pork Meat (kg/capita)	Beef and Veal (kg/capita)
Australia	6.8	30.5	20.0	21.5
Türkiye	4.6	11.5	0.0	11.5
Israel	3.4	42.0	0.5	21.0
Norway	3.0	12.5	17.8	12.3
The United Kingdom	2.4	19.5	14.7	10.0
New Zealand	2.0	24.0	15.5	7.8
Switzerland	0.8	8.5	17.5	12.5
Canada	0.6	23.5	14.6	17.0
Mexico	0.4	22.0	14.8	8.3
The United States	0.3	34.0	21.0	22.5
Korea	0.2	13.0	28.5	12.0
Japan	0.1	12.0	15.2	6.5
Chile	0.1	21.8	17.2	16.5
Colombia	0.05	21.6	9.0	8.5

8.3.3 Generational and Cultural Differences

Meat consumption varies across age groups, generations, and cultural contexts. Younger generations, Generation Z and Millennials, exhibit a greater preference for plant-based diets, vegetarianism, and veganism compared to older cohorts (Makowska, Boguszewski and Hrehorowicz, 2024). Older adults are increasingly adopting flexitarian diets for health reasons, such as managing cholesterol or blood pressure (Jeżewska-Zychowicz *et al.*, 2024).

Cultural and religious norms also shape meat intake. In South Asia, vegetarianism is culturally and religiously embedded, resulting in low per capita consumption (Devi *et al.*, 2014; Shridhar *et al.*, 2014). Conversely, Europe, North America, and Oceania have some of the highest meat consumption levels globally. Economic growth and urbanization drive "nutrition transitions" in developing countries, shifting diets from traditional plant-based foods to greater intake of meat, dairy, fats, and processed foods (Popkin, 2003; Popkin, 2014). Rising incomes and urban lifestyles, particularly in China, are closely linked with increased meat consumption and higher prevalence of diet-related noncommunicable diseases.

8.4 Diversity in Meat Production Systems

8.4.1 Industrialized Livestock Farming: Efficiency and Scale

By 2050, the global population is projected to exceed 9 billion, accompanied by accelerated urbanization and rising per capita incomes. These changes will alter dietary preferences toward more diverse and nutritionally rich foods, increasing demand for meat and milk and promoting intensive livestock farming (FAO, 2006, 2009). Urban consumers are increasingly concerned about food sources and animal welfare, amplifying pressure on the food system. To meet this challenge, global food production must rise by approximately 70% (Knudsen *et al.*, 2006). Meat production alone is expected to more than double, from 229 million metric tons in 1999–2001 to 465 million metric tons by 2050.

Three primary forces are driving the transformation of livestock systems from traditional to industrial operations: rapid population growth, demographic shifts, particularly urbanization and age structure, and improved socioeconomic status (Stevenson, 2015). Dietary transitions in developing countries' urban areas further accelerate demand; for example, per capita meat consumption increased from 10 kg in 1964–1966 to 26 kg in 1997–1999 (Delgado *et al.*, 1999). These trends have fueled the rise of industrial or factory farming, which policymakers consider more efficient than traditional extensive systems (Abath, 2017). This phenomenon, often referred to as the "Livestock Revolution", has profound implications for economic growth, livelihoods, and the environment (Arango *et al.*, 2020).

Successful adaptation to these changes requires widespread adoption of technology, training programs, and capacity-building initiatives to equip farmers and workers with modern skills and enhance social capital in sustainable agriculture (divulga edital para o Processo, 2025). Financial and digital literacy are essential to optimize resource use and avoid inefficiencies (Chikazunga, 2013). Small- and medium-scale farmers, in particular, face barriers to implementing sustainable technologies if access to external funding remains limited (Galhena, Freed and Maredia, 2013). Addressing these challenges will be critical for meeting future food demands sustainably while balancing economic, environmental, and social objectives.

8.4.2 Smallholder and Traditional Systems: Role in Food Security

Smallholder farms play a vital role in enhancing household food security and offer multiple benefits. They provide self-sufficiency, particularly at the household level, but face challenges such as climate change, gender disparities, and inequalities in land and water access, which threaten their productivity (Chikazunga, 2013).

These farms typically rely on family labor, including women, children, and elders, for management (Galhena, Freed and Maredia, 2013). To ensure national food security, smallholders must (1) increase food availability, (2) generate income and livelihoods, (3) support dietary diversity, and (4) buffer households

against market-related shocks (Bosc *et al*., 2013). Food production by smallholders can directly enhance household nutrition through consumption or indirectly by generating income for local food purchases (Pray, Masters and Ayoub, 2017).

Traditional livestock systems, which utilize local resources and practices such as transhumance, provide essential ecosystem services while supporting millions of rural households. These systems contribute to several Sustainable Development Goals, including no poverty (SDG 1), zero hunger (SDG 2), decent work and economic growth (SDG 8), climate action (SDG 13), and life on land (SDG 15). Extensive livestock practices improve soil quality, sequester carbon, reduce habitat degradation, and aid in fire prevention (Rouet-Leduc *et al*., 2021; Su, Xu and Zhang, 2023).

Their alignment with natural ecosystem functioning enhances resilience to climate change, offering a sustainable alternative to intensive agriculture (Bonilla-Cedrez *et al*., 2023; Canton, 2021). By maintaining ecological balance while supporting livelihoods, smallholder and traditional livestock systems remain crucial for sustainable food security and environmental conservation.

8.4.3 Comparative Analysis of Productivity and Sustainability

Livestock production systems across the continent are highly diverse, shaped by climate, landscape, and socioeconomic and cultural factors (Canton, 2021). FAO (2010) classifies these systems based on crop integration, land use, agro-ecological zones, production intensity, and product type. A widely accepted distinction categorizes systems into grazing, mixed farming, and industrial operations, defined primarily by land use patterns (Seré, 1995).

Intensifying beef production can reduce greenhouse gas (GHG) emissions per unit of product by supplying balanced, nutrient-rich diets. These diets, often higher in grains and supplements, can lower methane emissions, increase daily weight gains, reduce slaughter age, and optimize pasture use by temporarily removing animals from paddocks (Alves, 2020). While concerns exist about the environmental costs of producing more cereals, expansion can rely on improved productivity and the use of low-yield pastures or integrated livestock–crop systems (Basso, Neves and Grossi-De-Sa, 2024).

Sustainable intensification requires shifting toward capital-intensive, land-saving technologies that improve economic and technical performance while reducing environmental impacts (Basso, Neves and Grossi-De-Sa, 2024). Key interventions include integrated crop–livestock systems (ICLS), integrated crop–livestock–forestry systems (ICLFS), improved forages, herd genetic enhancement, pasture management, feed supplementation, and sustainable agricultural practices (Pereira *et al*., 2024). ICLS and ICLFS are particularly promising in Brazil, promoting farmer training, higher incomes, employment opportunities, and diversified production with lower environmental footprints.

However, adoption faces barriers, including cultural resistance. Strategies to overcome these challenges include demonstrating profitability, fostering partnerships between beef and crop farmers, sharing risks, and enhancing economic viability through cooperatives or associations (Garcia *et al*., 2017). Climate change adds further stress, challenging production systems' capacity to maintain consistent income. Transitioning from extensive to sustainably intensive beef farming requires technology adoption supported by robust innovation systems capable of integrating diverse farmer practices (Malafaia *et al*., 2021).

Overall, sustainable intensification of beef production depends on balancing technological adoption, environmental stewardship, and socioeconomic feasibility, ensuring that beef systems remain productive, resilient, and environmentally responsible.

8.5 Environmental and Ethical Impacts

8.5.1 Greenhouse Gas Emissions from Livestock

As global demand for meat rises, concerns over the environmental impacts of livestock production have intensified. Beyond supporting food security and economic development, livestock systems exert substantial pressure on ecosystems through greenhouse gas (GHG) emissions, air pollution, and resource

depletion. GHG emissions from livestock occur via both direct and indirect pathways (Bhatta *et al.*, 2015). Direct emissions arise mainly from enteric fermentation and manure management, while indirect emissions result from land-use change, livestock-driven desertification, feed production, and postharvest activities. The primary gases involved are methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O).

FAO (2022) data indicate that farm-gate emissions from crop and livestock production increased by approximately 15% between 2000 and 2022, reaching 7.1 gigatons of CO_2–equivalent per year, with livestock accounting for 53% of this total: 37% from enteric fermentation and 10% from manure decomposition (FAO, 2020). Methane emissions from ruminants are influenced by feed type and quality, production level, energy efficiency, growth rate, temperature, and intake, with fibrous diets producing higher outputs (FAO, 2016). Consequently, beef and lamb systems are among the highest per-unit emitters of GHG.

Methane is produced in the rumen via microbial fermentation, where hydrogen (H_2) is converted into CH_4, an energetically inefficient process that can waste 6–12% of dietary energy (Sejian *et al.*, 2012). Anaerobic manure decomposition further generates methane and nitrous oxide (Sejian *et al.*, 2012). Manure management, especially slurry storage, is a significant source of emissions, with microbial consortia driving gas production (Schnurer and Jarvis, 2010). Environmental factors such as temperature, moisture, pH, microbial load, organic matter, and feed type strongly influence emission intensity, with warmer, wetter conditions increasing GHG release (Bull, 2005).

The accumulation of these gases enhances atmospheric long-wave radiation retention, raising global temperatures and intensifying the hydrological cycle. This leads to more frequent flooding in tropical and temperate regions and increased drought frequency and severity in arid and semiarid zones (Ozuesen and Turp, 2025).

8.5.2 Land Use, Deforestation, and Biodiversity Loss

Livestock production is a major driver of land-use change, deforestation, and biodiversity loss. Large-scale forest clearing for grazing and feed crop cultivation, particularly soy, has caused extensive habitat destruction and ecosystem degradation (Jafari *et al.*, 2024). Meat production is highly land-intensive; for instance, global beef production occupies roughly 30 million km^2, whereas poultry requires less than 2 million km^2 (GRAIN and IATP, 2018). This disproportionate land demand exerts considerable pressure on natural ecosystems.

Evidence from South Africa shows that grazing-based livestock systems reduce plant species abundance and contribute to biodiversity loss (Slayi, Zhou and Thamaga, 2024). In Indonesia, cattle grazing and the expansion of fodder crops have driven large-scale deforestation, disrupting both terrestrial and aquatic ecosystems (Castro-Nunez *et al.*, 2021; González-González *et al.*, 2021; Negret *et al.*, 2021). Livestock expansion also heightens the risk of invasive species introduction through animal transport, feed movement, and altered land-use patterns. In beef production, clearing native vegetation for pasture not only destroys habitats for indigenous species but also promotes the spread of invasive species, intensifying competition for resources and accelerating ecosystem degradation (Sesay *et al.*, 2024).

8.5.3 Animal Welfare Concerns across Systems

Alongside environmental concerns, ethical issues, particularly animal welfare, are increasingly central to discussions on livestock sustainability. Intensification strategies aimed at boosting productivity and reducing emission intensity can raise concerns about animal health and welfare. Thus, mitigation strategies must balance environmental goals with ethical considerations.

Current greenhouse gas (GHG) mitigation approaches in livestock can be divided into two categories: those that directly suppress rumen methanogenesis and those that reduce emission intensity by improving production efficiency without directly targeting methane (Adesogan *et al.*, 2013). Because methane represents lost energy, mitigation can also improve feed efficiency, especially in high-producing dairy cows. Dietary and chemical interventions—such as anti-methanogenic antibiotics, electron acceptors (nitrates), lipids, ionophores (monensin), and chemical inhibitors like bromochloromethane

or chloroform—have shown potential to reduce methane (Eckard, Grainger and De Klein, 2010; Knight *et al.*, 2011; Mitsumori *et al.*, 2012; Odongo *et al.*, 2007). However, these can disrupt rumen function and pose health risks, including liver and kidney damage, if improperly administered (Ilett *et al.*, 1973).

Ethically favorable alternatives focus on improving production efficiency through enhanced diet digestibility, animal health, reproductive performance, intensive breeding, and optimized housing (Llonch *et al.*, 2017). Higher productivity reduces emission intensity, thereby lowering overall GHG emissions per unit of product (Gerber *et al.*, 2011). Moving forward, sustainable livestock systems will require integrated strategies combining technological innovation, precision farming, alternative proteins, and supportive policies to align environmental mitigation with animal welfare, food security, and societal expectations.

8.6 Technological Innovations and Their Implications

8.6.1 Precision Livestock Farming and Digital Monitoring

In recent decades, the meat industry has undergone a significant transformation driven by advances in science and technology. Rising global demand for animal protein, alongside concerns about environmental sustainability, food safety, and animal welfare, has made technological innovation central to modern meat production. Precision livestock farming (PLF) is a key development that combines digital tools and data-driven approaches to optimize animal management, enhance productivity, improve welfare, and reduce environmental impacts.

PLF employs sensors, cameras, and acoustic devices to continuously monitor animal behavior, physiology, and environmental conditions in real time. This enables early detection of stress and disease, allowing timely interventions that improve welfare and reduce economic losses (Berckmans, 2013). Automation tools, such as robotic milking, automated feeding, and waste management systems, further enhance efficiency by lowering labor needs and standardizing management. Data from PLF platforms can guide breeding, feeding, and overall resource optimization.

Wearable and environmental sensors capture vital signs (heart rate, respiration, temperature) and ambient factors (temperature, humidity, air quality). These devices can be attached to animals, installed in housing, deployed on pastures, or operated via drones. AI and machine learning processes the data to detect anomalies and patterns, supporting early interventions that can indirectly reduce greenhouse gas emissions by improving feed efficiency and rumen function (Andonovic *et al.*, 2018; Shields and Orme-Evans, 2015; Wathes *et al.*, 2005).

However, PLF adoption faces challenges. High capital costs, technical limitations, and harsh farm conditions limit access, especially for smallholders. Large volumes of complex data pose interpretation challenges, while concerns over data security, legal responsibility, and overreliance on automation remain. Addressing these issues is crucial for responsible, inclusive, and effective adoption of PLF technologies (Bozzo *et al.*, 2017, 2021; Hackfort, 2021; Kamphuis, Steeneveld and Hogeveen, 2015).

8.6.2 Genetic Improvement and Breeding Strategies

Genetic improvement has long been central to enhancing meat production, and recent advances in genomic tools, gene editing, and reproductive technologies offer new opportunities to boost productivity, improve animal welfare, and reduce environmental impacts, while raising ethical and regulatory considerations (Van Eenennaam, 2017).

Historically, conventional breeding programs in cattle, pigs, and small ruminants focused on growth rates, carcass composition, meat quality, and reproductive efficiency. Pig breeding improved muscle-to-fat ratios, and cattle selection emphasized faster growth and uniform carcass traits. While these approaches increased output, they also caused unintended issues, including lameness, reproductive disorders, disease susceptibility, and reduced genetic diversity. Modern breeding objectives now prioritize health, welfare, and adaptability alongside productivity (Mrode, 2014; Oltenacu and Algers, 2005).

The advent of genomic selection has revolutionized breeding, using dense DNA marker data to predict breeding values more accurately and rapidly (Meuwissen, Hayes and Goddard, 2001). This enables targeted selection for disease resistance, feed efficiency, and reduced methane emissions. Genome editing tools, such as CRISPR-Cas9, allow precise modifications, including hornless cattle and PRRS-resistant pigs, with future potential to enhance feed efficiency and lower emissions. Genetically improved animals require fewer inputs per unit of meat, lowering production costs and environmental impact (Wall, Simm and Moran, 2010).

Genetic strategies also support sustainability: selecting for residual feed intake in beef cattle reduces methane output, while breeding small ruminants for parasite resistance minimizes anthelmintic use, promoting both animal health and ecosystem preservation (Pickering *et al.*, 2015).

However, intensive selection and genetic modification raise ethical concerns, such as welfare issues observed in Belgian Blue cattle. Public acceptance depends on transparent communication about benefits for sustainability, welfare, and food security. Adoption also varies: high-income countries are advancing genomic technologies more rapidly, while low-income regions face infrastructural and financial barriers. Ensuring equitable and ethical implementation of genetic innovations is essential for the future of sustainable meat production.

8.6.3 Advances in Meat Processing and Value Addition

Advances in meat processing technologies have markedly improved product safety, quality, sustainability, and consumer appeal. Nonthermal methods, such as high-pressure processing (HPP) and pulsed electric fields (PEF), enhance microbiological safety while preserving nutritional and sensory qualities. Packaging innovations, including modified atmosphere packaging (MAP) and vacuum skin packaging, extend shelf life, reduce food waste, and improve supply chain efficiency (Mcmillin, 2017).

Rising consumer demand for convenience and health has driven the development of value-added meat products. Functional meats enriched with omega-3 fatty acids, plant-based ingredients, or probiotics address nutritional needs, while ready-to-eat and ready-to-cook products cater to busy urban lifestyles (Toldrá and Reig, 2011). Enhanced utilization of slaughter by-products through rendering and bio-extraction converts waste into biofuels, animal feed, pharmaceuticals, and other value-added products, reducing environmental impact and supporting circular economy principles (Jayathilakan *et al.*, 2012).

Digital technologies are increasingly applied to improve transparency and sustainability across the meat supply chain. Blockchain-based traceability systems verify product origin, processing history, and safety compliance, reinforcing consumer trust and regulatory adherence.

Future developments will focus on integrating energy-efficient processing, sustainable packaging, and circular production models to meet evolving consumer expectations and environmental standards. Collectively, these technological innovations are transforming meat processing toward safer, more sustainable, and higher-value products.

8.7 Policy and Market Interventions

8.7.1 Global and National Policy Responses

Experts and global organizations have proposed various strategies to reduce meat consumption as part of efforts to make food systems healthier and more environmentally sustainable. Reducing meat intake is considered a key step toward improving public health and mitigating environmental impacts (Sievert *et al.*, 2022). There is a clear link between daily dietary choices and human health, and increasing attention is being paid to the environmental consequences of food production. Agriculture accounts for roughly 25% of global greenhouse gas (GHG) emissions, with meat—particularly beef—being a major contributor (Willits-Smith *et al.*, 2020).

Excessive consumption of red meat poses significant risks to both health and the environment. While red meat provides essential nutrients such as protein, heme iron, zinc, and B vitamins, growing evidence indicates that high intake is associated with increased risks of chronic diseases, including cardiovascular

disease, type 2 diabetes, and certain cancers. Additionally, higher meat consumption contributes to GHG emissions, environmental pollution, and biodiversity loss (Poore and Nemecek, 2018; Wyness, 2016). Policymakers are increasingly interested in measures that minimize these health and environmental impacts.

One promising approach is to introduce warning labels on red meat products to educate consumers about potential risks (James *et al*., 2022). Another strategy is applying taxes to red meat, similar to those on alcohol or sugary beverages. Studies suggest that both labeling and taxation can effectively reduce red meat consumption (Abadie *et al*., 2016).

Encouraging shifts from red meat to pulses offers dual benefits: pulses are nutritious and have a lower environmental footprint (Harwatt *et al*., 2017). If consumers instead turn to meat substitutes, environmental benefits may still be achieved, though health gains could be smaller, as some substitutes are high in sodium and other less healthy ingredients (Farsi *et al*., 2022). Moreover, the health impact of these measures depends on the type of meat consumed afterward; while processed and unprocessed meat have similar environmental effects, processed red meat is linked to a higher risk of diet-related chronic diseases (Micha, Michas and Mozaffarian, 2012).

8.7.2 Certification Schemes, Labeling, and Consumer Trust

Food quality certifications play a crucial role in both local and global food systems, particularly in the meat industry. These certification programs vary in their creation and implementation; some are voluntary, while others are mandatory. They can be administered by governments, private companies, or other organizations and are commonly referred to as quality assurance systems. These systems establish standards related to food safety, animal welfare, and environmental impacts, ensuring that meat purchased by consumers meets the specified criteria (Tarabella, Varese and Cesarani, 2019).

Promoting healthier, more sustainable diets can be supported through information sharing, price adjustments, improved accessibility, and regulatory measures that shape the food environment (Just and Byrne, 2020). Labeling schemes are an inexpensive and effective way to educate consumers, helping them identify sustainable products and make informed choices. Additionally, such labels encourage companies to raise their environmental and ethical standards (Canavari and Coderoni, 2020). Labeling generally covers four domains: environmental impact (e.g., organic or carbon footprint labels), ethics (e.g., animal welfare labels), social factors (e.g., fair trade labels), and health (e.g., nutrition labels) (Sonntag *et al*., 2023). Their effectiveness depends on consumer attitudes, with environmentally conscious individuals more likely to value and select responsibly produced food (Ghvanidze *et al*., 2017).

Eco-labels can help consumers reduce intake of environmentally intensive foods, such as meat, which contributes significantly to greenhouse gas emissions (Gerber *et al*., 2013). Meat traceability systems further support food safety by enabling rapid detection of hazards, preventing fraud, and ensuring regulatory compliance (Robson *et al*., 2021; Zhang, Mankad and Ariyawardana, 2020). Consumer trust is critical, as it influences perceptions of quality and adherence to standards by producers, distributors, and retailers (Bozic, 2017). While traditional quality assessment relied on visible cues like color, texture, fat content, or price (Hastie *et al*., 2020), modern consumers increasingly consider attributes such as safety, nutrition, environmental sustainability, and animal welfare, which cannot be visually assessed.

With globalization and the growing complexity of food supply chains, the risks of food fraud and safety breaches have increased. Consequently, consumers now require additional information and assurances—beyond appearance or taste—to make informed decisions regarding safety, nutrition, sustainability, and ethical production practices (Seo, Kim and Nurhidayati, 2020; Yeh, Menozzi and Török, 2020).

8.7.3 Trade Dynamics and Market Access

As urban populations grow and incomes rise, global trade in red and processed meat has increased significantly to meet the growing demand (Tilman and Clark, 2014). This expansion in the meat trade can contribute to a higher prevalence of diet-related diseases in importing countries. Greater meat consumption, driven by international trade, poses challenges to promoting healthy, sustainable diets (Chung and Liu, 2019).

Trade agreements under the World Trade Organization (WTO) have facilitated increased flows of red and processed meat between nations. To address associated health risks, the WTO should collaborate closely with organizations such as the FAO and the World Health Organization (WHO). Mechanisms like the Technical Barriers to Trade Agreement can help ensure that public health considerations are incorporated into trade rules. In addition, governments at national and regional levels must implement policies to mitigate the health impacts of rising red and processed meat imports, particularly the growing burden of diet-related noncommunicable diseases (Chung *et al*., 2020).

Market access for smallholder farmers is vital to improving livelihoods and nutrition. When farmers can reach markets, they increase their income, which can be used to enhance household food security and dietary quality (Abay and Hirvonen, 2017). Food and nutrition security depend not only on the quantity of food but also on access to a variety of nutrient-rich foods. Improved market access enables the availability of diverse and nutritious foods, helping households meet these needs (Usman and Haile, 2019). Higher income also allows farmers to afford better health care and nutrition, contributing to reduced poverty and improved well-being (Sibhatu, Krishna and Qaim, 2015).

8.8 Rise of Alternative Proteins

8.8.1 Plant-Based Meat Analogue: Development and Acceptance

The growing global population has driven increases in meat production and consumption, raising environmental concerns such as excessive land and water use, pollution, greenhouse gas emissions, climate change, and biodiversity loss. Animal-based protein production is resource-intensive and generates high emissions, prompting experts to recommend reducing meat intake (Machovina, Feeley and Ripple, 2015).

In response, many individuals are adopting vegetarian diets or reducing meat consumption, creating a rising demand for plant-based meat alternatives, a trend expected to continue (Toribio-Mateas, Bester and Klimenko, 2021). Factors such as religious beliefs and the high cost of producing animal proteins further support the shift toward nonanimal protein diets. Plant-based proteins provide a sustainable alternative, enabling the production of meat-like products that mimic meat in nutrition and texture, commonly referred to as meat substitutes (Gibson and Dwivedi, 1970).

These substitutes are typically made by processing plant protein concentrates or isolates—such as soy and wheat gluten—through extrusion to produce textured vegetable proteins. These are then mixed with water, binders, oils, and seasonings to create plant-based meat products. Soy is used in products like tofu and tempeh, while wheat gluten forms seitan. These proteins are favored for their high nutritional value and their ability to replicate the sensory qualities of meat (Hashizume, 1978).

The food industry continues to develop new plant-based products to meet consumer demand, offering sustainable options that appeal to vegetarians and flexitarians alike (Godfray *et al*., 2018). Consumer acceptance improves with exposure, education, and tasting opportunities, reducing food neophobia over time. Studies indicate that positive perceptions of taste, texture, aroma, nutrition, and environmental benefits encourage repeated use and openness to other plant-based alternatives (Godfray *et al*., 2018; Roininen, Lähteenmäki and Tuorila, 1999). This shift is part of a broader diversification of the global protein supply, moving from a system reliant on conventional livestock toward an integrated portfolio of alternative sources, as conceptualized in Figure 8.2.

8.8.2 Cultivated Meat: Opportunities and Regulatory Landscape

Cultivated meat, also known as cultured, cell-based, lab-grown, in vitro, or clean meat, has gained significant attention recently due to growing consumer and food industry interest. It is seen as a promising solution to address the environmental, health, and ethical challenges posed by conventional meat production (Ianovici *et al*., 2022).

Cultivated meat is produced through cellular agriculture, a process motivated by several concerns: the rising global population, the environmental impact of traditional livestock farming (including land use, greenhouse gas emissions, and biodiversity loss), ethical issues surrounding animal slaughter, and

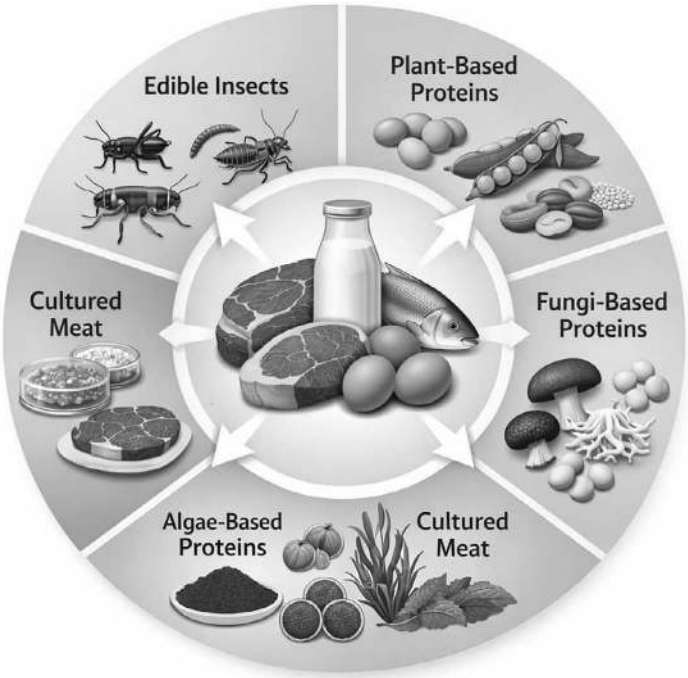

FIGURE 8.2 Future protein portfolio: From conventional to alternative sources.

health risks such as zoonotic diseases and antibiotic use (Stephens and Ellis, 2020). Rather than raising and slaughtering animals, the process begins with a small tissue sample (biopsy) from which cells are isolated and then grown into muscle tissue. Stem cells are commonly used because they can proliferate and differentiate into various cell types (Seah *et al.*, 2022).

Cells for cultivated meat are derived from adult stem cells, which have limited proliferation, or pluripotent stem cells, which can multiply indefinitely. Muscle cell types typically used include muscle satellite cells, mesenchymal stem cells, fibro-adipogenic progenitors, embryonic stem cells, and induced pluripotent stem cells (Reiss, Robertson and Suzuki, 2021). Two categories of products are expected to enter the market: unstructured items such as burgers, sausages, and nuggets, followed later by structured products like chicken breasts and beef steaks (O'neill *et al.*, 2021). Achieving tissue that mimics natural meat requires aligned muscle fibers and evenly distributed fat (Jo, Nie and Takeuchi, 2021).

The cultivated meat sector has expanded rapidly, attracting millions in investment and numerous start-up companies. Despite market growth, regulatory progress has been slow, as approval is granted on a country-by-country basis. In the United States, the FDA and USDA are collaborating to develop a regulatory framework to support industry advancement (Santos *et al.*, 2023).

8.8.3 Insect Proteins and Microbial Fermentation

As researchers increasingly seek high-quality protein sources with lower environmental impact, edible insects have gained considerable attention. Compared to traditional livestock, insects provide equal or superior nutritional value while requiring less water, feed, and land (Mancini *et al.*, 2022).

Among alternative proteins, insects play a significant role in meeting the growing global demand. Their proteins contain all essential amino acids, as well as vitamins and minerals such as calcium, iron, and zinc. Insects also provide healthy saturated and unsaturated fatty acids. In terms of digestibility, insect proteins are easier to digest than most plant-based proteins and are comparable to conventional animal protein sources. Their energy content is similar to other meat products (Zielińska *et al.*, 2015).

Food fortification has become a widely used strategy globally to improve the nutritional value of common foods. Insect-based flours, being highly digestible and protein-rich, are increasingly used to fortify various food products (Gaglio *et al.*, 2021). Environmentally, insect protein offers several advantages over traditional sources, including lower water and land use and reduced greenhouse gas emissions, benefiting both human health and the planet. However, taste and consumer acceptance remain critical factors in adoption (Huis *et al.*, 2013; Megido *et al.*, 2016).

Fermentation plays an important role in enhancing the flavor and nutritional profile of insect-based proteins. Microbes and enzymes break down proteins into amino acids, improving digestibility and taste (Ebenebe and Okpoko, 2016). Fermentation also influences the microbiome of host organisms and in vitro systems, often depending on diet composition (Young *et al.*, 2020). Processing methods such as fermenting insect paste or sauces improve palatability, making insect-based foods more appealing. Additionally, bacteria help recycle by-products in large-scale insect farming, break down artificial feed, and are present in processed, stored, and traded insects, underscoring the integral role of microorganisms in insect food production (Klunder *et al.*, 2012).

8.9 The Role of Circular Bioeconomy (CBE) in Meat Systems

8.9.1 Waste Valorization and Nutrient Recycling

Rapid global population growth has intensified the demand for food, energy, and materials, placing increasing pressure on finite natural resources. Overreliance on nonrenewable resources and their uncontrolled exploitation has driven environmental degradation, including rising greenhouse gas emissions and accelerated climate change. In response, the bioeconomy has emerged as a strategic approach, replacing fossil-based materials with renewable biological resources for the production of bio-based products and bioenergy.

Conventional linear economic models, characterized by a "take–make–dispose" pattern, promote resource extraction, short product lifespans, and waste generation, leading to persistent depletion. In contrast, the circular economy adopts a regenerative framework, retaining materials, products, and energy within the system as long as possible through recycling, reuse, repurposing, and biological reintegration. Extending this concept, the CBE integrates renewable biological resources, wastes, and by-products to sustainably generate value-added products such as biofuels, biomaterials, and biochemicals. Consequently, the CBE has gained attention as a critical pathway toward environmental, economic, and social sustainability (Nargotra *et al.*, 2024; Ramos Huarachi *et al.*, 2023).

Livestock systems play a pivotal role in the CBE by acting as biological upcyclers, converting human nonedible biomass into nutrient-dense foods and valuable co-products. Much of the global agricultural biomass, including crop residues, processing by-products, and fibrous forages, is unsuitable for direct human consumption. Ruminants, supported by specialized gastrointestinal microbiota, can convert low-quality plant biomass into high-quality animal-source foods, along with co-products such as hides, wool, and manure (Makkar, 2016; Van Zanten *et al.*, 2016). Monogastric animals also contribute by converting energy-dense agro-industrial by-products into valuable products (Ripple *et al.*, 2014).

Upcycling biomass via livestock production delivers ecological and economic benefits by redirecting organic residues into productive pathways. Livestock systems enhance resource circularity, reduce waste, and support nutrient recycling. Manure serves as an organic fertilizer, reducing reliance on synthetic nitrogen (N) and phosphorus (P) inputs, improving soil fertility, and mitigating environmental impacts (Herrero *et al.*, 2015; Zielińska and Bułkowska, 2024). Advanced processing technologies, including anaerobic digestion and thermochemical conversion, enable biogas and biochar production while improving nutrient availability and reducing greenhouse gas emissions (Silva *et al.*, 2025; Rout *et al.*, 2023). Nutrient recovery technologies, such as struvite precipitation and ammonia stripping, further enhance N and P recovery, supporting sustainable crop production (Porterfield *et al.*, 2020).

In meat production, CBE principles maximize resource efficiency by converting low-value biomass and by-products into high-value outputs. Crop residues and agro-industrial by-products can be incorporated

into livestock diets, reducing food–feed competition and enhancing sustainability (Mcallister *et al.*, 2025; Ripple *et al.*, 2014). Animal by-products from meat processing, including hides, bones, and fats, can be transformed into collagen, gelatin, and bio-based compounds for pharmaceuticals, cosmetics, and bioenergy. Collectively, these strategies demonstrate how livestock systems can embody the CBE, strengthening nutrient cycling, reducing environmental impacts, and supporting sustainable food production.

8.9.2 Integration with Crop–Livestock Systems

Integrated crop–livestock systems (ICS) illustrate the principles of the CBE by reconnecting crop and animal production to improve ecological, economic, and resource-use efficiencies. Modern ICS reimagine traditional mixed farming practices, utilizing crop residues as livestock feed and returning manure to croplands, thereby closing nutrient cycles and enhancing overall system performance. Long-term studies have demonstrated that ICS can significantly increase soil organic carbon (SOC). For instance, crop–pasture rotations in Uruguay stored more SOC in surface soils than continuous grain cropping, indicating enhanced soil resilience and carbon sequestration potential (González-Sosa *et al.*, 2024).

Field experiments in China have further shown that dairy cow manure applications enhance soil biological fertility and improve key physical properties compared with non-manured systems (Han *et al.*, 2023). Ecologically, ICS promote soil health (Hatano, Mukumbuta and Shimizu, 2024), increase water retention, and facilitate efficient nutrient cycling (Xu, Jagadamma and Rowntree, 2018). Rotational grazing enhances soil structure and aggregate stability, ensures more uniform manure distribution, reduces CO_2 emissions (Baronti *et al.*, 2022), and stimulates microbial activity, collectively improving soil fertility. These synergistic effects reduce reliance on external inputs, such as synthetic fertilizers and purchased feed, lowering production costs and environmental impacts.

Life cycle assessments (LCAs) of South American mixed crop–livestock systems report lower greenhouse gas emission intensity and improved nutrient circularity compared with specialized mono-enterprise systems, emphasizing the energy and material efficiency advantages of integration (Pereyra-Goday *et al.*, 2024). From a management perspective, advanced manure processing and nutrient recycling technologies are critical, as improved manure management enhances nutrient-use efficiency and reduces losses, thereby mitigating environmental trade-offs (Qu, Groot and Zhang, 2025).

Supportive policies are essential to incentivize integrated production, land-sharing practices, and effective manure utilization, while innovations in precision grazing, nutrient mapping, and decision-support tools are required to optimize system performance without compromising productivity. Overall, shifting from decoupled production systems to integrated, circular designs foster resilient, low-input meat production systems that align with CBE objectives, combining environmental sustainability with economic and social benefits.

8.9.3 Life Cycle Thinking (LCT) in Meat Production

LCT provides a comprehensive framework for assessing the environmental impacts of meat production systems across the entire supply chain, from "cradle-to-gate" or beyond. By applying LCA, LCT enables direct comparisons between conventional, integrated, and alternative production systems. LCA establishes system boundaries upfront, covering raw material extraction, feed production, animal rearing, slaughter, and processing, while quantifying key environmental indicators such as greenhouse gas emissions, land and water use, and eutrophication potential (Sukuman *et al.*, 2025).

Standardizing functional units and system boundaries is essential for meaningful comparisons. For example, impacts can be expressed per kilogram of carcass weight or per 100 g of edible protein, allowing benchmarking across production systems, as illustrated in recent LCA studies of poultry and feed production (Lucas and Kebreab, 2025). A key challenge in applying LCT to livestock systems is multifunctionality, since these systems produce multiple outputs, including meat, milk, manure, fiber, and draught power. The choice of functional units and allocation methods, economic versus physical, can substantially influence results. For instance, an LCA of Icelandic lamb production revealed significant differences in environmental impacts when expressed per kilogram of edible meat versus per unit of protein (Shrivastava *et al.*, 2025).

Looking forward, prospective LCA (pLCA) allows scenario-based assessments of future innovations, including cultivated meat, novel feed additives, and large-scale adoption of CBE practices. Ex ante LCA studies of cell-based meat suggest substantial reductions in land use and greenhouse gas emissions under projected scenarios. Similarly, pLCA analyses have compared meat-based and plant-forward dietary patterns under 2050 socioeconomic scenarios (Sevigné-Itoiz *et al.*, 2021).

Overall, LCT, supported by LCA, offers a robust, system-wide method for evaluating the environmental footprint of meat production. It addresses the complexities of multi-output systems, enables benchmarking across production models, and provides insights to guide sustainable transitions toward CBE strategies in the meat sector.

8.10 Looking Ahead: Scenarios and Strategic Pathways

8.10.1 Projections for Global Meat Demand

According to FAO, the global population is projected to reach 9.7 billion by 2050, an increase of roughly one-third from 2015, posing a significant challenge to global food security. Future growth in meat consumption will be shaped not only by population expansion but also by technological innovation and environmental constraints (Henchion *et al.*, 2021). Rising populations indicate that global demand for meat will continue to increase, particularly in low- and middle-income countries where rapid urbanization and income growth are driving dietary transitions (Jia *et al.*, 2023).

Projected meat demand presents several challenges. First, if current consumption trends persist, the total global meat intake in 2030 is expected to be 72% higher than in 2000, primarily driven by substantial increases in pork and poultry consumption. Second, under conventional concentrated animal feeding operations (CAFOs), the production of this meat could generate over 1.9 billion tons of greenhouse gas emissions by 2030. Addressing these environmental impacts will require solutions that may be difficult to implement, highlighting the importance of policymakers prioritizing strategies to meet future meat demand sustainably (Fiala, 2008). These projections underscore the need for strategic planning in livestock systems that balances socioeconomic equity, ecological sustainability, and nutritional needs (Springmann and Freund, 2022).

Rising incomes and the adoption of healthier eating habits in developing nations are expected to further drive the consumption of animal-derived foods (Popkin, 2017). Poultry consumption is increasing globally, as chicken is relatively affordable compared to ruminant meat and typically has a smaller environmental footprint (Godfray, 2017). Conversely, red meat consumption is stagnant or declining in high-income countries, driven by health concerns, ethical considerations, and growing awareness of climate impacts (Willett, Rockström and Loken, 2019a). Future scenarios must therefore account for these divergent global meat consumption patterns and trajectories, reflecting the widening gap between developing and developed nations (Sans and Combris, 2015).

8.10.2 Balancing Nutrition, Environment, and Livelihoods

For thousands of years, meat has played a crucial role in human diets, providing high-quality proteins, vitamins, and minerals that are often difficult to obtain from other sources (Cocking *et al.*, 2020). Meat is particularly valuable as a source of high biological value protein, iron, vitamin B12, other B-complex vitamins, zinc, selenium, and phosphorus (Pereira and Vicente, 2013). However, when a diverse range of other foods is available and regularly consumed, it is possible to meet these nutritional requirements without including meat in the diet. Large prospective studies and meta-analyses conducted in affluent Western countries generally indicate that individuals with high intakes of red and processed meat exhibit moderately higher overall mortality rates. Among the documented negative effects, the most robust evidence links heavy consumption of processed red meat to an increased risk of colon cancer (Pereira and Vicente, 2013).

From an environmental perspective, meat production generates significantly higher greenhouse gas emissions per unit of energy compared to plant-based diets. Methane, a potent greenhouse gas with a

lower atmospheric half-life than CO_2 but a substantially higher warming potential, is primarily produced during meat production (Pereira and Vicente, 2013). In the United States and other high-income countries, the consumption of meat and saturated fats often exceeds nutritional requirements, which contributes to a heightened risk of chronic diseases such as diabetes mellitus, cardiovascular disease, and several types of cancer (Marangoni *et al.*, 2015).

It is important to recognize that policies aimed at reducing meat consumption in wealthier nations should not compromise the nutritional needs of minority populations whose diets rely heavily on animal-derived foods. Striking a balanced approach to meat consumption is therefore essential to simultaneously ensure environmental sustainability and nutritional equity, particularly in regions where nutrition challenges remain acute, such as among women and children in low-income areas (Fanzo and Davis, 2021; Herrero *et al.*, 2013).

Globally, livestock production systems are becoming increasingly intensive to meet rising demand for animal-derived foods. This intensification places significant pressure on land use, especially regarding the provision of feed for pigs, poultry, and dairy production. Consequently, policy research focused on managing demand, alongside research aimed at improving feed efficiency and identifying alternative feed resources, is critical for advancing more sustainable livestock production systems (Herrero and Thornton, 2013).

8.10.3 Policy and Innovation Priorities for 2030 and Beyond

The European Commission (2020) emphasizes that achieving holistic food and nutrition security requires a transition toward more sustainable, health-promoting diets, which, in turn, demands a comprehensive reorganization of the food system. To maximize co-benefits, a thorough and detailed understanding of the multiple components of current food systems and their interconnections is essential. The European Commission prioritizes the development of future-proof sustainable food systems with a strong focus on inclusivity and human health. Key policy instruments, such as the European Green Deal and the Farm to Fork strategy, are central to advancing these objectives. Complementing these efforts, the EU's Food 2030 research and innovation policy framework supports the creation of sustainable, innovative, and integrated food systems that respect planetary boundaries. Effective implementation of these policies is expected to yield benefits for communities, the environment, the climate, and human health (European Commission, 2020; Marcinkowska-Lesiak *et al.*, 2025).

While conventional meat will remain an important source of nutrition, modifications in production practices are necessary to mitigate its environmental and ethical impacts. Alternative proteins, such as insects and cultured (lab-grown) meat, provide additional options that could enhance sustainability. However, these alternatives face challenges related to consumer acceptance, regulatory frameworks, and scalable production. Insect protein raises concerns regarding cultural acceptance and allergenicity, whereas cultured meat remains technologically complex and costly to produce. To ensure food safety, reduce production costs, and standardize processing methods, further research is required. Additionally, establishing equitable market conditions will necessitate international collaboration and supportive policies (Marcinkowska-Lesiak *et al.*, 2025; Varzakas and Smaoui, 2024).

8.11 Conclusion and Recommendations

The global meat industry is at a critical turning point. On the one hand, meat consumption continues to increase in developing regions due to rising incomes and population growth, while on the other hand, consumption in higher-income regions is declining due to growing environmental, ethical, and health concerns. This divergence highlights a fundamental challenge for the sector: how to meet the rising demand for high-quality protein in emerging economies while simultaneously reducing the environmental footprint of meat production and addressing animal welfare concerns.

At present, the meat industry's future sustainability remains uncertain. Livestock production is a major contributor to greenhouse gas emissions, land degradation, biodiversity loss, and environmental pollution, and animal welfare issues persist in several production systems. These challenges underscore the urgent need for structural changes across the meat value chain.

Encouragingly, technological innovation and systems-based approaches, such as CBE principles, are creating new opportunities for transformation. However, meaningful progress requires coordinated efforts among all stakeholders. Producers and industry actors should adopt more efficient, climate-smart production practices, integrate precision technologies to reduce emissions, and enhance resource-use efficiency through waste reduction and valorization. Policymakers must support this transition through effective regulatory frameworks and incentives, including sustainability standards, eco-labeling, and market-based instruments, while ensuring that small-scale producers are not disproportionately disadvantaged.

At the same time, researchers and technology developers should continue to advance alternative protein sources, including plant-based and cultured meat, with a focus on improving scalability, affordability, and consumer acceptance, while rigorously evaluating their environmental performance. Consumers also play a crucial role; increased awareness of the environmental and ethical implications of dietary choices can encourage demand for sustainably produced meat and a gradual shift toward more plant-based diets.

Overall, addressing the complex challenges of the global meat system requires collective action. A balanced approach involving producers, industry, policymakers, researchers, and consumers is essential to align nutritional needs with environmental limits and ethical responsibilities. By adopting precision farming, alternative proteins, and circular, low-waste food systems, the meat sector can move toward a more sustainable, resilient, and socially acceptable future.

Conflict of Interest

The authors declare no conflict of interest.

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9

Structure and Composition of Meat and Adipose Tissues

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9.1 Introduction

9.1.1 Importance of Understanding Meat and Adipose Tissue Composition

Meat, a primary source of high-quality protein and essential nutrients, is largely composed of two biological tissues: skeletal muscle and adipose tissue. The structure and biochemical composition of these tissues significantly influence not only the quality and safety of meat but also its technological properties, sensory appeal, and nutritional profile (Purslow *et al.*, 2020). The skeletal muscle serves as the functional and structural core of meat, comprising muscle fibers, connective tissue, and associated biochemical compounds, while adipose tissue contributes to energy storage, insulation, and importantly, flavor and juiciness during consumption (Gagaoua *et al.*, 2021; Joo *et al.*, 2013).

Understanding the micro- and macro-structural characteristics of muscle tissue, including fiber-type distribution, sarcomere length, and the density of connective tissues such as perimysium and endomysium, provides essential insights into meat tenderness and water-holding capacity (WHC)—two critical determinants of consumer acceptance (Listrat *et al.*, 2016; Picard *et al.*, 2019). Similarly, detailed knowledge of the types and distribution of adipose tissue, namely, subcutaneous, intermuscular, and intramuscular fat (IMF), is fundamental to assessing meat quality traits like marbling, oxidative stability, and nutritional value (Hocquette and Gondret, 2006; Pethick *et al.*, 2022).

Biochemically, meat is a rich matrix of water, proteins, lipids, carbohydrates, and micronutrients. The relative proportions and structural organization of these components are determined by a combination of genetics, physiology, nutrition, and postmortem processes (Choe and Kim, 2019; Koohmaraie and Geesink, 2006). For instance, the ratio of myofibrillar to sarcoplasmic proteins can influence muscle contraction dynamics and ultimately impact tenderness and cooking loss (Huff-Lonergan and Lonergan, 2005). Similarly, the fatty acid composition within adipose tissue, particularly the balance of saturated and unsaturated fatty acids, plays a key role in determining both the nutritional value of meat and its oxidative stability during storage (Wood *et al.*, 2008).

An accurate understanding of these compositional attributes enables researchers and meat technologists to manipulate key variables through breeding, feeding, and processing strategies aimed at enhancing meat quality and consistency (López-Bote, 1998; Prieto *et al.*, 2020). Furthermore, cellular and molecular insights into muscle and fat tissue development have opened avenues for identifying biomarkers of meat quality, helping optimize production outcomes and predict shelf life performance (Gagaoua *et al.*, 2019). These advancements are crucial not only for improving product quality but also for addressing economic challenges related to meat waste, yield, and value addition in the meat industry.

As global protein demands continue to escalate alongside heightened consumer expectations for quality, transparency, and nutrition, an in-depth comprehension of the structural and compositional characteristics of meat and adipose tissue becomes increasingly essential. It serves as the foundation for developing predictive models, optimizing meat processing workflows, and ensuring food safety and traceability throughout the supply chain (Toldrá, 2021).

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9.1.2 Relevance to Sustainable Meat Technology

In recent years, sustainability has emerged as a defining challenge for the global meat sector. The production and processing of animal-derived foods are under increasing scrutiny due to their associations with greenhouse gas emissions, land and water use, and ethical concerns related to animal welfare (Gerber *et al*., 2013; Poore and Nemecek, 2018). In this context, understanding meat and adipose tissue composition is not only a scientific necessity but also a strategic asset for developing sustainable and resource-efficient meat production systems.

Efficient utilization of muscle and fat tissues can contribute significantly to reducing waste and improving carcass yield. For example, improving the uniformity of muscle fiber types and minimizing excessive connective tissue can enhance processing efficiency and consumer satisfaction, reducing product rejection and losses (Purslow, 2018). Likewise, optimizing the IMF content and fatty acid profile can improve meat's nutritional quality while reducing reliance on synthetic additives for flavor and texture enhancement (Hocquette *et al*., 2018; Jiang *et al*., 2016).

Sustainable meat technologies also encompass advancements in genetic selection, precision feeding, and animal husbandry practices that target specific tissue traits. Selective breeding for favorable muscle fiber characteristics, marbling, and oxidative stability can enhance both the nutritional profile and shelf life of meat products (Brooks and Savell, 2004; Dodson *et al*., 2010). Moreover, feed strategies tailored to modulate lipid metabolism and adipogenesis have shown promise in producing healthier meat with enhanced levels of polyunsaturated fatty acids and bioactive lipids (Scollan, Price and Morgan, 2014).

The emergence of cultured meat and meat analogues underscores the increasing importance of replicating the functional and compositional features of native meat tissues. Cultured meat technologies aim to recapitulate the structural complexity of muscle and adipose tissue using scaffold materials, growth factors, and stem cells, informed largely by our understanding of in vivo tissue development (Ben-Arye and Levenberg, 2019; Bhat, Kumar and Fayaz, 2015). Here, knowledge of sarcomere alignment, fiber cross-linking, and lipid infiltration becomes critical in recreating the sensory and nutritional qualities of traditional meat.

Additionally, integrating tissue composition data into precision livestock farming (PLF) systems can enable real-time monitoring and decision-making. Technologies such as near-infrared spectroscopy, ultrasound imaging, and biomarker assays are being used to predict carcass traits and optimize resource allocation across the production chain (Pérez-Juan *et al*., 2021; Picard, Gagaoua and Micol, 2020). These innovations contribute to reducing inputs per unit of meat produced and minimizing environmental impact, thereby advancing sustainability goals.

Applications range from bioactive peptides and omega-3 fatty acids to cosmetics, pharmaceuticals, and biodegradable materials, all of which hinge on understanding the molecular composition of muscle and fat tissues.

In sum, a comprehensive grasp of meat and adipose tissue composition supports the transition toward more sustainable, ethical, and efficient meat systems. It bridges the gap between fundamental science and practical innovation in a rapidly evolving global food landscape.

9.2 Muscle Tissue: Structural Overview

9.2.1 Hierarchical Organization of Muscle: Muscle Fiber, Fascicles, and Myofibrils

Skeletal muscle is a highly specialized and structurally intricate tissue responsible for voluntary movement, posture maintenance, and metabolic functions. Its organization follows a complex hierarchical model, where each level contributes to both the mechanical functionality and biochemical integrity of the entire muscle system (Listrat *et al*., 2016). This hierarchical structure extends from the entire muscle organ down to the molecular level, including muscle fibers, fascicles, myofibrils, and sarcomeres, all embedded within connective tissue layers (Figure 9.1). Understanding this architecture is fundamental to interpreting the physiological responses of muscle to exercise, growth, postmortem changes, and meat quality attributes (Zhao, Bai and Li, 2022).

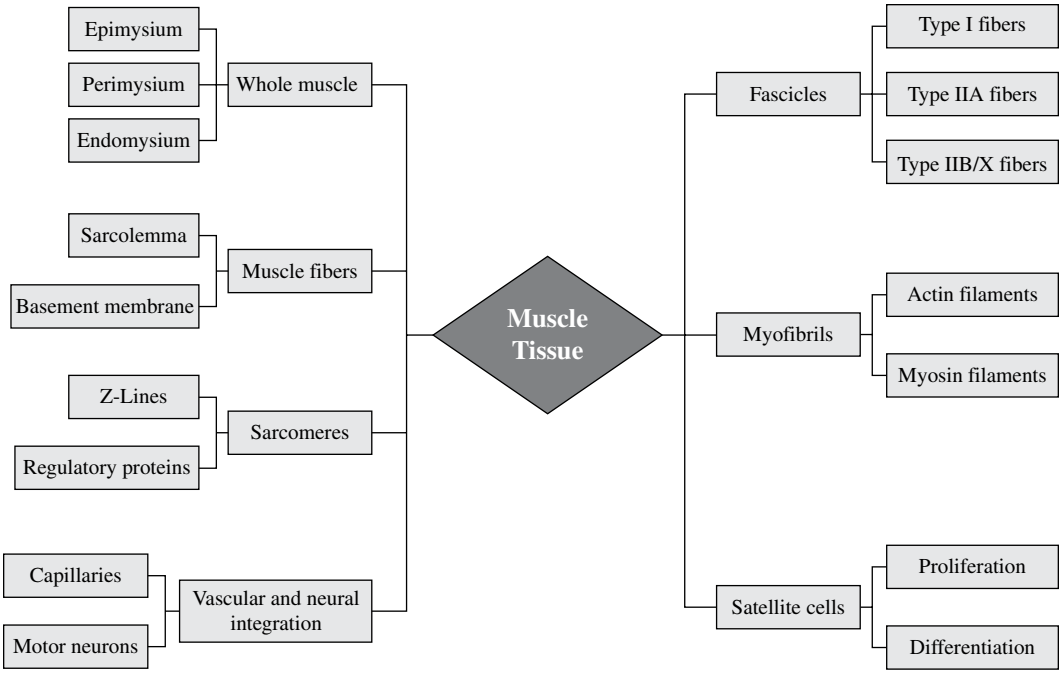

FIGURE 9.1 Muscle tissue structural overview.

9.2.1.1 Whole Muscle and Connective Tissue Framework

The skeletal muscle is composed of bundles of muscle fibers organized into fascicles, which are in turn grouped together to form the complete muscle organ. These components are surrounded by specialized connective tissue layers: epimysium (surrounding the entire muscle), perimysium (encasing each fascicle), and endomysium (enveloping individual muscle fibers) (Tessier *et al.*, 2015). These connective tissues, primarily composed of collagen and elastin, play critical roles in transmitting contractile forces, supporting vascular and nerve networks, and contributing to the meat's texture postslaughter (Nishimura, 2015). The connective tissue architecture varies across species and muscle types, influencing tenderness and functionality (Albrecht and Wegner, 2009).

9.2.1.2 Fascicles and Muscle Fibers

Fascicles represent intermediate bundles consisting of 10–100 muscle fibers aligned longitudinally. Each muscle fiber (or myofiber) is a large, multinucleated cell formed by the fusion of myoblasts during embryogenesis (Schiaffino and Reggiani, 2011). Muscle fibers are surrounded by a sarcolemma (plasma membrane) and a basement membrane that facilitates structural integrity and molecular signaling (Charge and Rudnicki, 2004). Within the fiber, hundreds to thousands of myofibrils are organized in parallel, extending from one end of the fiber to the other. These myofibrils are the primary contractile elements of muscle tissue.

Muscle fibers are broadly categorized based on their metabolic and contractile properties into Type I (slow oxidative), Type IIA (fast oxidative-glycolytic), and Type IIB/X (fast glycolytic) fibers (Lefaucheur, 2010). These fiber types differ in mitochondrial content, myosin heavy chain (MyHC) isoforms, glycogen content, and capillary density, significantly influencing meat color, tenderness, and flavor (Pette and Staron, 2000; Ryu and Kim, 2005).

9.2.1.3 Myofibrils and Sarcomeres

Myofibrils are cylindrical structures (approximately 1–2 μm in diameter) composed of repeating units called sarcomeres, which are the fundamental contractile units of skeletal muscle (Clark *et al.*, 2002).

Sarcomeres are delineated by Z-lines and contain overlapping thin (actin) and thick (myosin) filaments. The organized pattern of these filaments creates the striated appearance of skeletal muscle (Gokhin *et al*., 2015). Sarcomere length and alignment directly affect the muscle's ability to contract and its subsequent tenderness as meat (Listrat *et al*., 2016).

Embedded within the sarcomere are regulatory proteins such as troponin, tropomyosin, and titin, which modulate contraction and contribute to muscle elasticity and structural stability (Bang *et al*., 2001; LeWinter and Granzier, 2013). The cytoskeletal network, particularly desmin and costameres, connects myofibrils to the sarcolemma and extracellular matrix, facilitating coordinated contraction and force transmission (Trotter and Samora, 2001).

9.2.1.4 Satellite Cells and Muscle Regeneration

Satellite cells, located between the sarcolemma and the basement membrane of muscle fibers, serve as muscle stem cells responsible for growth and repair (Mauro, 1961; Yin, Price and Rudnicki, 2013). Upon activation due to injury or hypertrophic stimuli, satellite cells proliferate, differentiate, and fuse with existing fibers or form new fibers, maintaining muscle plasticity (Charge and Rudnicki, 2004). The density and activity of satellite cells vary between muscle types and species, influencing muscle growth potential and postmortem proteolysis rates in meat (Picard *et al*., 2015).

9.2.1.5 Vascular and Neural Integration

Muscle tissue is richly vascularized and innervated, essential for delivering oxygen and nutrients, removing metabolic waste, and initiating contraction. Capillaries run parallel to muscle fibers, with density varying among fiber types; oxidative fibers typically have greater capillary networks (Wang *et al*., 2021). Neural input through motor neurons regulates contraction and influences fiber type through activity-dependent plasticity (Kernell, 2006). These networks also impact postmortem muscle metabolism and the biochemical conversion of muscle to meat (England *et al*., 2014).

9.2.2 Sarcomere Structure and Muscle Contraction Mechanism

The sarcomere is the smallest contractile and structural unit of skeletal muscle, extending from one Z-line to the next. Its arrangement of thick (myosin) and thin (actin) filaments is responsible for muscle contraction and plays a pivotal role in the postmortem transformation of muscle to meat. Structurally, the sarcomere comprises myosin filaments anchored at the M-line and actin filaments anchored at the Z-line, with titin and nebulin acting as molecular scaffolds that regulate elasticity and filament alignment (Granzier and Labeit, 2006). This lattice architecture directly influences meat tenderness, as sarcomere shortening during rigor mortis is a major determinant of final texture (Savell, Mueller and Baird, 2005).

Muscle contraction in the living animal is governed by the sliding filament mechanism, whereby myosin heads cyclically bind to actin in the presence of calcium and ATP, generating force through cross-bridge cycling (Rassier, 2017). After slaughter, ATP depletion leads to the formation of permanent actomyosin bonds, locking the sarcomere in a contracted state. The extent of sarcomere shortening depends on chilling rate, pH decline, and muscle temperature. Excessive shortening, known as cold shortening, results in increased toughness (Koohmaraie and Geesink, 2006).

Postmortem, elevated intracellular calcium levels also activate μ-calpain, a protease that degrades structural proteins such as titin, nebulin, and desmin, facilitating tenderization during aging (Goll *et al*., 2019). The rate of proteolysis and sarcomere degradation varies with species, muscle type, and processing practices. Technological interventions such as electrical stimulation accelerate glycolysis, hasten rigor onset, and prevent cold shortening, thereby preserving sarcomere length and improving tenderness (Kim *et al*., 2018). Understanding the sarcomere's role in contraction and postmortem proteolysis is thus critical for optimizing meat quality parameters, including texture and WHC.

9.2.3 Types of Muscle Fibers (Type I, Type IIa, Type IIb)

Skeletal muscle fibers are broadly categorized into three main types based on their contractile and metabolic characteristics: Type I (slow-twitch oxidative), Type IIa (fast-twitch oxidative-glycolytic), and Type IIb (fast-twitch glycolytic). Each fiber type exhibits distinct biochemical, structural, and functional properties that significantly influence meat quality attributes such as color, tenderness, and WHC (Picard *et al*., 2015).

Type I fibers are characterized by a high content of mitochondria, myoglobin, and oxidative enzymes, enabling sustained contraction with high fatigue resistance. These fibers appear red due to abundant myoglobin and capillary density and are predominantly found in muscles involved in posture and endurance activities (Lefaucheur, 2010). In meat, Type I–rich muscles typically exhibit darker color, higher pH stability, and better oxidative stability (Choi and Kim, 2009).

Type IIa fibers possess intermediate properties, utilizing both aerobic and anaerobic metabolism. These fibers support moderate speed and fatigue resistance and are more adaptable to physiological changes and stress. In the context of meat production, a higher proportion of Type IIa fibers is often associated with improved tenderness and moderate WHC (Ryu and Kim, 2005).

Type IIb fibers rely predominantly on glycolytic metabolism, have fewer mitochondria, lower myoglobin content, and fatigue rapidly. These fibers are suited for short bursts of activity and are pale in appearance. Meat with a high concentration of Type IIb fibers often shows pale, soft, exudative (PSE) characteristics due to rapid postmortem glycolysis and low pH, resulting in decreased WHC and poor texture (Karlsson, Klont and Fernandez, 2014).

The proportion and distribution of fiber types vary by species, breed, muscle function, and even processing interventions such as electrical stimulation and chilling (Nissen, Oksbjerg and Therkildsen, 2006). Selective breeding and dietary management can influence muscle fiber composition, offering strategies to optimize meat quality traits for specific market demands (Kim *et al*., 2018). A deep understanding of muscle fiber physiology is therefore essential for improving carcass quality and consistency in meat production systems.

9.2.4 Connective Tissue Components: Endomysium, Perimysium, and Epimysium

Connective tissue in skeletal muscle is composed of three hierarchical layers: *endomysium*, *perimysium*, and *epimysium*, each contributing to muscle structure, function, and postmortem meat quality. These collagen-rich matrices serve not only as mechanical support systems but also play crucial roles in determining meat tenderness, WHC, and the efficiency of postmortem proteolysis (Purslow, 2018).

The *endomysium* is the innermost layer of connective tissue that envelops individual muscle fibers. It is composed primarily of type I and type III collagen fibers along with proteoglycans and glycoproteins, forming a highly hydrated matrix that facilitates nutrient and metabolite exchange between muscle cells and capillaries (Toldrá and Flores, 2021). Although its contribution to overall muscle stiffness is minimal, alterations in endomysial integrity can influence the fragmentation index and therefore the perceived tenderness of cooked meat (Christensen *et al*., 2011).

Surrounding bundles of muscle fibers is the *perimysium*, the most structurally and functionally significant connective tissue layer affecting meat quality. Composed of dense irregular connective tissue rich in thick collagen fibers, the perimysium is the primary contributor to background toughness in cooked meat (Lepetit, 2008). It organizes fascicles and is involved in force transmission, shear resistance, and the mechanical properties of meat. Age-related cross-linking of perimysial collagen results in increased resistance to heat solubilization, thereby negatively impacting tenderness (Nishimura, 2010).

The *epimysium* forms the outermost sheath that encases the entire muscle. Though relatively sparse compared to the perimysium, it provides protection, shape retention, and transmits contractile force to tendons and bones. It is denser and thicker, contributing marginally to the sensory attributes of meat unless consumed as part of whole cuts (Yu *et al*., 2017).

Postmortem, the enzymatic degradation of intramuscular connective tissue is limited compared to myofibrillar proteins. While calpains target myofibrils, matrix metalloproteinases (MMPs) and cathepsins

TABLE 9.1

Structure and Composition of Meat (Skeletal Muscle) Tissue

Aspect	Description	Key References
Muscle fiber types	Red (Type I), white (Type IIa, IIb) fibers differing in metabolism and myoglobin content	
Muscle fiber structure	Multinucleated fibers surrounded by sarcolemma	
Myofibrils	Contractile elements composed of sarcomeres	
Sarcomere	Functional unit containing actin and myosin filaments	
Actin	Thin filament protein contributing to contraction	
Myosin	Thick filament protein with ATPase activity	
Connective tissue	Endomysium, perimysium, epimysium	
Collagen	Major connective tissue protein influencing tenderness	Bailey and Light, 1989
Elastin	Provides elasticity, resistant to heat	
Sarcoplasm	Cytoplasmic fluid containing enzymes	
Myoglobin	Oxygen-binding pigment affecting meat color	Mancini and Hunt, 2005
Water content	Constitutes ~75% of muscle	
Protein content	~18–22% of muscle tissue	
Lipids	Intramuscular fat (marbling)	Wood *et al.*, 2008
Minerals	Iron, zinc, phosphorus	
Enzymes	Glycolytic and proteolytic enzymes	Huff-Lonergan and Lonergan, 2005
Postmortem changes	Rigor mortis, proteolysis	
pH decline	Due to lactic acid formation	
Ultrastructure	Z-line, I-band, A-band	
Functional role	Movement and support	

have been implicated in modifying connective tissue structures, albeit to a lesser extent (Christensen *et al.*, 2011). Consequently, muscles with higher connective tissue content, such as those used in locomotion, require either mechanical or thermal processing interventions to improve palatability.

Understanding the organization and biochemical properties of endomysium, perimysium, and epimysium is essential in meat science for predicting eating quality and optimizing processing strategies.

Table 9.1 presents the structure and composition of meat (skeletal muscle) tissue.

9.3 Biochemical Composition of Muscle Tissue

The biochemical composition of muscle tissue is summarized and illustrated in Figure 9.2, providing the overview of key components.

9.3.1 Water Content and Its Role in Muscle Tissue

Water is the predominant constituent of muscle tissue, accounting for approximately 75% of the total weight of fresh meat, although this proportion can vary depending on animal species, age, muscle type, and postmortem conditions (Huff-Lonergan and Lonergan, 2005; Lawrie and Ledward, 2014). The distribution and mobility of water within muscle tissue are key determinants of meat quality, particularly in relation to juiciness, tenderness, appearance, and WHC, which significantly affect consumer acceptance and processing yield (Purslow *et al.*, 2016).

Water in muscle exists in three distinct forms: bound water, immobilized water, and free water. Bound water is tightly associated with proteins and is not easily removed, while immobilized water is held within the myofibrillar matrix by capillary forces and is susceptible to structural changes in the muscle. Free water, loosely held in extracellular spaces, is readily lost during storage or processing (Bertram *et al.*, 2006). The structural integrity of muscle, including the organization of myofibrils and the integrity

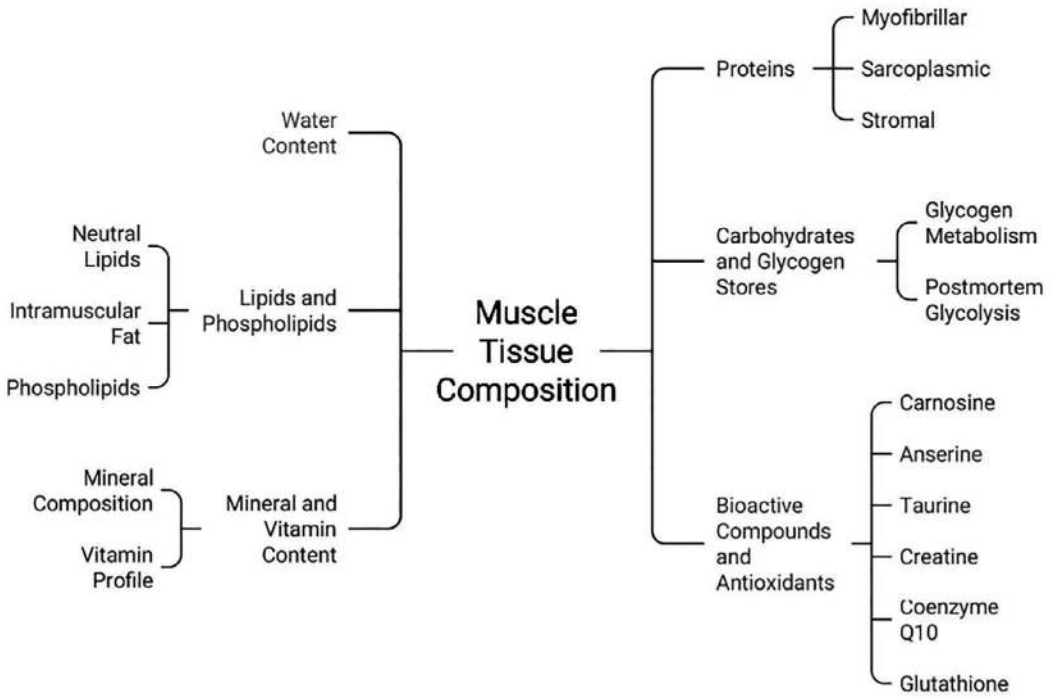

FIGURE 9.2 Biochemical composition of muscle tissue.

of the sarcolemma and extracellular matrix, plays a critical role in determining the location and binding strength of water (Offer and Trinick, 1983).

Postmortem biochemical changes such as pH decline, protein denaturation, and enzymatic proteolysis influence water retention. A rapid pH drop, especially under warm conditions, leads to protein unfolding, exposing hydrophobic regions and reducing the muscle's ability to retain water—a phenomenon associated with PSE meat (Huff-Lonergan and Lonergan, 2005). Conversely, slow pH decline may result in dark, firm, dry (DFD) meat with unusually high WHC due to limited protein denaturation (den Hertog-Meischke, Smulders and van Logtestijn, 1997).

WHC is not only a functional trait but also an indicator of protein structural stability. Myofibrillar proteins, particularly myosin and actin, contribute significantly to WHC by providing hydrophilic binding sites for water molecules. Mechanical disruptions (e.g., grinding or cutting) and thermal processing further modulate water distribution, influencing cook loss and juiciness (Tornberg, 2005). Moreover, muscle-specific differences, such as fiber-type distribution and IMF, also impact WHC (Cheng and Sun, 2008).

Technological interventions, such as salt addition, phosphate treatment, or high-pressure processing, aim to optimize water retention in processed meat products by altering protein structure and electrostatic interactions (Zhao, Zhou and Xu, 2017). As such, understanding the molecular and physical basis of water distribution in muscle is essential for meat scientists and processors to enhance both quality and economic value.

9.3.2 Proteins: Myofibrillar, Sarcoplasmic, Stromal

Proteins are the most significant dry matter constituents of muscle tissue, comprising approximately 18–22% of fresh muscle weight and playing pivotal roles in meat quality, nutrition, and functionality (Lawrie and Ledward, 2014). These proteins are traditionally classified into three major categories based on solubility and function: myofibrillar, sarcoplasmic, and stromal proteins. Each group contributes uniquely to the structural and biochemical properties of meat and its postmortem transformation.

9.3.2.1 Myofibrillar Proteins

Myofibrillar proteins represent around 50–55% of total muscle proteins and are primarily responsible for muscle contraction and meat texture. They include myosin, actin, tropomyosin, troponin, and titin, all integral components of the sarcomere, the basic contractile unit (Huff-Lonergan and Lonergan, 2005). Myosin and actin form cross-bridges during contraction and are crucial for gelation and emulsification in processed meats (Xiong, 2005). These proteins are salt-soluble and exhibit functional properties such as water-binding, viscosity, and protein–protein interactions, which are exploited in meat processing for forming stable meat gels and emulsions (Tornberg, 2005).

9.3.2.1.1 Sarcoplasmic Proteins

Sarcoplasmic proteins, comprising about 30–35% of total muscle proteins, are water-soluble and include enzymes involved in glycolysis, myoglobin, and other pigments. Myoglobin is central to meat color, existing in various redox states (deoxymyoglobin, oxymyoglobin, and metmyoglobin), which influence consumer perception (Faustman *et al*., 2010). Sarcoplasmic enzymes are also key regulators of postmortem metabolism, affecting pH decline, energy depletion, and the onset of rigor mortis (Koohmaraie and Geesink, 2006). Changes in these proteins can alter meat tenderness, color stability, and shelf life.

9.3.2.2 Stromal Proteins

Stromal proteins are insoluble connective tissue proteins, making up about 10–15% of total muscle proteins. The main components include collagen, elastin, and reticulin, which form the endomysium, perimysium, and epimysium around muscle fibers (Purslow, 2005). Collagen, the most abundant stromal protein, contributes to meat toughness, especially in older animals or heavily exercised muscles, due to increased cross-linking (Nishimura, 2010). While collagen has limited functionality in raw meat, thermal processing can denature it into gelatin, improving meat tenderness when cooked slowly.

The intricate interplay between these protein fractions determines the nutritional quality, processing behavior, and sensory characteristics of meat. For example, high myofibrillar content enhances protein functionality, while excessive stromal proteins can negatively affect tenderness. Thus, knowledge of muscle protein composition is crucial in meat science and technology for optimizing meat quality, processing strategies, and consumer satisfaction.

9.3.3 Lipids and Phospholipids

Lipids are critical biochemical constituents of muscle tissue, significantly influencing meat flavor, juiciness, texture, and nutritional quality. They constitute approximately 1–13% of fresh muscle weight, depending on species, muscle type, and animal age (Joo *et al*., 2013). The primary lipid classes in muscle include neutral lipids (mainly triglycerides [TGs]) and polar lipids (notably phospholipids), each playing distinct biological and technological roles in meat science. While TGs are stored within IMF (marbling), phospholipids are structural components of cellular membranes and are highly reactive substrates for lipid oxidation.

9.3.3.1 Neutral Lipids and IMF

Neutral lipids, mainly TGs, are stored in adipocytes interspersed between muscle fibers and bundles. These lipids are composed predominantly of monounsaturated (MUFA) and saturated fatty acids (SFA), although their profile varies by species and diet. High levels of IMF are positively correlated with sensory attributes like tenderness, flavor, and juiciness (Purslow, Gagaoua and Bekhit, 2021). For instance, IMF enhances mouthfeel and provides a matrix for flavor compound retention and release during cooking. Furthermore, dietary manipulation, such as omega-3 enrichment through flaxseed or fish oil supplementation, can alter the lipid profile of meat to improve its nutritional functionality (Chaiwang, Kreuzer and Leiber, 2021).

9.3.3.2 Phospholipids and Membrane Dynamics

Phospholipids constitute approximately 0.5–1.0% of fresh muscle and are primarily located in the sarcolemma, mitochondria, and sarcoplasmic reticulum. They include phosphatidylcholine, phosphatidylethanolamine, phosphatidylinositol, and sphingomyelin, which are integral to maintaining membrane fluidity, signal transduction, and ion transport (Tian *et al*., 2022). Unlike neutral lipids, phospholipids are rich in polyunsaturated fatty acids (PUFA) such as arachidonic and docosahexaenoic acid, which render them highly susceptible to lipid peroxidation (Domínguez *et al*., 2021). This oxidative degradation can produce volatile aldehydes and ketones that impact meat aroma and shelf life stability (Estevez and Petracci, 2021).

9.3.3.3 Functional and Oxidative Implications

The lipid composition of muscle influences various postmortem biochemical processes. Lipid oxidation is a major determinant of meat quality deterioration, affecting color stability, flavor, and nutritional value (Zhang *et al*., 2020). The oxidative susceptibility of phospholipids also makes them crucial biomarkers in assessing the oxidative stability of fresh and processed meats. Antioxidant strategies such as the use of dietary polyphenols or packaging technologies (e.g., modified atmosphere packaging) are increasingly adopted to mitigate phospholipid oxidation and preserve meat quality (Kanner, 2020; Muela, Monge and Sañudo, 2021).

9.3.4 Carbohydrates and Glycogen Stores

Carbohydrates, though present in relatively small quantities in muscle tissue (typically <1%), play a pivotal role in postmortem metabolism, meat quality, and preservation. The predominant carbohydrate in muscle is glycogen, a branched polysaccharide that serves as the primary energy reservoir. Glycogen's role becomes particularly crucial after slaughter, where it undergoes anaerobic glycolysis, resulting in lactic acid accumulation and pH decline, processes fundamental to meat tenderization, WHC, and shelf stability (Zhao *et al*., 2021).

9.3.4.1 Glycogen Metabolism and Postmortem Glycolysis

Glycogen is stored within the sarcoplasm of muscle fibers and is metabolized into glucose-1-phosphate by glycogen phosphorylase, which enters the glycolytic pathway. Postmortem, the absence of oxygen shifts energy production toward anaerobic glycolysis, causing lactic acid buildup that lowers muscle pH from around 7.2 to ultimate pH values between 5.4 and 5.8 (England *et al*., 2016). The rate and extent of this pH drop are critical for meat quality attributes such as color, tenderness, and WHC. Inadequate glycogen reserves at slaughter result in high ultimate pH (>6.0), often associated with DFD meat, while excessive glycolysis can lead to PSE meat especially in pork and poultry (Barbut, 2019; Petracci and Cavani, 2012).

9.3.4.2 Factors Affecting Glycogen Levels

Preslaughter factors such as animal stress, handling, feed withdrawal, and transportation can significantly impact glycogen stores. Stress elevates catecholamine release, which accelerates glycogenolysis and depletes reserves prior to slaughter (Zhao *et al*., 2021). In ruminants and pigs, animals exposed to acute or chronic stress tend to show altered glycogen metabolism, affecting postmortem muscle biochemistry and meat quality (Ouali *et al*., 2013). Nutritional strategies like carbohydrate loading or high-energy diets preslaughter have shown potential to increase muscle glycogen reserves and stabilize postmortem glycolysis (Nair *et al*., 2019).

9.3.4.3 Implications for Meat Quality

The pH decline due to glycogen breakdown is intrinsically linked to proteolytic enzyme activity, particularly calpains and cathepsins, which contribute to muscle protein degradation and tenderization

(Warner *et al.*, 2022). Moreover, pH affects myoglobin stability and thus meat color, as well as microbial shelf life. High-pH meat is more prone to bacterial growth, while low-pH meat may suffer from poor WHC and pale appearance (Jeleníková, Pipek and Staruch, 2008). As such, glycogen quantification and pH monitoring are routine quality control parameters in meat processing plants (Matarneh *et al.*, 2021).

9.3.5 Mineral and Vitamin Content

Skeletal muscle tissue serves as a significant dietary source of essential minerals and vitamins, contributing to the nutritional value of meat and its derivatives. These micronutrients not only fulfill critical biological functions within living muscle but also impact postmortem metabolic processes, meat color stability, oxidative resistance, and consumer health outcomes (Lombardi-Boccia, Lucherini and Aguzzi, 2022). The bioavailability of minerals and vitamins in meat is generally high, making it a key contributor to human micronutrient intake, especially in diets with limited plant diversity.

9.3.5.1 Mineral Composition and Functional Roles

Muscle tissue contains a broad spectrum of macro- and micro-minerals, including potassium (K), phosphorus (P), sodium (Na), magnesium (Mg), calcium (Ca), iron (Fe), zinc (Zn), and selenium (Se) (Wójciak, Dolatowski and McDonnell, 2020). Potassium and phosphorus are the most abundant, contributing to cellular osmotic balance, ATP production, and buffering systems. Iron, predominantly present as heme iron in myoglobin, is critical for oxygen transport and redox processes and is more bioavailable than non-heme iron found in plant sources (Lombardi-Boccia, Lucherini and Aguzzi, 2022). Zinc plays structural and catalytic roles in numerous enzymes, while selenium is vital for antioxidant selenoproteins such as glutathione peroxidase, which mitigates oxidative stress in both muscle tissue and human cells (Pereira and Abreu, 2022).

The concentration of these minerals varies based on species, muscle type, diet, age, and genetic background (Pintado *et al.*, 2021). For instance, red muscles often contain more iron due to elevated myoglobin levels, whereas white muscle fibers tend to have lower mineral density. Furthermore, grass-fed animals may have higher selenium and iron content compared to grain-fed ones due to the mineral content of forage (Khan, Jo and Tariq, 2020).

9.3.5.2 Vitamin Profile in Muscle Tissue

Muscle is also an important reservoir for water-soluble B-complex vitamins and some fat-soluble vitamins. The B group, particularly thiamine (B1), riboflavin (B2), niacin (B3), pyridoxine (B6), and cobalamin (B12), plays vital roles in energy metabolism, amino acid conversion, and nucleic acid synthesis. Among these, vitamin B12 is found almost exclusively in animal products, making meat essential in preventing cobalamin deficiency, especially in vulnerable populations (Allen, 2018). Additionally, vitamin D is stored in small quantities in muscle and adipose tissue, particularly in animals exposed to sunlight or supplemented diets (Cashman, Ritz and Kiely, 2021).

The vitamin content in meat is highly sensitive to storage, processing, and cooking methods, with some B vitamins (e.g., thiamine and folate) being susceptible to thermal degradation. Newer meat preservation techniques such as high-pressure processing and vacuum packaging have shown improved retention of these labile compounds during storage (Pintado *et al.*, 2021).

9.3.5.3 Nutritional and Technological Relevance

Minerals and vitamins significantly influence muscle physiology and meat technology. For example, iron and zinc deficiencies in animals have been linked to altered muscle enzyme activities and reduced growth performance, impacting carcass quality (Pereira and Abreu, 2022). In meat processing, iron and copper act as pro-oxidants, affecting lipid and pigment oxidation, which in turn influences shelf life,

flavor, and color stability (Suman and Joseph, 2014). Consequently, balancing mineral intake during animal rearing is crucial for ensuring both meat quality and human nutritional adequacy.

9.3.6 Bioactive Compounds and Antioxidants in Muscle Tissue

Muscle tissue is not only a rich source of macronutrients but also contains a variety of bioactive compounds and endogenous antioxidants that contribute to both meat quality and human health. Bioactive molecules, such as carnosine, anserine, taurine, creatine, coenzyme Q10 (CoQ10), and glutathione, are naturally synthesized within muscle and possess antioxidant, anti-inflammatory, and cytoprotective properties (Mora, Sentandreu and Toldrá, 2021; Zhang *et al.*, 2022). These compounds are particularly concentrated in skeletal muscle due to its high metabolic activity and oxidative demand, with concentrations varying according to species, muscle fiber type, and physiological state (Jayasena *et al.*, 2014).

9.3.6.1 Carnosine, Anserine, and Taurine

Carnosine (β-alanyl-L-histidine) and its methylated analog anserine are dipeptides abundant in Type II (fast-twitch) muscle fibers. They exhibit proton-buffering capacity, which is crucial in delaying pH decline during postmortem glycolysis and thus stabilize meat color and texture (Boldyrev, Aldini and Derave, 2013). Furthermore, carnosine acts as a metal chelator and radical scavenger, reducing lipid and protein oxidation during storage (Zhang *et al.*, 2022). Taurine, a sulfur-containing amino acid, plays a role in osmoregulation, membrane stabilization, and antioxidant defense, and is notably present in red meat from beef, lamb, and pork (Wójciak, Dolatowski and McDonnell, 2020).

9.3.6.2 Creatine and Coenzyme Q10

Creatine is another notable compound in muscle tissue, present both in free form and as phosphocreatine, functioning primarily in energy buffering during rapid contractions. It also exhibits mild antioxidant activity, indirectly supporting cellular redox status (Sestili *et al.*, 2011). Coenzyme Q10 (ubiquinone) is a lipophilic antioxidant localized in the mitochondrial membrane, where it supports electron transport and scavenges lipid peroxyl radicals, thus protecting both muscle cells and meat lipids from oxidative degradation (Mora, Sentandreu and Toldrá, 2021).

9.3.6.3 Glutathione and Enzymatic Antioxidants

The glutathione (GSH) system represents a central antioxidant defense mechanism in muscle. It functions in thiol-disulfide exchange, hydrogen peroxide detoxification, and maintenance of protein thiol groups (Lobo *et al.*, 2022). GSH works synergistically with glutathione peroxidase (GPx) and glutathione reductase, which are essential in regulating oxidative stress during muscle activity and in preserving meat quality postmortem (Estévez and Xiong, 2019). Other enzymatic antioxidants such as superoxide dismutase (SOD) and catalase also protect muscle tissue from reactive oxygen species (ROS), especially in oxidative fiber types with high mitochondrial content (Jayasena *et al.*, 2014).

9.3.6.4 Relevance to Meat Science and Human Health

The presence and stability of bioactive compounds and antioxidants in muscle tissue are critical in determining meat shelf life, sensory attributes, and nutritional value. During aging and storage, oxidative stress leads to lipid peroxidation and myoglobin oxidation, which can be mitigated by these intrinsic antioxidants (Estévez, 2015). Moreover, dietary intake of these bioactives through meat consumption has been linked to neuroprotective, antiaging, and anti-fatigue effects in humans (Mora, Sentandreu and Toldrá, 2021; Zhang *et al.*, 2022). Processing techniques such as high-pressure treatment and antioxidant enrichment can further enhance the retention and functionality of these compounds in meat products (Pintado *et al.*, 2021).

9.4 Adipose Tissue: Structure and Function

Adipose tissue in meat animals exists in several anatomical depots, with varying physiological functions and implications for meat quality. The primary types include subcutaneous adipose tissue (SAT), intermuscular adipose tissue (IMAT), and intramuscular adipose tissue, each distinguished by their location, cellular composition, metabolic activity, and impact on sensory and nutritional traits of meat (Chung *et al*., 2018; Hocquette *et al*., 2010).

9.4.1 Subcutaneous Adipose Tissue

SAT is located beneath the skin and constitutes the largest fat depot in most meat animals. It serves as an energy reservoir, thermal insulator, and mechanical protector. In meat processing, SAT influences carcass grading, chilling efficiency, and fat trimming losses (Histologically, SAT consists predominantly of unilocular white adipocytes and exhibits a high lipid-to-protein ratio. The fatty acid profile of SAT is influenced by genetics, diet, and species, typically showing higher proportions of saturated and monounsaturated fatty acids (Smith, Gill and Lunt, 2020).

While SAT is essential for animal survival, its accumulation is often considered undesirable in commercial meat production due to increased carcass fatness and reduced lean yield. However, moderate SAT contributes to the prevention of cold shortening during postmortem cooling by acting as an insulator, thereby indirectly supporting meat tenderness (Pethick *et al*., 2004).

9.4.2 Intermuscular Adipose Tissue

IMAT is deposited between muscle groups, often within fascial layers. It is anatomically distinct from SAT and IMF and contributes less prominently to flavor or texture. IMAT development is more genetically regulated than diet-sensitive (Du *et al*., 2013). In carcass evaluation, IMAT affects the visual appeal of primal cuts and may be removed during butchering, thereby impacting retail value.

Functionally, IMAT shares similar lipid storage characteristics with SAT but displays slightly lower metabolic turnover rates (Lee, Choe and Kim, 2021). Although it has limited direct impact on palatability, excessive IMAT accumulation may signal metabolic inefficiencies or over-fattening, both of which are undesirable traits in lean meat production systems (Gondret, Lebret and Louveau, 2017).

9.4.3 Intramuscular Adipose Tissue: Marbling

Intramuscular adipose tissue (IMF), or marbling, is interspersed among muscle fibers and fascicles and is considered the most desirable form of fat deposition in high-quality meat products. Unlike SAT and IMAT, IMF is directly correlated with meat juiciness, tenderness, and flavor, making it a key determinant in meat quality grading systems (Hocquette *et al*., 2010; Smith *et al*., 2021). Marbling consists of small adipocyte clusters integrated within the perimysial and endomysial connective tissue network.

IMF development is influenced by complex interactions between genetics (e.g., breed), nutrition (particularly high-energy diets), hormonal regulation, and developmental timing (Du *et al*., 2013). Unlike SAT, IMF accumulates later in ontogeny and requires specific metabolic cues such as insulin sensitivity and lipogenic gene expression (Wang *et al*., 2021). Notably, IMF displays higher concentrations of polyunsaturated fatty acids (PUFAs) and bioactive lipids such as conjugated linoleic acids, which enhance its nutritional profile (Chung *et al*., 2018).

Recent advances in meat science emphasize IMF manipulation through nutrigenomics, metabolic programming, and precision feeding to optimize marbling without excessive SAT deposition (Piao *et al*., 2023). Given its contribution to sensory quality and consumer preference, IMF remains a focal point in both academic research and industrial meat production strategies.

9.4.4 Cellular Composition: Adipocytes, Stromal Vascular Cells

Adipose tissue, beyond its role as an energy reservoir, is a metabolically dynamic organ composed of heterogeneous cell populations. The two principal cellular components of adipose tissue are adipocytes and the stromal vascular fraction (SVF), which includes preadipocytes, fibroblasts, vascular endothelial cells, pericytes, immune cells, and mesenchymal stem cells (MSCs) (Vishvanath and Gupta, 2019). Understanding the cellular architecture of adipose tissue is essential in meat science, as the balance between these components influences adipogenesis, fat deposition, and ultimately, the quality attributes of meat.

9.4.4.1 Adipocytes: The Lipid-Storing Cells

Adipocytes are terminally differentiated cells specialized in lipid storage and endocrine signaling. In meat animals, they are primarily unilocular white adipocytes that store TGs in a large central lipid droplet, surrounded by a thin cytoplasmic rim and a peripheral nucleus (Smith, Gill and Lunt, 2020). The differentiation of preadipocytes into mature adipocytes termed adipogenesis is governed by a cascade of transcriptional regulators, including PPARγ, C/EBPα, and SREBP1c, whose expression is influenced by nutrition, genetics, and hormonal signals (Liu *et al.*, 2021).

Adipocytes not only determine the extent of fat deposition but also contribute to the fatty acid profile and marbling distribution in muscle tissues. Their size and number vary by depot; for instance, intramuscular adipocytes are generally smaller and more dispersed than subcutaneous adipocytes, resulting in finer marbling patterns associated with high meat quality (Chung *et al.*, 2018; Piao *et al.*, 2023).

Importantly, adipocytes exhibit endocrine functions, secreting adipokines such as leptin, adiponectin, and resistin, which regulate lipid metabolism and inflammation (Frazier, K. N. (2023) These factors not only modulate fat deposition in the animal but also influence postmortem muscle biochemistry, potentially affecting meat aging and tenderness.

9.4.4.2 Stromal Vascular Cells: Support and Signaling

SVF is a diverse mixture of non-adipocyte cells that play essential roles in adipose tissue development, remodeling, and metabolic regulation. Key cellular constituents include the following:

- *Preadipocytes:* These are adipocyte precursors residing in the SVF. Upon receiving adipogenic stimuli, such as insulin and glucocorticoids, preadipocytes differentiate into mature adipocytes through mitotic clonal expansion and activation of adipogenic transcription factors (Gondret, Lebret and Louveau, 2017).
- *Endothelial Cells:* Adipose tissue is highly vascularized, and endothelial cells line the capillaries that provide oxygen and nutrients essential for adipocyte function and growth. Angiogenesis and adipogenesis are tightly coupled processes; thus, endothelial cell activity influences the rate and pattern of fat accretion in different depots (Han *et al.*, 2020).
- *Immune Cells:* Macrophages, lymphocytes, and neutrophils within the SVF modulate adipose tissue inflammation, which in turn affects lipid metabolism and meat quality. Inflammatory responses, especially in over-fattened animals, may lead to oxidative stress and altered muscle-to-fat ratios (Zhang *et al.*, 2021).
- *Mesenchymal Stem Cells:* Multipotent stem cells in the SVF have the capacity to differentiate into adipocytes, chondrocytes, and myocytes. The lineage commitment of MSCs is a critical factor in regulating the balance between muscle and fat development, especially in intramuscular regions (Muhlhausler *et al.*, 2010).

The SVF also contains fibroblasts and pericytes, which contribute to extracellular matrix (ECM) remodeling and capillary stability, respectively. ECM dynamics, governed by the interplay of these cells, impact tissue elasticity and IMF infiltration (Listrat *et al.*, 2016).

9.4.4.3 Relevance to Meat Quality and Production

The interactions between adipocytes and stromal vascular cells are crucial for the regulation of adipose tissue expansion and functionality. Depot-specific differences in SVF composition and signaling pathways lead to distinct patterns of fat deposition that directly affect marbling, fat firmness, and sensory properties of meat (Hocquette *et al.*, 2010).

Emerging omics technologies such as single-cell RNA sequencing and spatial transcriptomics have provided deeper insights into the cellular heterogeneity of adipose tissue in livestock, uncovering novel regulators of adipogenesis that may be leveraged to optimize carcass traits and fat distribution (Sun *et al.*, 2024).

9.4.5 Development and Deposition in Livestock

Adipose tissue development and deposition in livestock is a complex, tightly regulated biological process that influences carcass composition, energy balance, thermoregulation, and most notably, meat quality. The spatiotemporal accumulation of fat in different anatomical depots, including subcutaneous, intermuscular, and intramuscular sites, is governed by genetic, nutritional, hormonal, and environmental factors (Wang *et al.*, 2021). A thorough understanding of adipose development is critical for optimizing production efficiency and enhancing desirable traits such as marbling and tenderness in meat animals.

9.4.5.1 Ontogeny of Adipose Tissue

Adipose tissue originates from MSCs within the embryonic mesoderm, which differentiate into preadipocytes and subsequently into mature adipocytes. This adipogenesis is orchestrated through two main phases: determination and terminal differentiation. In the determination phase, MSCs commit to the adipogenic lineage under the influence of early transcription factors such as Zfp423 and Pref-1. The terminal differentiation phase is marked by the activation of PPARγ and C/EBPα, which drive the transcription of genes involved in lipid uptake, synthesis, and storage (Ahmadian *et al.*, 2013; Sun, Zhang and Zhou, 2023).

Adipogenesis begins during fetal development, but the major wave of adipocyte hyperplasia and hypertrophy typically occurs in the postnatal period. The timing and extent of these phases vary among species and fat depots. Notably, IMF develops later and at a slower rate than subcutaneous and visceral fat, largely due to its unique vascularization and microenvironment (Zhang *et al.*, 2022).

9.4.5.2 Depot-Specific Fat Deposition

The chronology and extent of fat deposition follow a distinct anatomical pattern: visceral > subcutaneous > intermuscular > intramuscular (Picard *et al.*, 2015). Subcutaneous fat is the first to accumulate and is considered the most responsive to dietary energy surpluses. Intramuscular adipocytes, responsible for marbling, are last to develop and are more sensitive to hormonal and genetic regulation (Liu *et al.*, 2021).

Several studies have demonstrated depot-specific differences in adipocyte size, proliferation capacity, and gene expression profiles. For instance, intramuscular adipocytes exhibit higher expression of angiogenic and oxidative genes, supporting their specialized role in enhancing meat flavor and juiciness (Hausman *et al.*, 2014; Sun, Zhang and Zhou, 2023).

9.4.5.3 Regulatory Mechanisms

Genetic regulation plays a pivotal role in fat deposition. Specific genes such as *FABP4*, *SCD*, *ADIPOQ*, and *LEP* have been identified as key modulators of adipogenesis and lipid metabolism in various livestock species. Breed differences significantly influence fat deposition; for example, Wagyu cattle exhibit superior marbling ability compared to Holstein or Charolais breeds due to enhanced expression of lipogenic genes Gotoh *et al.*, 2018; Muroya, Oe and Ojima (2013).

Nutritional factors, especially energy density and the composition of dietary fatty acids, modulate adipose development by affecting the expression of lipogenic enzymes such as acetyl-CoA carboxylase and fatty acid synthase (Zhao *et al.*, 2021). Feeding strategies such as high-grain finishing or supplementation with unsaturated fatty acids have been used to selectively enhance IMF deposition without increasing subcutaneous fat.

Endocrine and paracrine signals, including insulin, growth hormone (GH), thyroid hormones, and glucocorticoids, further mediate adipose tissue development. Insulin, in particular, promotes glucose uptake and lipogenesis in adipocytes, while GH generally inhibits lipid storage (Bonnet *et al.*, 2010). The cross-talk between adipocytes and other stromal vascular cells, such as macrophages and endothelial cells, adds additional layers of regulatory complexity.

9.4.5.4 Impact on Meat Quality

The pattern and extent of fat deposition significantly affect meat quality parameters such as tenderness, juiciness, flavor, and overall palatability. IMF or marbling is especially valued in premium meat markets due to its positive correlation with consumer preference (Hocquette *et al.*, 2010). In contrast, excessive subcutaneous and visceral fat may reduce carcass yield and processing efficiency.

Moreover, early-life nutritional programming has been shown to influence adipose tissue development and long-term fat distribution. For instance, undernutrition during prenatal stages may reduce total adipocyte number, predisposing animals to altered fat deposition postnatally (Muhlhausler and Smith, 2009). Such findings underscore the importance of precision feeding and genetic selection to modulate adipose tissue development for targeted meat quality outcomes.

9.5 Biochemical Composition of Adipose Tissue

9.5.1 Lipid Classes: TGs, Phospholipids, and Sterols

Adipose tissue is a highly specialized connective tissue primarily involved in energy storage, endocrine regulation, and thermogenesis. The biochemical landscape of adipose tissue is predominantly defined by its lipid constituents, which are critical not only for metabolic functions in animals but also significantly influence meat quality in the context of food science. The major lipid classes found in adipose tissue are TGs, phospholipids, and sterols, each contributing distinct structural and functional roles.

9.5.1.1 Triglycerides

TGs, also known as triacylglycerols, are the most abundant lipid type in adipose tissue, constituting up to 80–90% of the total lipid content (Kershaw and Flier, 2004). Structurally, TGs are esters derived from one molecule of glycerol and three fatty acid chains, which may vary in chain length and degree of unsaturation. These variations influence not only the physical properties of adipose tissue but also the oxidative stability and flavor development of meat products (Wood *et al.*, 2008). In livestock, TG composition is influenced by genetics, diet, and species-specific lipid metabolism. For instance, ruminants exhibit a higher proportion of saturated fatty acids due to microbial hydrogenation in the rumen, whereas monogastric animals deposit more unsaturated fatty acids (Warren *et al.*, 2008).

From a functional perspective, TGs serve as a dense energy reserve, providing approximately 9 kcal/g upon oxidation (Lengi *et al.*, 2019). Their mobilization is tightly regulated by hormonal signals such as insulin, leptin, and catecholamines. During fasting or energy-deficient states, hormone-sensitive lipase (HSL) catalyzes the hydrolysis of TGs, releasing free fatty acids and glycerol into circulation (Rosen and Spiegelman, 2014). This process is essential for maintaining systemic energy balance and influences muscle–fat interactions that are vital to postmortem meat quality attributes.

9.5.1.2 Phospholipids

Phospholipids constitute a smaller proportion (about 5–10%) of adipose lipids but are crucial for maintaining cellular membrane integrity and function (Nieman *et al.*, 2015). They are amphipathic molecules composed of glycerol, two fatty acid tails, and a phosphate group linked to an additional polar molecule such as choline or ethanolamine. In adipocytes, phospholipids are predominantly localized in the monolayer membrane surrounding lipid droplets and in plasma and organelle membranes (Cushman *et al.*, 2018).

Phospholipids play essential roles in intracellular signaling, membrane fluidity, and adipogenesis. Additionally, they serve as reservoirs for bioactive lipids like arachidonic acid, which can be enzymatically converted into eicosanoids as important mediators of inflammation and metabolic regulation (Cabrera-Reyes *et al.*, 2022). In meat science, the composition and oxidation of phospholipids are linked to the development of rancid off-flavors and reduced shelf life, especially in meats rich in polyunsaturated fatty acids.

9.5.1.3 Sterols

Sterols are another minor but biochemically significant class of lipids in adipose tissue. The most abundant sterol is cholesterol, which serves as a precursor for steroid hormones (e.g., cortisol, androgens), bile acids, and vitamin D (Gondret and Lebret, 2021). Cholesterol is a vital component of lipid rafts in cellular membranes, modulating membrane fluidity and facilitating signal transduction.

In the context of livestock, the cholesterol content in adipose tissue varies with species, age, and fat depot location (Smet *et al.*, 2004). Importantly, while the total sterol content in meat is relatively low compared to other lipid classes, its health implications have received significant attention in nutritional studies. Moreover, cholesterol oxidation products (COPs), generated during meat processing and storage, are considered potential risk factors for cardiovascular disease (Martínez *et al.*, 2023). Thus, understanding sterol composition is essential for both quality control and the development of functional meat products with improved lipid profiles.

In Table 9.2, the structure and composition of adipose (fat) tissue are depicted.

TABLE 9.2

Structure and Composition of Adipose (Fat) Tissue

Aspect	Description	Key References
Adipocyte type	White adipocytes dominant in meat animals	
Cell structure	Large lipid droplet with peripheral nucleus	
Lipid content	Triglycerides constitute ~90%	
Fat deposition	Subcutaneous, visceral, intermuscular, intramuscular	Wood *et al.*, 2008
Intramuscular fat	Determines marbling and palatability	Hocquette *et al.*, 2010
Fatty acid profile	Saturated, monounsaturated, polyunsaturated	
Oleic acid	Dominant MUFA in ruminant fat	Wood *et al.*, 2008
Phospholipids	Structural lipids in cell membranes	
Cholesterol	Component of adipose tissue	McNamara, 2010
Connective tissue	Supports adipocyte clusters	
Vascularization	Rich blood supply for lipid metabolism	
Lipogenesis	Fat synthesis from glucose	
Lipolysis	Breakdown of stored triglycerides	
Hormonal regulation	Insulin, leptin, catecholamines	Rosen and Spiegelman, 2014
Color variation	White to yellow depending on carotenoids	
Texture	Softness influenced by fatty acid composition	
Thermal behavior	Melting point varies with saturation	
Nutritional role	Energy storage and insulation	
Sensory contribution	Flavor, juiciness	Hocquette *et al.*, 2010
Functional role	Energy reserve and cushioning	

9.5.2 Fatty Acid Profiles and Nutritional Implications

Adipose tissue in livestock serves not only as a depot for energy storage but also as a determinant of the fatty acid composition of meat, which significantly influences its nutritional and functional properties. The profile of fatty acids in adipose tissue is a complex matrix, encompassing saturated fatty acids (SFAs), monounsaturated fatty acids (MUFAs), and polyunsaturated fatty acids (PUFAs), whose proportions vary based on species, diet, age, sex, and anatomical location of the fat depot (Alfaia *et al*., 2010; Wood *et al*., 2008). These lipid fractions are pivotal not only to the technological characteristics of meat but also to its health value from a consumer perspective.

9.5.2.1 Fatty Acid Composition in Livestock Adipose Tissue

Typically, SFAs such as palmitic acid (C16:0) and stearic acid (C18:0) are the most predominant in ruminant adipose tissue due to biohydrogenation processes in the rumen (Scollan, Price and Morgan, 2014). MUFAs, particularly oleic acid (C18:1 n-9), are commonly elevated in IMF and are positively associated with desirable eating qualities such as juiciness and flavor (Pérez-Santaescolástica *et al*., 2018). PUFAs, including essential fatty acids such as linoleic acid (C18:2 n-6) and α-linolenic acid (C18:3 n-3), are usually present in lower concentrations in ruminants, as unsaturated fatty acids undergo extensive microbial hydrogenation in the foregut (Shingfield *et al*., 2010).

9.5.2.2 Nutritional Significance of Fatty Acid Profiles

The fatty acid composition of adipose tissue directly affects the health implications of meat consumption. High levels of SFAs, especially lauric (C12:0), myristic (C14:0), and palmitic acids, are associated with increased plasma low-density lipoprotein (LDL) cholesterol and cardiovascular risk (Mensink, 2016). However, stearic acid is generally considered neutral with respect to plasma cholesterol levels.

On the other hand, MUFAs, particularly oleic acid, have been shown to exert cardioprotective effects by reducing LDL cholesterol and increasing high-density lipoprotein (HDL) levels (Chwingshackl and Hoffmann, 2014). Similarly, n-3 PUFAs such as eicosapentaenoic acid (EPA, C20:5 n-3) and docosahexaenoic acid (DHA, C22:6 n-3) have been linked to anti-inflammatory, antiarrhythmic, and TG-lowering properties, contributing to the prevention of cardiovascular and neurodegenerative diseases (Calder, 2015).

The ratio of n-6 to n-3 PUFAs is a critical nutritional index. Modern diets are typically skewed toward higher n-6 PUFA intake, promoting pro-inflammatory responses. Therefore, improving the n-6/n-3 PUFA ratio in meat ideally toward 4:1 or lower is a major goal in functional meat development (Simopoulos, 2016). This can be achieved through feeding strategies that include marine oils, flaxseed, or other rich sources of α-linolenic acid.

9.5.2.3 Biohydrogenation and Isomerization in Ruminants

The unique microbial environment in the rumen results in the biohydrogenation of unsaturated fatty acids, leading to the formation of bioactive fatty acid isomers such as conjugated linoleic acid (CLA), particularly the *cis*-9, *trans*-11 isomer (Jenkins *et al*., 2008). CLA has been shown to possess anticarcinogenic, antiatherogenic, and body composition–modulating effects in both experimental models and humans (Dilzer and Park, 2012). Hence, CLA-rich ruminant meats can be considered value-added functional foods.

9.5.2.4 Implications for Meat Quality and Human Health

From a technological standpoint, the FA profile influences fat firmness, oxidative stability, and flavor development. Higher PUFA content is associated with softer fat and greater susceptibility to lipid oxidation, which can negatively affect shelf life and sensory quality. Conversely, higher MUFA content is associated with improved flavor and oxidative stability.

In human nutrition, optimizing the FA profile of meat is a key strategy to align with health recommendations. This includes reducing SFA content while enriching MUFA and PUFA levels, particularly n-3 FAs, without compromising meat palatability or processing quality (Jiménez-Colmenero *et al*., 2010).

9.5.3 Role of Adipokines and Other Bioactive Molecules

Adipose tissue is increasingly recognized as an active endocrine organ that secretes a variety of biologically active molecules, collectively termed adipokines, along with cytokines, growth factors, and lipid mediators that profoundly influence metabolism, inflammation, and homeostasis in both animals and humans. These secreted factors are involved in intercellular communication between adipose tissue and other organ systems and play crucial roles in regulating energy balance, insulin sensitivity, immunity, and reproductive function (Choe *et al*., 2016; Trayhurn and Wood, 2005).

Among the most well-characterized adipokines is leptin, a 16-kDa hormone predominantly secreted by white adipocytes. Leptin regulates appetite and energy expenditure through hypothalamic signaling and plays a role in immune modulation, reproductive function, and lipid metabolism (Kershaw and Flier, 2004; Zhang *et al*., 1994). In livestock, leptin gene polymorphisms are associated with fat deposition, feed efficiency, and carcass traits (Nkrumah *et al*., 2005). Another major adipokine, adiponectin, enhances insulin sensitivity and exhibits anti-inflammatory and anti-atherogenic effects. Interestingly, adiponectin levels inversely correlate with adiposity, which contrasts with most other adipokines (Petersen and Shulman, 2018). In ruminants, adiponectin is implicated in the regulation of lipid metabolism in skeletal muscle and liver, contributing to IMF development (Bonnet *et al*., 2010).

Resistin and visfatin are additional adipokines with notable functions. Resistin is involved in the development of insulin resistance and inflammatory responses (Steppan *et al*., 2001), while visfatin, also known as nicotinamide phosphoribosyltransferase (NAMPT), modulates NAD biosynthesis and cellular metabolism, influencing adipocyte differentiation and metabolic regulation (Garden *et al*., 2020; Otero *et al*., 2006).

Beyond proteinaceous adipokines, adipose tissue secretes bioactive lipids such as prostaglandins, lipoxins, and endocannabinoids, which mediate paracrine and endocrine effects on metabolism, inflammation, and vascular tone (Dumas and Le Lay, 2021). Additionally, cytokines such as tumor necrosis factor-alpha (TNF-α) and interleukin-6 (IL-6) are released from stromal vascular cells and infiltrating immune cells within adipose depots. These cytokines contribute to low-grade chronic inflammation, particularly in metabolically dysfunctional fat depots, and are implicated in the pathogenesis of insulin resistance and metabolic disorders (Hotamisligil, 2006).

In livestock, the local and systemic effects of adipokines extend to growth regulation, feed efficiency, reproductive performance, and disease resistance, making them potential biomarkers and targets for genetic and nutritional modulation (Hou *et al*., 2021). Moreover, the balance between pro-inflammatory and anti-inflammatory adipokines is increasingly considered a determinant of *meat quality traits*, such as IMF deposition and oxidative stability.

9.6 Factors Affecting Muscle and Adipose Tissue Composition

The key factors influencing muscle and adipose tissue composition, including species and breed differences, animal age and sex, nutrition and feeding practices, and genetic and environmental interactions, are presented in Figure 9.3, highlighting the key factors impact on muscle and adipose tissue composition.

9.6.1 Species and Breed Differences

Species and breed differences are among the primary biological determinants influencing the composition of both muscle and adipose tissues in meat animals. These variations significantly affect meat quality parameters such as tenderness, marbling, flavor, and nutritional value, thereby shaping consumer preference and market value (Hocquette *et al*., 2010; Pethick *et al*., 2022). The interplay of genetic factors

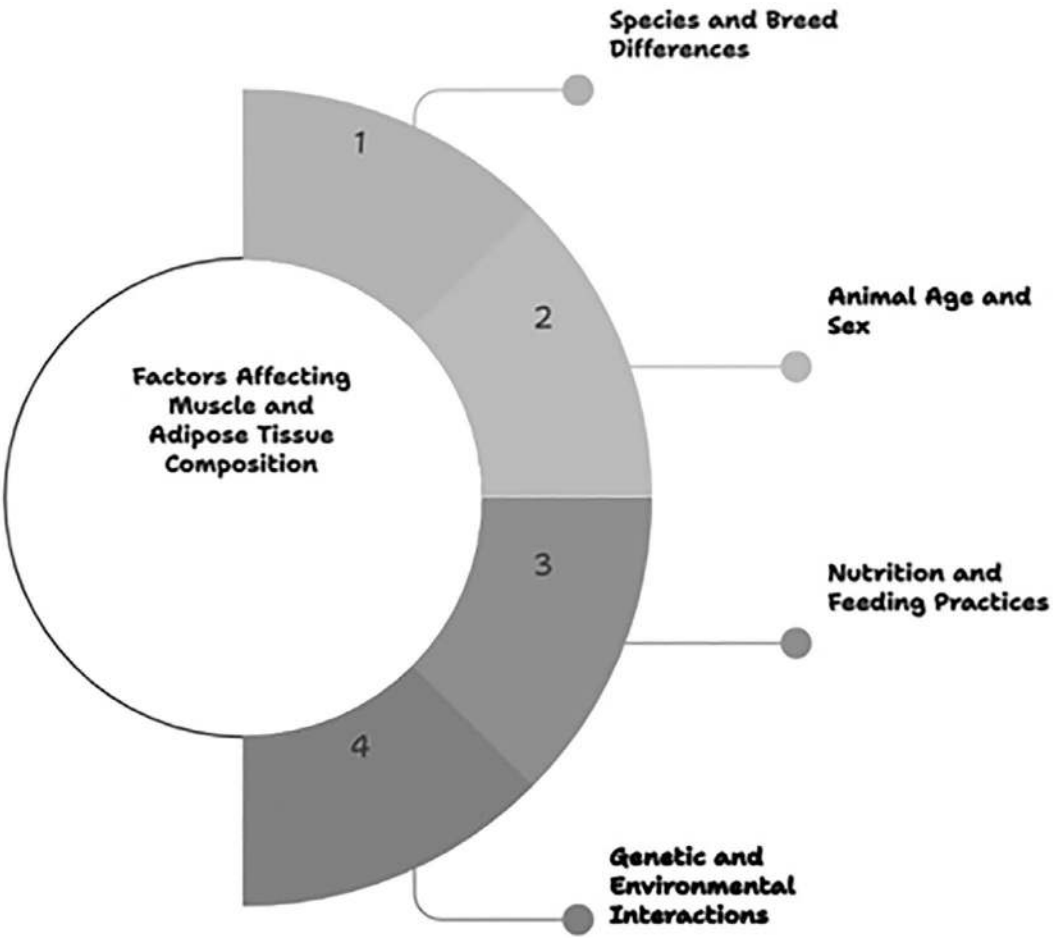

FIGURE 9.3 Factors affecting muscle and adipose tissue composition.

within and between species dictates the quantity and quality of muscle fibers, the type and distribution of adipose tissue, and the biochemical constituents within these tissues.

9.6.1.1 Muscle Composition Variability

In terms of muscle structure, species such as cattle, pigs, sheep, and poultry exhibit differing proportions of muscle fiber types, which directly influence meat characteristics. Ruminants like cattle and sheep tend to have a higher proportion of oxidative type I fibers, especially in locomotion muscles, which are associated with enhanced myoglobin content and red coloration (Joo *et al.*, 2013; Picard, Gagaoua and Micol, 2020). Conversely, pigs and poultry exhibit greater proportions of glycolytic type II fibers, particularly type IIb, which contributes to faster postmortem pH decline, higher glycogen storage, and paler meat appearance (Choi and Kim, 2009; Jeong *et al.*, 2017). These histochemical and biochemical differences are genetically controlled, although environmental and nutritional interventions can modulate them.

Within species, breed-specific differences further contribute to muscle fiber characteristics and myofibrillar protein content. For instance, Wagyu cattle are genetically predisposed to higher IMF deposition and finer marbling compared to Angus or Holstein breeds (Gotoh *et al.*, 2018). Similarly, Iberian pigs exhibit greater lipid accumulation and higher oleic acid content in muscle compared to commercial lean breeds like Duroc or Landrace (Tejeda, González and Pérez, 2020). These differences are crucial for determining meat juiciness, flavor retention, and tenderness.

9.6.1.2 Adipose Tissue Distribution and Composition

Adipose tissue deposition patterns also vary widely among species and breeds. Ruminant animals primarily accumulate subcutaneous and intermuscular fat, while monogastrics like pigs tend to store higher amounts of subcutaneous fat and IMF (Ladeira *et al.*, 2016). In addition, adipocyte size and number differ significantly. For example, Bos taurus breeds generally have more numerous but smaller adipocytes in intramuscular depots compared to Bos indicus breeds, which exhibit larger but fewer adipocytes (Du *et al.*, 2013; Silva, Teixeira and Bessa, 2021). These differences affect not only the amount but also the fatty acid composition of stored lipids.

Breed differences also influence the biochemical composition of adipose tissue. Certain breeds have a greater capacity for synthesizing unsaturated fatty acids due to higher stearoyl-CoA desaturase activity, which plays a vital role in enhancing the nutritional profile of meat lipids (Wood *et al.*, 2008). For example, Hanwoo cattle exhibit a higher proportion of monounsaturated fatty acids compared to crossbred or foreign breeds (Cho *et al.*, 2021). Similarly, genetic selection in pigs has been used to modify fatty acid profiles, enhancing the content of oleic acid while reducing saturated fatty acids.

9.6.1.3 Implications for Meat Quality and Industry

Understanding species and breed-specific muscle and fat traits is critical for the meat industry, particularly in the design of breeding programs aimed at improving meat quality. Genetic selection for marbling, tenderness, and fatty acid composition has become a focal point in premium meat markets (Hocquette *et al.*, 2020). Moreover, breed-specific nutritional management is essential to optimize desirable tissue characteristics while ensuring sustainability and economic efficiency.

In summary, both species and breed exert significant influence on the histological structure, biochemical composition, and functional properties of muscle and adipose tissue. These differences underpin the variability in meat quality observed across different animal products and serve as foundational knowledge for targeted genetic and nutritional interventions.

9.6.2 Animal Age and Sex

The composition and functional properties of muscle and adipose tissues in livestock are significantly influenced by the age and sex of the animal. These biological factors modulate the biochemical, histological, and physiological development of muscle fibers and fat depots, thereby impacting meat quality attributes such as tenderness, juiciness, color, marbling, and lipid profile (Kłobukowski, Szymańska and Kowalski, 2023; Listrat *et al.*, 2016).

9.6.2.1 Effect of Age on Muscle and Fat Development

As animals mature, there is a dynamic shift in muscle fiber composition and adipose tissue deposition. In early developmental stages, myogenesis predominates, characterized by an increase in the number of muscle fibers, whereas postnatal muscle growth is driven by hypertrophy, particularly through satellite cell activity and protein accretion (Du *et al.*, 2010). Younger animals generally exhibit a higher proportion of oxidative type I fibers, resulting in more tender meat due to lower collagen cross-linking and reduced connective tissue maturation (Joo *et al.*, 2013).

With age, muscle fibers undergo a transformation toward more glycolytic type II fibers, especially type IIb in monogastrics like pigs, contributing to altered metabolic properties and reduced tenderness (Kim *et al.*, 2018). Simultaneously, collagen becomes more thermally stable due to increased cross-linking, which negatively affects meat texture (Purslow, Gagaoua and Bekhit, 2021). Additionally, IMF tends to increase with age, enhancing flavor and juiciness but also altering the fatty acid profile, often increasing saturated fat content (Bonfatti *et al.*, 2013).

In terms of adipose tissue, subcutaneous and visceral fat depots expand progressively with age due to adipocyte hypertrophy and hyperplasia. The lipid class distribution also changes with age, with older animals typically showing higher proportions of TGs and saturated fatty acids (Bures *et al.*, 2020). The expression of key adipogenic genes such as PPARγ and C/EBPα also increases, promoting lipid accumulation.

9.6.2.2 Influence of Sex on Tissue Composition

Sex-related hormonal differences significantly affect tissue development and composition. In intact males, higher circulating levels of testosterone inhibit fat deposition and promote lean muscle mass by stimulating protein synthesis and muscle fiber hypertrophy (Barton-Gade, 2008; Mayoral, Gallego and Hidalgo, 2021). Conversely, females and castrated males (steers or barrows) generally exhibit greater fat accumulation, particularly intramuscular and subcutaneous fat, due to lower androgen levels and increased lipogenesis (Chen *et al*., 2020).

Females often deposit more IMF and have a higher proportion of unsaturated fatty acids in adipose tissue, which contributes to improved meat palatability and nutritional quality (Peña *et al*., 2018). In some species, estrogen has been shown to influence the distribution of fat between depots, favoring subcutaneous over visceral accumulation (Orellana *et al*., 2009).

Moreover, sex influences muscle fiber composition and metabolic characteristics. Male animals may have larger muscle fibers and greater glycolytic enzyme activity, while females may show increased mitochondrial content and oxidative capacity (Liu, Xu and Li, 2015). These physiological differences contribute to variation in tenderness, WHC, and overall meat quality across sexes.

9.6.3 Nutrition and Feeding Practices

Nutrition and feeding strategies play a pivotal role in modulating the composition of muscle and adipose tissue in livestock, directly influencing meat quality, growth performance, and carcass traits. The quantity, quality, and type of nutrients provided throughout the animal's growth period significantly affect protein deposition, IMF content, fatty acid profiles, and adipocyte metabolism (Hocquette *et al*., 2010; Pethick *et al*., 2020).

9.6.3.1 Macronutrient Composition and Muscle Development

Protein intake is essential for muscle accretion and the development of lean body mass. Adequate dietary protein enhances satellite cell proliferation and myofiber hypertrophy, particularly in growing animals. Conversely, protein deficiency leads to reduced muscle protein synthesis, negatively impacting muscle growth and meat yield. The type and digestibility of dietary protein also affect muscle composition; for example, rumen-protected amino acids in ruminants improve nitrogen utilization and lean gain efficiency (Muhlisin, Lee and Lee, 2020).

Carbohydrate- and energy-rich diets, particularly those high in starch, promote rapid growth and fat deposition. High-energy diets increase the expression of lipogenic genes such as fatty acid synthase (FASN) and acetyl-CoA carboxylase (ACC), leading to enhanced lipid biosynthesis and IMF accumulation (Lee, Choi and Do, 2018). The balance between muscle and fat deposition is particularly sensitive to the energy-to-protein ratio, requiring precise adjustment based on species, breed, and production stage.

9.6.3.2 Dietary Fat and Fatty Acid Composition

The type of dietary fat has a profound effect on the fatty acid profile of adipose tissue and muscle. Supplementation with unsaturated fatty acids, especially polyunsaturated fatty acids (PUFAs) such as omega-3 and omega-6, can enrich muscle tissues with health-beneficial lipids, improve meat quality, and reduce saturated fatty acid content (Scollan, Price and Morgan, 2014). For example, feeding linseed or fish oil in ruminants has been shown to increase docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA) concentrations in both muscle and fat depots (Juárez *et al*., 2021).

However, the biohydrogenation process in the rumen poses a limitation for PUFA enrichment in ruminants, necessitating the use of rumen-protected fats or direct supplementation with specific oil sources. In monogastrics such as pigs and poultry, dietary lipids are more directly deposited into tissues, making them more responsive to fatty acid manipulation via diet (Wood *et al*., 2008).

9.6.3.3 Feeding Regimes and Management Strategies

Feeding frequency, timing, and system (e.g., ad libitum versus restricted feeding) also influence tissue composition. Restricted feeding may improve feed efficiency but can compromise IMF deposition and marbling, whereas ad libitum feeding generally enhances fat accumulation, including desirable IMF under controlled conditions (Hocquette *et al*., 2010). The use of growth promoters, ionophores, or metabolic modifiers such as β-adrenergic agonists can further influence nutrient partitioning, favoring lean muscle gain over fat (Dilger and Johnson, 2020).

Moreover, the finishing diet particularly in grain-fed versus pasture-fed systems has marked effects on muscle and fat quality. Grain feeding increases IMF and modifies fatty acid profiles toward higher monounsaturated fats, whereas pasture feeding enriches tissues with omega-3 PUFAs and conjugated linoleic acid (CLA), which are beneficial for human health (Vahmani, Rolland and Gibb, 2015).

9.6.4 Genetic and Environmental Interactions

The interplay between genetic background and environmental conditions is central to determining the composition of muscle and adipose tissue in livestock. This dynamic relationship, often referred to as genotype-by-environment interaction (G×E), influences the expression of phenotypic traits, including growth rate, IMF, adipocyte differentiation, and muscle fiber characteristics (Cassady, Maltecca and Ashwell, 2022). Understanding G×E interactions is critical for optimizing breeding strategies, feeding regimes, and management practices to enhance meat quality and production efficiency.

9.6.4.1 Genetic Influence on Tissue Composition

Genetics establishes the foundational capacity for muscle growth and fat deposition. Key genes such as PPARG, SCD, LEP, FABP4, and DGAT1 regulate adipogenesis, lipogenesis, and muscle fiber differentiation (Yin *et al*., 2021). For instance, variations in the DGAT1 gene significantly affect IMF content in cattle, whereas LEP polymorphisms are associated with fat thickness and carcass yield (Ma, Yang and Zhou, 2019). Modern genomic selection programs now leverage single nucleotide polymorphisms (SNPs) and genome-wide association studies (GWAS) to identify and select animals with favorable alleles for carcass composition traits (Li *et al*., 2022).

However, the genetic potential of animals can only be fully realized when environmental conditions such as nutrition, climate, and housing are optimal. Poor management or suboptimal diets can mask or suppress desirable genotypic effects, particularly for traits with moderate to low heritability like IMF (Rauw, Kanis and Veerkamp, 2020).

9.6.4.2 Environmental Modulation of Gene Expression

Environmental factors can modulate gene expression through epigenetic mechanisms, such as DNA methylation and histone modifications, influencing both muscle and fat development (Bahar, Melzer and Kliem, 2023). For example, maternal nutrition during gestation can cause long-term effects on offspring's muscle fiber number and adiposity through epigenetic programming (Zhou, Lin and Wang, 2019). Heat stress, another significant environmental factor, downregulates genes involved in muscle protein synthesis while upregulating inflammatory and oxidative stress markers, ultimately compromising muscle growth and increasing fat deposition (Ladeira, Chizzotti and Di Marco, 2021).

Furthermore, nutrient–gene interactions are particularly significant. Diets enriched in specific fatty acids can modulate lipogenic gene expression, while high-energy feeding enhances the activity of transcription factors like SREBP-1c and ChREBP, promoting adipocyte hypertrophy (Hocquette *et al*., 2010). These environmentally induced changes highlight the importance of tailoring feeding strategies to the genetic potential of individual animals or breeds.

9.6.4.3 Implications for PLF

The integration of genomic data with environmental and phenotypic information is a key component of PLF. Novel statistical models and machine learning algorithms are increasingly employed to predict G×E interactions and individual performance traits under varying management systems (Chen, Li and Gondro, 2023). These tools allow producers to make informed decisions regarding breeding, nutrition, and health to achieve optimal tissue composition outcomes.

9.7 Postmortem Changes and Their Impact on Composition

9.7.1 Muscle to Meat Conversion

The transformation of muscle into meat postmortem is a highly orchestrated biochemical and structural process that significantly influences the final quality and composition of meat. This conversion is initiated immediately after slaughter when blood circulation ceases, cutting off oxygen and nutrient supply to the muscle cells. The ensuing shift from aerobic to anaerobic metabolism triggers a cascade of changes, primarily the accumulation of lactic acid due to glycolysis, resulting in a progressive decline in pH from approximately 7.2 to 5.5 (Zhu and Li, 2022). This acidification is a critical determinant of protein denaturation, WHC, and meat color (Ouali *et al*., 2013).

A key biochemical event in this conversion is the depletion of adenosine triphosphate (ATP). In the absence of ATP, actomyosin cross-bridges in muscle fibers become irreversibly fixed, leading to the development of rigor mortis to a rigid state that marks the onset of meat texture formation (England *et al*., 2021). The timing and extent of rigor mortis are influenced by species, temperature, muscle type, and preslaughter stress (Kim *et al*., 2018). Rapid pH decline in conjunction with high carcass temperature may result in PSE meat, while delayed pH decline with extended ATP persistence may lead to DFD meat (Lonergan, Huff-Lonergan and Grubbs, 2018).

Enzymatic proteolysis plays a pivotal role in the postmortem tenderization process. Endogenous proteases such as calpains and cathepsins are activated under acidic conditions, degrading key myofibrillar and cytoskeletal proteins like desmin, titin, and troponin-T (Huff Lonergan, Zhang and Lonergan, 2010). This proteolytic activity disrupts the sarcomeric structure and contributes to the improvement of meat tenderness during aging (Geesink and Koohmaraie, 2019). The extent of proteolysis and subsequent tenderization can vary depending on the breed, age, and muscle fiber composition of the animal (Picard *et al*., 2019).

Moreover, oxidative processes occurring postmortem can alter lipid stability and myoglobin oxidation state, affecting flavor and color stability. ROS produced during mitochondrial dysfunction may initiate lipid peroxidation, particularly in phospholipid-rich membranes, compromising both nutritional quality and shelf life (Estevez and Petracci, 2021). Antioxidant capacity within muscle tissues, influenced by diet and genetics, modulates the rate of oxidative degradation.

9.7.2 Lipid Oxidation and Proteolysis

Lipid oxidation and proteolysis are two critical biochemical events occurring postmortem that significantly impact the quality, nutritional value, and shelf life of meat. These processes, while distinct in their mechanistic pathways, are interrelated and influence key meat quality traits such as flavor, color, tenderness, and oxidative stability.

Lipid oxidation in muscle and adipose tissues is primarily driven by the presence of unsaturated fatty acids, oxygen, and pro-oxidative catalysts such as heme iron and ROS. This nonenzymatic, free radical-mediated process initiates with the abstraction of hydrogen from the methylene group of unsaturated fatty acids, leading to the formation of lipid radicals and subsequent peroxides (Estevez and Petracci, 2021). The secondary products of lipid oxidation, including malondialdehyde and aldehydes such as hexanal, are responsible for the development of rancid flavors and off-odors, which compromise consumer acceptability. Polyunsaturated fatty acids (PUFAs) are particularly susceptible to oxidative degradation, making meats rich in these lipids more vulnerable to quality deterioration (Ponnampalam *et al*., 2017).

The rate of lipid oxidation is influenced by various factors, including species, muscle type, antioxidant capacity, and storage conditions. Postmortem muscle metabolism results in the disruption of cellular membranes, releasing mitochondrial and lysosomal enzymes that exacerbate oxidative damage (Amaral, Silva and Lannes, 2018). Additionally, myoglobin and its oxidized derivatives, particularly metmyoglobin, can act as pro-oxidants, further accelerating lipid peroxidation in muscle systems (Faustman *et al*., 2010). While synthetic antioxidants such as butylated hydroxytoluene (BHT) have been used in meat preservation, recent trends emphasize the incorporation of natural antioxidants such as tocopherols, polyphenols, and plant extracts to mitigate lipid oxidation without compromising safety or consumer preference (Šimat *et al*., 2021).

Proteolysis, on the other hand, involves the enzymatic breakdown of muscle proteins postmortem, primarily contributing to meat tenderization and aging. The major proteolytic systems implicated include the calpain–calpastatin system, cathepsins, and the ubiquitin–proteasome pathway (Huff Lonergan, Zhang and Lonergan, 2010). Calpains (especially μ-calpain) are calcium-dependent cysteine proteases responsible for degrading key structural proteins such as desmin, titin, nebulin, and troponin-T within the myofibril, leading to weakening of muscle fiber integrity and enhanced tenderness (Geesink and Koohmaraie, 2019). The degree and rate of proteolysis depend on pH decline, temperature, muscle type, and endogenous enzyme activity.

Moreover, oxidative stress can negatively impact proteolysis by promoting the oxidation of proteases and their inhibitors. Oxidized calpains, for instance, show reduced activity, limiting the extent of protein degradation and negatively affecting meat tenderness (Liu *et al*., 2021). Therefore, oxidative and proteolytic events must be considered simultaneously, as they jointly determine the postmortem quality trajectory of meat products.

9.7.3 WHC and Texture Development

WHC is a critical quality trait in meat science, referring to the ability of muscle to retain its inherent water during application of external forces such as cutting, heating, or pressing. WHC significantly influences meat juiciness, tenderness, and yield, directly impacting consumer acceptance and processing functionality (Huff-Lonergan and Lonergan, 2005; Purslow, Gagaoua and Bekhit, 2021). Postmortem biochemical changes, particularly those affecting pH, protein structure, and myofibrillar integrity, play essential roles in determining WHC and subsequent texture development in meat.

Following slaughter, a sharp decline in muscle pH from neutral (~7.0) to acidic (~5.4–5.8) due to anaerobic glycolysis alters protein conformation and reduces net surface charge, facilitating protein–protein interactions that expel water (England *et al*., 2016; Offer and Cousins, 1992). Simultaneously, degradation of cytoskeletal and myofibrillar proteins through calpain-mediated proteolysis disrupts the myofibrillar lattice, creating space for water entrapment and modifying meat texture (Zhao, Bai and Li, 2022). Inadequate pH decline or excessive protein denaturation can lead to reduced WHC, resulting in PSE or DFD meat conditions (Choe and Kim, 2009; Kim *et al*., 2020).

The physical state of water in muscle tissue classified as bound, immobilized, or free is governed by structural interactions within the sarcomere. Immobilized water, held between myofibrils and within the filament lattice, is particularly affected by sarcomere shortening and proteolysis during postmortem aging (Huff-Lonergan and Lonergan, 2005). Short sarcomeres reduce WHC due to compacted myofibrils, while tenderizing proteolysis enhances WHC by increasing interfilament spacing and structural loosening (Purslow, Gagaoua and Bekhit, 2021).

Additionally, temperature and chilling rates modulate WHC and texture. Rapid chilling may cause cold shortening, resulting in tough meat with low WHC, whereas delayed chilling allows sufficient pH decline before temperature drops, preserving meat texture (Cheng *et al*., 2020; Savell, Mueller and Baird, 2005). From a processing perspective, high WHC is desirable as it minimizes drip loss, enhances yield, and improves functional properties for further processing (O'Neill, Troy and Mullen, 2022).

Texture development is intricately tied to the breakdown of cytoskeletal proteins such as desmin, titin, and nebulin, which occurs over aging periods (Kristensen and Purslow, 2001). The degree of proteolytic degradation not only affects WHC but also governs the sensory properties of meat, particularly tenderness. While WHC and tenderness often correlate positively, excessive proteolysis or prolonged storage can lead to undesirable mushy textures and flavor deterioration (Zhang *et al*., 2021).

9.8 Implications for Meat Quality and Sustainability

9.8.1 Texture, Juiciness, Flavor, and Color Attributes

The sensory characteristics of meat, namely, texture, juiciness, flavor, and color, are pivotal determinants of consumer acceptability and market value. These traits are intricately influenced by muscle fiber composition, IMF levels, postmortem biochemical transformations, and animal-related factors such as breed, age, diet, and handling (Toldrá, Mora and Reig, 2021).

Texture is a multifactorial attribute dictated primarily by muscle fiber–type distribution, connective tissue content, and the degree of proteolysis postmortem. Type I fibers (oxidative) contribute to tenderness due to their smaller fiber diameter and higher lipid content, whereas Type II fibers (glycolytic) tend to be associated with increased toughness (Alasnier, Faucitano and Lambertini, 2020). Moreover, collagen solubility and cross-linking play a significant role in determining meat toughness, particularly in older animals where heat-stable cross-links accumulate (Nishimura, 2015).

Juiciness is largely dependent on WHC, IMF content, and the structural integrity of the myofibrillar matrix (Purslow, Gagaoua and Bekhit, 2021). Higher IMF not only contributes to improved lubrication during mastication but also acts as a reservoir that retains moisture during cooking (Listrat *et al*., 2016). The WHC itself is influenced by pH decline postmortem, where a rapid drop leads to protein denaturation and reduced water retention, negatively impacting juiciness (Yu *et al*., 2018).

Flavor results from the interaction between volatile compounds generated during cooking and nonvolatile constituents such as free amino acids, reducing sugars, and nucleotides. Lipid oxidation plays a central role in the development of aroma-active aldehydes, ketones, and hydrocarbons, particularly from polyunsaturated fatty acids (PUFAs) (Huang *et al*., 2022). However, excessive oxidation can lead to rancid flavors, necessitating control through antioxidant strategies or dietary manipulation (Falowo, Fayemi and Muchenje, 2014).

Color is a critical quality attribute influencing initial purchase decisions. It is primarily governed by the myoglobin concentration and its chemical state oxymyoglobin (bright red), deoxymyoglobin (purple-red), and metmyoglobin (brown) (Suman and Joseph, 2013). Postmortem pH and oxygen partial pressure are key modulators of myoglobin oxidation. A slower pH decline favors oxymyoglobin stability and thus a desirable red color, while rapid acidification or oxidative stress can accelerate discoloration (Mancini and Hunt, 2005).

Collectively, these attributes are deeply interconnected. For instance, higher IMF enhances juiciness and flavor, while also contributing to a softer texture. Meanwhile, muscle fiber composition affects both tenderness and color stability. Current advances in genomics, feeding practices, and meat processing aim to optimize these sensory traits to meet evolving consumer preferences and sustainability targets (Hocquette *et al*., 2018).

9.8.2 Nutritional Quality and Human Health

The nutritional quality of meat is a multifaceted attribute shaped by its biochemical composition, including protein content and digestibility, lipid profile, micronutrient density, and the presence of bioactive compounds. From a human health perspective, meat serves as a dense source of essential amino acids, highly bioavailable iron (heme iron), zinc, B-complex vitamins (especially B12), and functional lipids, all of which play critical roles in immune competence, neuromuscular function, and overall metabolic health (Biesalski, 2022; McAfee *et al*., 2010).

Protein quality is among meat's most significant contributions to human nutrition. Skeletal muscle tissue consists of myofibrillar proteins such as myosin and actin, sarcoplasmic proteins, and connective tissue proteins like collagen, all of which contribute to a high digestibility score and complete amino acid profile (Pasiakos *et al*., 2015). Meat protein enhances muscle protein synthesis and supports the prevention of sarcopenia, particularly in aging populations (Phillips, Chevalier and Leidy, 2020). Furthermore, bioactive peptides derived from meat proteins exhibit antioxidant, antihypertensive, and immunomodulatory activities (Toldrá, Mora and Reig, 2021).

The *lipid composition* of meat, particularly the ratio of saturated (SFA), monounsaturated (MUFA), and polyunsaturated fatty acids (PUFA), strongly influences its health implications. While red meat is

often criticized for its SFA content, the presence of stearic acid, which is metabolically neutral, and higher MUFAs in IMF (e.g., oleic acid) partially offset concerns (Wood *et al*., 2008). Moreover, grass-fed animals typically exhibit more favorable PUFA profiles and omega-6 to omega-3 ratios, which are associated with reduced cardiovascular risk (Daley *et al*., 2010).

Micronutrients in meat, such as *iron*, *zinc*, and *vitamin B12*, contribute significantly to preventing micronutrient deficiencies worldwide. Heme iron, exclusive to animal sources, is absorbed at rates up to 25%, compared to 1–10% for non-heme iron from plants, making meat a valuable component in combating iron deficiency anemia (Hurrell and Egli, 2010). Vitamin B12, critical for neurological development and DNA synthesis, is also found almost exclusively in animal-derived foods (O'Connor, Møller and Kiely, 2022).

However, concerns have been raised regarding excessive consumption of processed and red meats, particularly in relation to colorectal cancer, cardiovascular disease, and type 2 diabetes risk. These concerns are often linked to factors such as nitrite/nitrate use in processed meats, heme iron-mediated oxidative stress, and high-temperature cooking generating heterocyclic amines (HCAs) and polycyclic aromatic hydrocarbons (PAHs) (Domingo, Nadal and Bigne, 2021). Nonetheless, recent meta-analyses suggest that moderate unprocessed red meat intake, especially from lean cuts and sustainably raised animals, does not significantly elevate chronic disease risk when consumed as part of a balanced diet (Clarke *et al*., 2023).

Innovations in meat production, including genetic selection, feeding strategies, and postharvest technologies, have enabled the development of meat with enhanced health profiles, such as reduced fat, improved fatty acid composition, and enriched micronutrient content (Juárez *et al*., 2021). Furthermore, the growing interest in "functional meat" products designed to deliver specific health benefits is expanding the role of meat in personalized nutrition paradigms (Gkarane *et al*., 2019).

9.8.3 Relevance to Processed and Cultured Meat Technologies

The compositional and structural intricacies of muscle and adipose tissues have profound implications for the development of processed and cultured meat technologies. Processed meat products, including emulsified sausages, restructured meat, and cured products, rely on the physicochemical properties of native tissues such as protein functionality, lipid behavior, and WHC for textural integrity, flavor development, and product stability (Toldrá, Mora and Reig, 2021). Similarly, cultured meat technologies aim to replicate the complex architecture and nutritional profile of conventional meat through in vitro cultivation of muscle satellite cells and adipogenic precursors, necessitating a deep understanding of muscle–adipose interactions and tissue morphogenesis (Post *et al*., 2020).

In processed meats, myofibrillar proteins (particularly myosin and actin) serve as key emulsifying and gelling agents during heat-induced gelation, forming the matrix that entraps fat and water (Chen *et al*., 2022). Any alteration in protein composition, oxidative stability, or pH significantly affects emulsion stability and final texture. Additionally, the inclusion of adipose tissue contributes essential lipid-derived flavor compounds, such as aldehydes and ketones formed through lipid oxidation and Maillard reactions, which are critical for consumer acceptability (Toldrá, Mora and Reig, 2021). For processed meats, optimizing the lean-to-fat ratio and preserving protein–lipid interactions are central to achieving desired functionality and palatability (Zhuang, Bowker and Buhr, 2021).

In the context of *cultured meat*, accurately reproducing the biochemical and biomechanical properties of conventional muscle and adipose tissue remains a significant technical challenge. Cultured muscle fibers must not only mimic the hierarchical structure (from myofibrils to fascicles) but also demonstrate contractility and metabolic characteristics akin to native muscle (Ben-Arye *et al*., 2020). Similarly, inclusion of in vitro cultured adipocytes is essential to deliver marbling, flavor precursors, and lipid-soluble nutrients that influence both taste and nutritional value (Specht *et al*., 2018). Recent studies have shown that co-culturing myogenic and adipogenic cells in a 3D scaffold environment enhances tissue maturation and simulates in vivo spatial arrangements (MacQueen *et al*., 2019).

Biomaterials and scaffold engineering are central to cultured meat success, as they support cell adhesion, proliferation, and differentiation while maintaining the physicochemical properties necessary for

mechanical stability and organoleptic quality (Zhang *et al*., 2021). Hydrogels composed of collagen, gelatin, or plant-derived polymers have been optimized to support myogenesis and adipogenesis in vitro (Jones *et al*., 2022). Moreover, the use of *bioreactors* to simulate physiological stimuli, such as cyclic strain or electrical impulses, is instrumental in promoting muscle fiber alignment, hypertrophy, and enhanced protein deposition, reflecting the structure–function relationship evident in native muscle (Kadim *et al*., 2015).

The nutritional profiling of cultured meat is another emerging focus area. Through metabolic engineering and media formulation, specific fatty acid profiles, amino acid compositions, or micronutrient concentrations can be modulated, potentially allowing production of "designer meats" that target specific health outcomes (Stephens, Sexton and Driessen, 2021). This adaptability offers a substantial advantage over conventional meat, whose composition is inherently variable and dependent on genetics, feed, and environment.

Ultimately, both processed and cultured meat technologies are converging toward a shared objective: producing meat analogs with consistent quality, improved nutritional attributes, and minimized environmental impact. Understanding the biochemical composition and functional properties of muscle and adipose tissues is not only foundational to achieving this goal but also critical to scaling up these technologies for commercial viability and consumer acceptance.

9.9 Analytical Methods for Characterizing Tissue Structure and Composition

9.9.1 Histological Techniques

Histological techniques are critical for characterizing the microstructure of muscle and adipose tissues, providing insights into cellular organization, fiber typing, connective tissue distribution, and lipid deposition. These techniques involve a series of systematic steps, including tissue fixation, embedding, sectioning, and staining, followed by light or electron microscopy to assess tissue architecture and cellular morphology (Cifuni, Claps and Morone, 2020). Proper fixation—typically using neutral buffered formalin or glutaraldehyde—preserves cellular integrity and prevents autolysis, which is crucial for obtaining reliable histological data (Bezerra, Pinheiro and Andrade, 2023).

Paraffin embedding remains the most widely used approach for muscle and fat tissue analysis, allowing thin sectioning (5–10 μm) for routine microscopic observation. However, cryosectioning with optimal cutting temperature (OCT) compound is preferred for preserving enzymatic activity or antigenicity in immunohistochemical and enzymatic histochemistry protocols (Zhao, Bai and Li, 2022). Staining techniques are tailored based on the tissue components of interest. Hematoxylin and eosin (H&E) staining provides a general overview of muscle fibers and connective tissue. In contrast, more specific stains like Masson's trichrome highlight collagen distribution, and Oil Red O or Sudan Black B stains are utilized to visualize lipid accumulation in adipose tissues (Wang *et al*., 2021).

Fiber-type differentiation in skeletal muscle is critical in meat science, as it influences metabolic characteristics and meat quality. Histochemical staining for myofibrillar ATPase at varying pH levels or immunohistochemistry targeting specific myosin heavy chain isoforms are commonly employed to classify muscle fibers into Type I, IIA, and IIB categories (Vestergaard, Therkildsen and Oksbjerg, 2020). These differences correlate with postmortem glycolytic potential, WHC, and tenderness. Additionally, histological imaging platforms integrated with digital pathology and image analysis software (e.g., ImageJ, CellProfiler) now allow quantitative morphometric analyses of fiber diameter, adipocyte size, and collagen content (Sun, Zhang and Zhou, 2023).

Advanced histological techniques have expanded into immunofluorescence microscopy and confocal laser scanning microscopy (CLSM), enabling three-dimensional visualization of protein expression and tissue architecture with subcellular resolution (Radaelli, Felisberto and de Souza, 2017). Such methods are pivotal for studying satellite cells, vascularization, and the remodeling processes in response to genetic, nutritional, or environmental interventions. Moreover, multiplex immunolabeling combined with automated image acquisition systems facilitates high-throughput evaluation of tissue heterogeneity in livestock.

Overall, histological techniques remain indispensable for elucidating the structure–function relationship in meat-producing tissues. Their continuous refinement through integration with molecular and computational tools enhances precision in meat quality assessment and supports innovations in meat production and tissue engineering (Lee, Choe and Kim, 2021).

9.9.2 Spectroscopic and Imaging Tools

Spectroscopic and imaging tools have become essential for nondestructive, rapid, and high-throughput characterization of meat and adipose tissue composition and structure. These techniques allow for the in situ evaluation of molecular constituents, structural organization, and physicochemical properties, offering vital insights for meat science and quality control. Among the spectroscopic modalities, near-infrared spectroscopy (NIRS), mid-infrared (MIR) spectroscopy, Raman spectroscopy, and nuclear magnetic resonance (NMR) are widely utilized, while advanced imaging approaches such as hyperspectral imaging (HSI), magnetic resonance imaging (MRI), and computed tomography (CT) enable spatially resolved compositional analysis (Zhang *et al.*, 2022).

NIRS has gained prominence in assessing protein, moisture, and IMF content due to its rapid data acquisition and minimal sample preparation. NIRS spectra reflect overtone and combination vibrations of C—H, O—H, and N—H bonds, which can be modeled using multivariate statistical approaches for compositional predictions (Prieto *et al.*, 2017). Similarly, MIR spectroscopy, with its higher molecular specificity, provides detailed functional group information, aiding in the identification of lipid oxidation markers and collagen cross-linking (Ropodi, Panagou and Nychas, 2017). Raman spectroscopy, leveraging inelastic light scattering, complements infrared techniques by enabling the detection of muscle protein conformation, unsaturation levels in lipids, and mitochondrial integrity (Al-Jowder, Kemsley and Wilson, 2020).

Hyperspectral imaging (HSI) integrates both spectral and spatial data, allowing mapping of heterogeneities in meat tissues. HSI is particularly effective for visualizing fat marbling, muscle fiber orientation, and tissue discoloration caused by oxidation or microbial activity (Wang, Zhu and Tu, 2023). Its application in muscle tissue grading and freshness evaluation is expanding rapidly, with machine learning models enhancing classification accuracy (Liu *et al.*, 2021). Magnetic resonance imaging (MRI) offers high-resolution images of internal tissue architecture without ionizing radiation. It is effective for visualizing water distribution, fat infiltration, and muscle deformation, providing a comprehensive evaluation of postmortem changes (Bertram, Malmendal and Toldam-Andersen, 2020).

Computed tomography (CT), including dual-energy CT, is employed for detailed 3D visualization and quantification of adipose and muscle compartments, enabling fat-to-lean ratio assessments crucial for carcass grading and breeding programs. X-ray micro-computed tomography (micro-CT) further enables analysis of adipocyte size, distribution, and vascularization in experimental meat science (Li *et al.*, 2022). Fluorescence imaging and multispectral imaging systems are also emerging as tools for detecting meat spoilage, oxidative degradation, and structural defects based on specific fluorophore emissions (Zhu, Sun and Zhang, 2020).

Recent trends emphasize hybrid techniques combining spectroscopy with imaging, such as Raman mapping or NIR-HSI, to enhance spatial resolution and chemical specificity. These tools not only streamline meat quality control but also support innovations in cultured meat, enabling real-time tissue monitoring during bioprocessing (Chaudhary, Singh and Ghosh, 2023). Overall, spectroscopic and imaging technologies are central to modern meat science, offering noninvasive, precise, and reproducible insights into tissue composition and structural integrity.

9.9.3 Chemical and Biochemical Assays

Chemical and biochemical assays are foundational to the quantitative and qualitative characterization of muscle and adipose tissues, enabling precise assessment of protein, lipid, carbohydrate, mineral, and enzymatic profiles that underpin meat quality and functionality. These assays offer essential data for nutritional evaluation, authentication, and understanding postmortem biochemical processes, often serving as reference methods for validating spectroscopic and imaging tools (Listrat *et al.*, 2016; Purslow *et al.*, 2020).

Protein content is typically determined via the Kjeldahl or Dumas combustion method, which estimate total nitrogen, assuming a standard conversion factor (Jones, Thomas and Holder, 2021). More refined analysis of specific protein fractions such as sarcoplasmic, myofibrillar, and stromal proteins is conducted through buffer extraction followed by SDS-PAGE or reverse-phase HPLC, providing insights into structural integrity and postmortem proteolysis (Zhu *et al*., 2022). Enzyme activity assays for cathepsins, calpains, and caspases are routinely used to assess proteolytic degradation linked to tenderness and aging, often quantified using fluorogenic or chromogenic substrates (Christensen *et al*., 2011).

Lipid analysis commonly involves Soxhlet or Folch extraction for total fat quantification, followed by gas chromatography (GC) to profile fatty acid composition. These analyses are critical for determining nutritional quality, oxidative stability, and species authenticity, especially in processed or blended meats (Mourot, 2021; Średnicka-Tober *et al*., 2023). Oxidative stability is further evaluated using thiobarbituric acid reactive substances (TBARS) assays, which quantify secondary lipid oxidation products such as malondialdehyde, a key indicator of rancidity and shelf-life (Zhang *et al*., 2020).

Glycogen and lactic acid assays reflect postmortem glycolysis, influencing meat pH and WHC. These are typically determined enzymatically or via colorimetric kits (Franco *et al*., 2018). Collagen content, affecting texture and chewiness, is measured by hydroxyproline assays following acid hydrolysis, differentiating between total and insoluble collagen fractions (Listrat *et al*., 2016).

Advanced biochemical profiling, such as metabolomics using LC-MS or NMR, is increasingly integrated into meat science to explore low-molecular-weight compounds and their metabolic pathways. These approaches enhance the understanding of breed-specific, feeding, and processing influences on meat biochemistry (Picard *et al*., 2019). Additionally, ELISA and Western blotting are employed to quantify specific proteins such as myoglobin, leptin, or growth factors, supporting studies on tissue metabolism, immune response, and adipogenesis (Bai, Li and Huang, 2021).

Altogether, chemical and biochemical assays continue to be indispensable for precise tissue characterization, offering a benchmark for modern analytical technologies and providing mechanistic understanding of the structural and functional evolution of meat and adipose tissues.

9.10 Future Perspectives

The future of meat science is undergoing a profound transformation, propelled by the convergence of tissue engineering, molecular biology, digital technologies, and sustainability-driven innovations. A deeper understanding of the structure and composition of muscle and adipose tissues not only advances fundamental meat science but also underpins emerging applications in cultured meat production, PLF, and the development of health-oriented meat products.

9.10.1 Advances in Tissue Engineering and Cultured Meat

Tissue engineering has emerged as a revolutionary field with the potential to produce cultured meat that mimics the structural and nutritional attributes of conventional meat without the need for animal slaughter. This involves cultivating myocytes and adipocytes in a controlled environment using scaffolds and bioreactors that simulate the physiological conditions of muscle and fat growth (Kadim *et al*., 2015; Post *et al*., 2020). Recent advances in 3D bioprinting and scaffold biomaterials have enhanced the spatial organization of cells, allowing for structured meat products with improved texture and marbling (Ben-Arye *et al*., 2020). Co-culturing muscle cells with adipose cells is increasingly recognized as essential for achieving the sensory properties of traditional meat, particularly juiciness and flavor (Zhang *et al*., 2021). As such, a detailed knowledge of native tissue architecture and biochemical composition serves as a blueprint for optimizing in vitro meat design.

9.10.2 Role of Biomarkers in Predicting Meat Quality

Biomarkers are gaining attention for their potential to predict meat quality traits such as tenderness, juiciness, color stability, and lipid oxidation susceptibility. Genetic markers and proteomic signatures

associated with muscle fiber type, connective tissue abundance, and lipid metabolism pathways have shown promise in early prediction models (Gagaoua, Terlouw and Picard, 2020; Picard *et al*., 2019).

9.10.3 Integrating Composition Analysis in PLF

PLF is reshaping animal agriculture by leveraging sensors, machine learning, and real-time data analytics to monitor animal health, behavior, and tissue development. Composition analysis technologies such as portable near-infrared spectroscopy (NIRS) and digital imaging are increasingly being integrated into PLF systems to assess carcass traits, IMF content, and muscle pH dynamically (Berckmans, 2017; Fernandes *et al*., 2023). These innovations facilitate individualized animal management, enhancing resource efficiency, reducing environmental impact, and improving product consistency. For example, coupling imaging data with genetic and nutritional inputs can support early interventions in growth strategies to enhance carcass yield and quality (Andretta, Pomar and Rivest, 2021).

9.10.4 Emerging Trends: Nutritional Modulation and Sustainability Innovations

Nutritional modulation remains a critical lever for enhancing meat quality and tailoring fatty acid profiles for human health. Dietary strategies incorporating omega-3 rich sources, antioxidants, or precision amino acid supplementation can influence adipose tissue composition and oxidative stability postmortem (Wood *et al*., 2008). On the sustainability front, circular approaches involving the valorization of agricultural by-products as feed inputs and the development of carbon-smart meat production systems are gaining traction. Integrating renewable energy in meat processing and adopting low-emission livestock breeds further reflect the sector's commitment to climate goals (Hocquette, 2022).

9.11 Conclusion

The structure and composition of muscle and adipose tissues represent a cornerstone of meat science, influencing not only the functional and sensory attributes of meat but also its nutritional quality, technological processing behavior, and sustainability footprint. Muscle tissue is organized in a hierarchical fashion, where bundles of myofibers containing aligned myofibrils and sarcomeres serve as the contractile machinery central to locomotion and postmortem biochemical transformations. Sarcomeric proteins such as actin, myosin, and titin, alongside regulatory proteins like troponin and tropomyosin, govern contraction and relaxation cycles, which, upon slaughter, undergo complex biochemical alterations resulting in meat formation. Parallelly, adipose tissue exhibits distinct depot-specific characteristics (subcutaneous, intermuscular, intramuscular), with functional roles extending beyond lipid storage to endocrine signaling and energy homeostasis. The biochemical profile of adipose tissue, including TGs, phospholipids, and bioactive fatty acids, significantly affects meat quality, particularly in relation to flavor, tenderness, oxidative stability, and nutritional value. Adipokines such as leptin and adiponectin, secreted by adipose cells, further modulate metabolic pathways and influence the interplay between fat and muscle development.

Numerous intrinsic and extrinsic factors modulate the composition of muscle and fat tissues. Age and sex affect the metabolic rate, collagen content, and fat deposition patterns, with younger animals typically producing leaner meat with lower connective tissue cross-linking. Nutritional strategies ranging from energy-dense diets to lipid source supplementation and micronutrient fortification have been shown to alter both muscle hypertrophy and adipogenesis, modifying lipid profiles and enhancing meat's functional and sensory traits. Genetic selection and environmental interactions also play a pivotal role; specific genotypes display superior marbling, muscle fiber characteristics, or fatty acid profiles under tailored rearing conditions, emphasizing the value of precision breeding programs in modern livestock production. Postmortem, biochemical processes such as glycolysis, pH decline, proteolysis (particularly via calpains and cathepsins), and lipid oxidation are crucial determinants of meat tenderness, flavor development, and color stability. Additionally, WHC and textural characteristics are intimately linked to myofibrillar integrity and sarcomere structure, which are affected by chilling rates, carcass handling, and enzymatic activity.

From a quality and sustainability perspective, the structure and composition of meat tissues underpin critical traits such as tenderness, juiciness, flavor, and color key determinants of consumer acceptance. Nutritional quality is directly linked to lipid and protein composition, including omega-3/omega-6 ratios, CLA content, and the presence of essential amino acids, all of which have implications for human health outcomes. In processed and cultured meat applications, understanding native tissue microarchitecture and molecular composition is vital for replicating authentic meat textures and functionalities. Modern analytical technologies such as histology, spectroscopy, imaging, and molecular assays have revolutionized our ability to characterize tissue composition and monitor quality, enabling more informed decision-making in meat processing and livestock management.

Looking forward, integrating advanced tools such as machine learning, omics-based biomarker discovery, and real-time sensing technologies into precision livestock systems holds promise for optimizing growth performance, predicting meat quality early, and reducing environmental burdens. Innovations in tissue engineering and cultured meat bioprocessing further require detailed structural and biochemical knowledge of muscle and fat to develop functional, nutritious, and sustainable alternatives to conventional meat. Thus, a deep understanding of muscle and adipose tissue composition not only advances scientific inquiry in meat biology but also supports the evolution of sustainable animal agriculture and novel protein development.

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10

Nutritional Composition of Meat: Benefits, Challenges, and Dietary Considerations

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10.1 Introduction

Meat has been a central component of human diets for millennia, serving concentrated energy, high-quality protein, and multiple micronutrients essential to growth, development, and the maintenance of physiological functions. In contemporary food systems, meat consumption lies at the junction of nutrition, culture, economy, and environment: it can help address micronutrient deficiencies and protein-energy malnutrition in vulnerable populations while intensive production and high per-capita intake in some regions pose significant public health and environmental concerns. Balancing these trade-offs requires an evidence-based understanding of meat's nutritional contributions, population-level consumption patterns, and health risks associated with different types and patterns of meat intake (Leroy *et al.*, 2023; Stadnik, 2024). Understanding these foundational roles provides a basis for examining why meat remains important in modern dietary patterns.

10.1.1 Importance of Meat in the Human Diet

Meat is a nutrient-dense food that supplies complete (high biological value) proteins containing all essential amino acids in proportions to support tissue synthesis and metabolic needs throughout the life course. It is also a exceptionally rich source of highly bioavailable micronutrients, notably heme iron, zinc, selenium, and vitamin B12 lacking (Klurfeld, 2018). These nutrients play critical roles in erythropoiesis, immune function, cognitive development, and cellular antioxidant defenses, making modest amounts of meat particularly valuable in diets for infants, young children, pregnant women, and older adults in contexts of high deficiency burden. For these reasons, the targeted inclusion of meat (or animal-source foods) is often an efficient strategy to improve nutrient adequacy where undernutrition or micronutrient deficiencies are prevalent (Sheffield, Fiorotto and Davis, 2024).

At the same time, culinary and cultural factors such as flavour, satiety, food traditions, influence acceptability and dietary patterns; in many food cultures, meat contributes disproportionately to dietary satisfaction and energy intake. When lean cuts are chosen, with minimal processing, meat can support balanced dietary patterns with minimal excess saturated fat and calories (Lindsey, 2024). These nutritional benefits provide the foundation for understanding global consumption trends and their implications.

10.1.2 Global Meat Consumption Trends

Global meat production and consumption have grown substantially over the last decades in a context of population growth, rising incomes, urbanization, and improvements in efficiency of production. Poultry has been the fastest-growing meat category in many regions due to lower production costs, shorter production cycles, and, for consumers, perceived favourable health attributes; trends in beef and pork are more heterogeneous across regions (Mottet and Tempio, 2017). International monitoring and outlooks by

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FAO and the OECD document continued expansion of global meat markets, while also highlighting market volatility due to changes in feed prices, trade disruptions, and policy shifts. At the same time, consumer concerns regarding health and sustainability have also increased interest in some markets in leaner meats, reduced processed meat intake, and in plant-based alternatives and flexitarian diets. These parallel trajectories rising overall demand in many low- and middle-income countries combined with selective reductions or substitution within some high-income populations generate key implications for nutrition policy, food security and environmental planning. These evolving consumption patterns provide the context for discussing meat's role in human health (OECD-FAO, 2025).

10.1.3 Role of Meat in Human Nutrition and Health

Meat supplies high-quality protein and bioavailable micronutrients that contribute to nutrient adequacy and support normal physiological functions. Evidence suggests that modest consumption of animal-source foods play a role in the prevention and treatment of iron-deficiency anemia and vitamin B12 deficiency, as well as supporting growth and cognitive development in children in settings of undernutrition (Geiker *et al.*, 2021).

Health consequences of meat consumption, however, are highly variable. Epidemiological evidence and mechanistic studies reveal significant heterogeneity by meat type, processing and cooking, and amount consumed. IARC classified processed meat as carcinogenic to humans (Group 1) and unprocessed red meat as probably carcinogenic to humans (Group 2A) primarily based on evidence linking processed meat consumption to colorectal cancer. Other observational studies and meta-analyses have related high intakes of both processed and certain high-fat cuts of red meat to increased cardiovascular disease, type-2 diabetes, and the risk of specific cancers (Li-Hua and Bajinka, 2025). Public health advice, therefore, often stresses limits on the intake of processed meats while choosing lean cuts, avoiding excessive portion sizes, and increasing plant-based protein sources where appropriate. (Qian *et al.*, 2020). Addressing these health concerns with a broader sustainability framework requires, context-specific guidance that acknowledges nutritional contributions of meat in in populations with nutrient deficiencies while promoting reduced consumption in populations with high meat intake. (Rust *et al.*, 2020). This framing provides the foundation for subsequent sections addressing the nutrient content of meat in detail, factors affecting its quality, and how these characteristics of meat inform dietary advisories.

10.2 Nutritional Composition of Meat

Meat is a widely consumed, nutrient-dense food that is rich in high-quality protein, essential fatty acids, vitamins, minerals, and bioactive compounds, which play essential roles in metabolic and physiological functions. Meat primarily skeletal muscle and surrounding fat is one of the foods that has been consumed by humans for over 3 million years (Leroy *et al.*, 2023). Meat can be broadly classified into three categories, including red meat, white meat, and seafood. Meat provides energy and several other nutrients that are important in nutrition and human health, including macro- and micronutrients (vitamins A, D, E, B-complex; minerals such as iron, zinc, selenium) and bioactive compounds (taurine, carnosine, anserine, creatine, coenzyme Q10, glutathione, carnitine) which support metabolic, physiological, and neurological function (Stadnik, 2024). The nutritional composition varies by species, age, cut, leanness, and processing.

To understand meats contribution to human health, it is essential to examine its macronutrients proteins, fats, and carbohydrates followed by micronutrients and bioactive compounds that provide additional physiological benefits.

10.2.1 Macronutrients in Meat

Meat is a major source of high-quality protein, essential fatty acids, and contains only small amount of carbohydrates. The content and quality of these macronutrients depend on species, type and cut of meat, feeding regime, rearing conditions, and post-slaughter processing. The nutritional characteristics of different meats and fish including protein content, Digestible Indispensable Amino Acid Score (DIAAS) fatty acid composition, and fat-based classification, are given in Table 10.1.

TABLE 10.1

Nutritional Profile of Meat and Fish: Protein Content, DIAAS Values, Fatty Acid Composition, and Fat Classification

Category	Meat/Fish Type	Protein (g/100 g)	DIAAS Value	Limiting Amino Acid	Total Fat (g/100 g)	Saturated Fat (g/100 g)	PUFA (g/100 g)	MUFA (g/100 g)	Cholesterol (mg/100 g)	References
Beef	Beef (ground, raw)	17.5	>100	Leucine	20	8.1	0.7	8.7	72	USDA, 2018
	Beef (ground, cooked)	25.9	<100	Leucine	15.4	5.9	0.484	6.67	88	Bailey *et al.*, 2020; USDA, 2018
	Beef (loin)	19.3	97–104	Leucine	17.1	6.91	2.56	7.41	82	Bailey *et al.*, 2020; USDA, 2018
	Beef (ribeye)	21.2	95–100	Leucine	6.57	2.65	0.189	2.77	60	USDA, 2018
	Beef (steak, pan-fried)	28.8	95–100	Leucine	21.1	8.18	1.71	8.86	98	USDA, 2018
	Beef (roast, boneless, raw)	31	–	–	3.72	1.42	0.285	1.56	78	USDA, 2018
Pork	Pork (ground)	17.8	–	–	21.2	7.87	1.91	9.44	72	USDA, 2018
	Pork (loin)	21.1	–	–	9.94	2.76	0.87	2.98	64	Vicente and Pereira, 2024
Poultry	Chicken breast (skinless)	22.5	108	Methionine + cysteine	2.62	0.563	0.424	0.689	73	Marinangeli and House, 2017
	Chicken wing (raw)	17.2	–	–	12.8	3.54	2.5	5.42	111	USDA, 2018
	Chicken thigh	16.5	–	–	16.6	4.52	3.47	6.94	98	USDA, 2018
	Turkey, whole, giblets (raw)	18.2	–	–	5.09	1.45	1.42	1.02	333	USDA, 2018
	Turkey (ground)	19.7	–	–	7.66	2.02	2.2	2.64	69	
Fish	Haddock	16.3	–	–	0.45	0.091	0.166	0.061	54	USDA, 2018
	Atlantic Cod	17.8	–	–	0.67	0.131	0.231	0.094	43	USDA, 2018
	Salmon	20.5	–	–	4.4	0.81	1.35	0.811	46	USDA, 2018

10.2.1.1 Protein Content and Quality

Among the richest protein sources, meat generally offers a high biological value, good digestibility, and a favorable protein-to-energy ratio. On average, raw meat contains ~22% protein of skeletal muscle weight, although the percentage varies by species and particular anatomical characteristics (Boateng, Nasiru and Agyemang, 2020). Chicken breast can be considered exceptionally rich in proteins (~30%).

Muscle proteins are broadly classified into myofibrillar proteins, which contain about 80% of total muscle proteins, including actin, myosin, tropomyosin, and the troponin complex; connective tissue proteins; and sarcoplasmic proteins, such as oxidative enzymes, lysosomal enzymes, and heme pigments. Myoglobin imparts a characteristic red color in meat and is a water-soluble globular protein (Boateng, Nasiru and Agyemang, 2020). Considering amino acid composition, there is a difference between red and white meats: red meat contains more branched-chain amino acids, such as leucine, while in white meat, lysine and histidine predominate (Zhang *et al.*, 2025).

Fish protein is regarded as a high-quality protein because of high content of essential amino acids lysine and methionine with digestibility ranging from 85% to 90%. (Pal *et al.*, 2018). Generally, the protein content of fish ranges from 16% to 21% and is dependent on species, breeding, and feeding (Ahmed *et al.*, 2022; Ryu, Shin and Kim, 2021). Anatomically, structural proteins constitute 70–80%, sarcoplasmic proteins constitute 20–30%, and connective tissue constitutes only 2–3% of fish muscle, making the meat very tender and highly digestible.

The quality of protein is assessed by the availability and digestibility of amino acids. Of the 20 amino acids needed for protein synthesis, 9 are indispensable, or IAAs, that must be provided by food, with the remainder considered DAAs. The FAO recommends the DIAAS as the preferred method for evaluating protein quality. A DIAAS value ≥1.0 indicates an excellent-quality protein source (FAO, 2011; Moughan and Lim, 2024).

10.2.1.2 Fat Content and Fatty Acid Profile

Fats within meat play the role of energy stores, providing, among other things, essential fatty acids important to human physiological and metabolic functions. Adipose tissue in meat is broadly classified into two types: subcutaneous (depot) fat and intramuscular fat (marbling). Depot fat consists predominantly of triglycerides (~90%), with low phospholipid content, while intramuscular fat has a high content of phospholipids that contribute to higher polyunsaturated fat levels (Urrutia, Alfonso and Mendizabal, 2018).

Although meat is an excellent source of high-quality protein, its fatty acid composition particularly that of certain red meats has received considerable attention because of its potential health implications. Common red meats, such as beef and pork, typically compromises approximately ~40% saturated fat, 5% trans-fat, 50% monounsaturated fat, and 4% polyunsaturated fat (FAO, 2023). Species, age, cut, and leanness are modifying factors. Saturated fat is higher in ruminants compared to nonruminants because of rumen fermentation and biohydrogenation of unsaturated fatty acids, which do not take place in monogastric animals such as pigs. Conjugated linoleic acid is present in ruminant meat, and it has been suggested to reduce the risk of metabolic disorders (Geiker *et al.*, 2021; Vahmani *et al.*, 2020).

Poultry meat, especially after skin removal, is low in cholesterol and saturated fat, with 60-70% of its fat as unsaturated fatty acids (Zhang *et al.*, 2025). Feed type affects fatty acid composition, and grain-fed animals show lower levels of omega-3 PUFA compared with grass-fed animals (Nogoy *et al.*, 2022).

Seafoods, both fish and shellfish, are rich in omega-3 polyunsaturated fatty acids. Deep-sea and fatty fish possess long-chain PUFAs like eicosapentaenoic acid (EPA, C20:5) and docosahexaenoic acid (DHA, C22:6); these are essential at every stage of life, as are their metabolites, the eicosanoids (Nava *et al.*, 2023; Zhang *et al.*, 2025). Fish also contain saturated and monounsaturated fats too (Torfadottir and Ulven, 2024). A balanced n-6/n-3 PUFA ratio helps cardiovascular health (Khalili Tilami and Sampels, 2018). Among the richest sources of long-chain n-3 PUFAs is cod liver (Torfadottir and Ulven, 2024). As per the ICMR-NIN 2024 guidelines, the amount of 20–50 g low-to-medium fat fish or 20 g oily fish provides 0.1 g n-3 PUFA.

10.2.1.3 Carbohydrates and Energy Value

The energy value of meat is derived primarily from its protein and fat content. The energy content of raw meat generally ranges from 165 to 183 kcal/100 g, lean beef provides ~150 kcal/100 g, and whole chicken ~239 kcal/100 g.

Meat is a poor source of carbohydrates; the principal carbohydrate stored as granules in muscle fibers is glycogen. Following slaughter, glycogen is metabolized through anaerobic glycolysis to produce lactic acid through postmortem biochemical changes, essentially glycolysis, resulting in a decline in muscle pH from ~7 to 5.5. This post-mortem acidification influences color, texture, and water-holding capacity of meat (Chauhan and England, 2018; Stempa and Bradley, 2021).

Preslaughter stress can further affect the content of carbohydrates and quality of meat. Chronic stress depletes glycogen, raising the pH and resulting in dark, firm, dry (DFD) meat, while acute stress accelerates the breakdown of glycogen, leading to pale, soft, exudative (PSE) meat because of rapid acid accumulation (Stajković *et al*., 2019). Seafood exhibits slightly higher carbohydrate content than terrestrial meat, due to higher presence of glycogen than raw oysters... raw oysters, scallops, and mussels containing 3–5%, while lobsters and crabs have nearly 0% carbohydrates.

10.2.2 Micronutrients in Meat

Although micronutrients are required in only in small amount, their role in human metabolic and physiological functions are indispensable. Plant-based diets often provide some of these nutrients in forms with lower bioavailability; hence, meat is a highly valuable source of bioavailable vitamins and minerals. Inclusion of animal foods, especially organ meats and small fish, significantly enhances both micronutrient intake and absorption. According to Beal and Ortenzi (2022), key micronutrients present in meats include water-soluble B-complex vitamins, fat-soluble vitamins A, D, and E, and minerals such as iron, zinc, selenium, and phosphorus, many of which serve as cofactors or components of coenzymes for critical biochemical processes. Because meat is concentrated source of essential micro-nutrients, reducing its consumption may lower dietary intake of nutrients unless these are replaced by other nutrient rich foods. (Stadnik, 2024).

10.2.2.1 Vitamins: B-complex, A, D, and E

The water-soluble B-complex vitamins play essential roles in energy metabolism and numerous cellular processes. But also as the following: thiamine (B1) as a coenzyme in glucose metabolism, riboflavin (B2) in protein, carbohydrate, and fat metabolism; B5 and B6 participate in neurotransmitter synthesis, red blood cell formation, and overall homeostasis (Juárez *et al*., 2021; Kennady *et al*., 2018). Poultry is an especially good source of B1, B5, and B6; Vitamin B12 is naturally found almost exclusively in animal-source foods plays a vital role in maturation and nucleoprotein synthesis of red blood cells, and white fish represent a very significant contribution to B vitamin intake (Badoni *et al*., 2021; Rueda Garc *et al*., 2024).

The highest concentrations of fat-soluble vitamins A, D, and E are in the liver and fat tissues of animals. Animal-derived pre-formed vitamin A (retinol) exhibits a higher bioavailability (~74%) compared to pro-vitamin A derived from plants (~15.6%), thus making even small intakes quite effective (Chungchunlam and Moughan, 2024). Content of beef liver retinol ranges between 1,602 µg RE/100 g and 26,083 µg RE/100 g, while in cod liver, it is ~25,000 µg/100 g (Schendel *et al*., 2022; Schulz *et al*., 2025).

Vitamin D is crucial for the health of bones, immunity, and calcium homeostasis during the first 1,000 days of life. Meat contains vitamin D as cholecalciferol and 25-hydroxy derivatives with direct biological activity. Vitamin D concentrations vary according to sunlight exposure, animal husbandry practices, and diet; indoor-raised pigs and poultry have lower vitamin D levels. Beef and lamb muscle contain about 0.56 and 0.47 µg/100 g, respectively. Seafood, and in particular fatty fish such as salmon, mackerel, and trout, is an excellent source. Wild-caught fish usually has higher levels from diet and environmental exposure (Cashman *et al*., 2020; Egelandsdal *et al*., 2024; Taylor *et al*., 2025).

Vitamin E, principally as α-tocopherol, is a powerful antioxidant that protects tissues from lipid peroxidation. Conventional meat generally contains modest amounts of vitamin E, Dietary biofortification of livestock has shown promise in improving human serum levels. Fatty fish, fish roe, and biofortified

TABLE 10.2

Vitamin B Content of Selected Meat and Seafood Sources (per 100 g edible portion)

	Vitamin B				
Meat Source	**B1 (mg)**	**B2 (mg)**	**B3 (mg)**	**B9 (µg)**	**B12 (µg)**
Beef, top sirloin, lean	0.05	0.10	7.87	9	1.5
Pork, loin, lean	0.75	0.25	8.0	0	0.7
Lamb, leg, lean	0.12	0.23	6.5	19	2.3
Chicken breast, raw	0.06	0.08	9.91	4	0.3
Chicken thigh, raw	0.07	0.16	4.62	2	0.2
Turkey breast, raw	0.05	0.11	9.6	4	0.6
Salmon, Atlantic, raw	0.23	0.38	8.9	25	3.2
Mackerel, Atlantic, raw	0.16	0.34	9	1	12.0
Tilapia, raw	0.04	0.07	3.9	24	1.9
Shrimp, raw	0.01	0.03	1.2	19	1.3
Mussels, raw	0.16	0.21	1.8	42	12.0

Source: USDA, 2018.

beef provide well-appreciable amounts, with salmon containing ~1.69 mg/100 g (Durazzo *et al.*, 2022; Silveira *et al.*, 2024). The concentration of key B-vitamins across different meat and seafood sources is summarized in Table 10.2.

10.2.2.2 Minerals: Fe, Zn, Se, and P

Meat is an excellent source of essential trace elements such as iron, zinc, selenium, and phosphorus, which are crucial for human metabolism and physiological functions.

Iron in meat is present predominantly as heme iron, which has a bioavailability of approximately 15–35%, whereas non-heme iron from plant sources is absorbed less efficiently (5–12%) (Rueda Garc *et al.*, 2024). Meat provides heme iron accounting for 30–70% of total iron red meat is considered one of the principal dietary sources of in most developed countries (Piskin *et al.*, 2022). The iron content also depends on muscle fiber type. Red fibers have more heme iron than white fibers, which explains the higher iron content in red meats (Ponnampalam *et al.*, 2019). Organ meats, like liver, and small fish enhance the absorption of both heme and non-heme iron (Piskin *et al.*, 2022). Certain fish possess 0.46–19.0 mg/100 g iron, while bivalves such as oysters may contain ~13.91 mg/100 g depending on the species (Mamun *et al.*, 2024).

Zinc is an important component of more than 50 enzymes and participates in many biological processes, including growth, development, and immune response. Zinc contents are relatively high (~30 mg/kg) in red meats, especially in beef and mutton, but it widely varies among species and cuts: beef, 2.30–7.70 mg/100 g; pork, 0.40–5.00 mg/100 g, and lamb, 2.10–9.40 mg/100 g (Juárez *et al.*, 2021; Mai *et al.*, 2024).

Selenium is an essential trace element and is incorporated into selenoproteins that exert antioxidant, anti-inflammatory, and immune-modulating effects. Meat is an important dietary source: beef contains 15–35 µg/100 g, pork contains 12–25 µg/100 g, and poultry contains 10–20 µg/100 g of selenium (Stadnik, 2024). Selenium content depends on feed, cut, and region; animals raised in selenium-poor soils have lower levels (Egelandsdal *et al.*, 2024). Seafood exhibits a wide range of selenium concentrations of 8.6–155.5 µg/100 g, with marine fish generally higher at 37.1–198.5 µg/100 g than freshwater species at 6.9–29.4 µg/100 g (Rueangsri *et al.*, 2025). Unique compounds, such as the amino acid selenoneine found in tuna and swordfish, have shown protective activity against hepatic steatosis and nonalcoholic fatty liver disease in experimental models (Miyata *et al.*, 2020).

Phosphorus (P) is essential in bone health, cellular growth, and energy metabolism, including the formation of hydroxyapatite in combination with calcium. Phosphorus in meat occurs predominantly in highly bioavailable organic forms, and its typical levels in terrestrial animals are as follows: beef, 150–190 mg/100 g; pork, 140–180 mg/100 g; poultry, 150–170 mg/100 g (Stadnik, 2024). Seafoods are richer in P, especially oily fish such as raw salmon (~200 mg/100 g), mackerel (~210 mg/100 g), and

tilapia (~190 mg/100 g), while dried small marine fish such as anchovy, sardine, and white sardine contain 220–250 mg/100 g dry weight (Khawar *et al*., 2024; Mamun *et al*., 2024).

10.2.3 Bioactive Compounds in Meat

In addition to macronutrients and micronutrients, meat also contains bioactive compounds that exert a range of physiological effects, including antioxidant, anti-inflammatory, neuroprotective, anti-aging, cholesterol-lowering, and antihypertensive effects (Kulczyński, Sidor and Gramza-Michałowska, 2019). Key bioactive compounds include taurine, carnosine, anserine, creatine, coenzyme Q10, carnitine, and bioactive peptides, Many of these bioactive compounds are present predominantly or exclusively in animal-source foods, making meat a valuable dietary source, particularly for physically active individuals and populations at risk of nutrient deficiencies (Hou *et al*., 2019; Wu, 2020).

10.2.3.1 Carnosine, Anserine, Creatine

Carnosine, a dipeptide formed from β-alanyl-L-histidine is abundant in the skeletal and brain tissues of land animals and fish. Carnosine functions as an antioxidant by reducing lipid oxidation, buffering intracellular pH, scavenging free radicals, serving as a precursor for neurotransmitter synthesis, and exerting anti-glycation activity (Qi *et al*., 2018; Uenoyama *et al*., 2019). Carnosine content in muscles depends on species, sex, age, and diet. Carnosine concentrations are generally higher in males and decline with advancing age. Chicken breast contains 130–800 mg/100 g depending on breed. Black Chinese chicken has the highest amount (Khumpeerawat, Duangjinda and Phasuk, 2021). Fishes have lower carnosine content. Cooking methods affect the retention of carnosine. Dry heat results in higher retention compared to moist heat (Juniper and Rymer, 2018; Pogorzelska-Nowicka *et al*., 2018).

Anserine is a methylated derivative of carnosine and occurs predominantly in vertebrate skeletal muscle it is particularly abundant in poultry, fish (salmon, trout), and beef tissues (Li and Wu, 2020). Its concentration depends on the muscle fiber type, with higher content in white fibers (Barbaresi *et al*., 2019). According to Sharma *et al*. (2022), anserine reaches a value of ~485 mg/100 g in broiler chicken breast. In general, functional properties related to metal chelation and pH buffering are attributed to anserine, similar to carnosine (Sharma *et al*., 2022).

Creatine (*N*-[aminoiminomethyl]-*N*-methyl glycine) is an important energy metabolism molecule. It participates in ATP regeneration (Zheng *et al*., 2025). According to Cuparencu *et al*. (2019), meat, poultry, and fish are abundant sources; urinary creatine levels rise after meat consumption. Creatine an endogenously synthesized compound that may become conditionally essential under certain physiological conditions. Thermal processing converts part of the creatine into creatinine and therefore reduces the levels within cooked meat (Korovljev *et al*., 2021). For example, lamb contains 464-1866 mg/100g when raw and 265-1188 mg/100g when cooked. Chicken breast and thigh have 221–251 mg/100 g, beef ~445 mg/100g, and fish ranges 200-700 mg/100g, with herring high at 650-1000 mg/100g (Ostojic, 2021; Wuertz and Reiser, 2023).

10.2.3.2 Taurine and Coenzyme Q10

Taurine is a sulfur-containing β-amino acid, chemically known as 2-aminoethanesulfonic acid, which is not used for protein synthesis but is essential for lipid metabolism, bile salt formation, osmoregulation, and neurodevelopment (Rais *et al*., 2022). Taurine is synthesized primarily in the liver and, to a lesser extent, in the brain from methionine and cysteine through vitamin B6-dependent pathways, is abundant seafood, beef, pork, and dark poultry meat. Taurine content varies widely: dark chicken meat (169 mg/100 g), light chicken meat (18 mg/100 g), oysters (396 mg/100 g), and mussels (655 mg/100 g) (Jairath *et al*., 2024).

Coenzyme Q10 (CoQ10) a fat-soluble quinone present predominantly in the inner mitochondrial membrane serving as an electron carrier in the mitochondrial electron transport chain, antioxidant defense, anti-aging effects, and immune modulation (Elbir and Oz, 2021). Meat, poultry, and fish are good sources of CoQ10; the highest levels can be found in organ meats. Lyophilized chicken heart contains 383.25 mg/kg, beef ~3.65 mg/100 g, and pork varies similarly (Kulczyński, Sidor and Gramza-Michałowska, 2019; Semeniuc *et al*., 2023).

10.3 Factors Affecting Meat Quality and Nutrient Composition

Meat quality and nutritional composition are influenced by a wide range of biological, environmental, and processing factors throughout the production-to-consumption chain. Genetics, among other species and breeds, feed composition; various methods of rearing; pre- and postslaughter treatments; storage conditions; and thermal or nonthermal cooking processes interact with each other in determining the characteristics of meat. These factors influence the texture, color, moisture content, distribution of fat, vitamin and mineral content, and functional bioactive compounds in meat (Pandey *et al.*, 2024; Yue *et al.*, 2024). Understanding the effect of these variables on meat quality is essential for optimizing both its nutritional value and sensory attributes. The nutritional composition of meat is shaped by multiple factors, including breed, feeding system, cooking practices, and processing methods, as illustrated in Figure 10.1.

10.3.1 Species and Breed Differences

Species and breed of an animal are two important influential factors in muscle fiber–type distribution, myoglobin content, intramuscular fat deposition, and connective tissue composition, which all eventually determine the most important quality attributes of meat: color, tenderness, juiciness, flavor, and nutrient composition. Compared with poultry, red meat generally contains higher concentrations of myoglobin, resulting in a darker colour and greater oxidative stability. Moreover, muscle fiber type, fat deposition, and organoleptic are strongly influenced by genetic factors and play a critical role in determining eating quality (Geletu *et al.*, 2021; Sakowski *et al.*, 2022).

The techniques of modern breeding and selection, such as marker-assisted selection or genomic selection, allow targeting the manipulation of marbling, intramuscular fat, tenderness, and juiciness so that desirable hereditary traits can be included much faster in following generations. Such advances in the selection of genetics are responsible for continued improvement in meat quality attributes, especially under commercial production systems (Sakowski *et al.*, 2022; Yue *et al.*, 2024).

10.3.2 Feed and Rearing Practices

The composition and quality of animal feed play a critical role in determining meat characteristics. Nutritional feed components impact growth rates, muscular glycogen stores, fatty acid profiles, antioxidant levels, and overall oxidative stability of meat (Clinquart *et al.*, 2022; Mir *et al.*, 2017). For example, certain dietary fatty acids are reflected in the tissue lipid composition, which influences the levels of

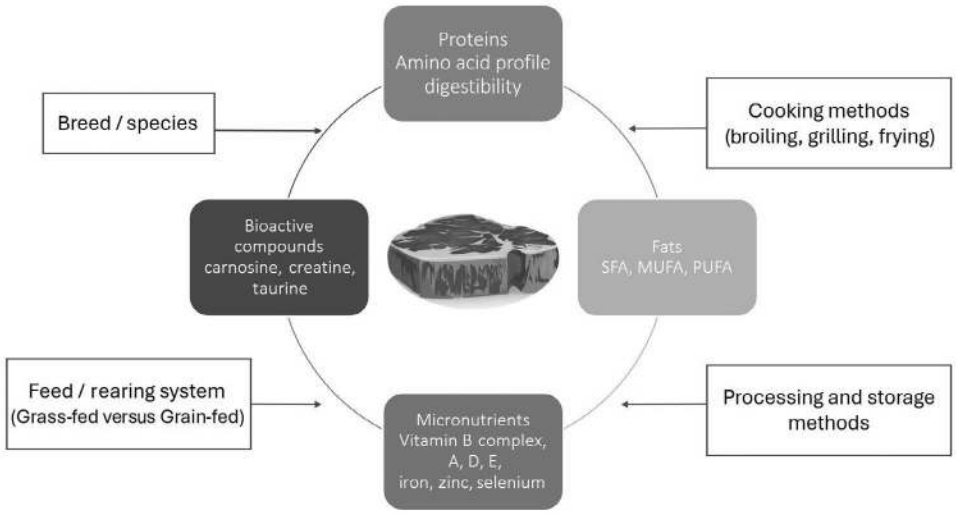

FIGURE 10.1 Key factors influencing the nutritional composition of meat.

polyunsaturated fatty acids directly and thus their susceptibility to oxidation, whereas antioxidants like tocopherols help preserve colour and flavour color and flavor and generally protect other nutrients.

Besides nutrition, rearing practices are among the most important factors influencing meat quality. Stocking density, thermal comfort, physical activity, and stress interact with nutrition, affecting carcass characteristics, moisture, and sensory properties. Animal welfare-oriented practices result in improvement in some quality attributes of meat, although the magnitude of responses may vary according to species, breed, or genetic background. For instance, rearing animals in a non-stressful environment with adequate space and nutrition generally results in meat with improved tenderness, juiciness, and a more favourable fatty acid profile (Clinquart *et al*., 2022; Pandey *et al*., 2024).

10.3.3 Slaughtering, Processing, and Storage Conditions

Preslaughter stress has a significant impact on muscle biochemistry, mainly glycogen content, a factor that will determine the extent of post-mortem glycolysis, the final pH, and meat quality. Low stores of glycogen could favor the development of PSE conditions, while chronic stress can induce DFD. Both PSE and DFD conditions compromise the quality, shelf life, and commercial of meat products (Clinquart *et al*., 2022; Geletu *et al*., 2021).

Stunning techniques, handling, and rigor mortis management during the time of slaughter affect the activity of proteolytic enzymes, firmness, and tenderness. The modes of processing after slaughter, such as packaging, hygiene in handling, and thermoregulation, contribute to microbial stability, color retention, and lipid oxidation and, therefore, influence both aspects of safety and sensory quality. More sophisticated storage methods, such as modified atmospheric packaging or the addition of antioxidants, will increase shelf life, reduce lipid oxidation, and stabilize color, although these interventions may sometimes modify flavor attributes according to the species (Clinquart *et al*., 2022; Geletu *et al*., 2021).

10.3.4 Effect of Cooking and Thermal Processing

The cooking process markedly modifies the structure and properties of proteins and connective tissue, thereby affecting meat tenderness, juiciness, and moisture retention (Mir *et al*., 2017). In general, cooking at high temperatures results in the loss of more moisture and proteins leading to a tougher meat product. Moreover, thermal processing improves microbial safety by inactivating pathogenic microorganisms. Further, thermal processing may reduce thermo-sensitive nutrients such as certain vitamins and bioactive compounds, especially in meats with a high content of PUFAs.

On the other hand, cooking methods at medium and low temperatures may preserve nutrients, retain antioxidant content, and enhance digestibility and bioavailability of some bioactive components. Hence, cooking method, temperature, and time will be of prime importance in maintaining nutritional values, optimizing texture, and developing flavor, in addition to the influences of species, breed, and feeding practices (Clinquart *et al*., 2022; Mir *et al*., 2017).

Meat quality and nutrient composition are highly dynamic attributes, influenced by a continuum of factors, ranging from genetics and feeding practices to slaughtering, storage, and cooking. Comprehensive understanding of these factors is vital to maximize not only nutritional benefits but also sensory qualities of the meat products.

10.4 Health Implications of Meat Consumption

Meat is a nutritionally dense food with significant benefits as well as potential risks depending on both quantity and type consumed. An understanding of these implications is essential in the promotion of optimal human health and the prevention of diet-related diseases.

10.4.1 Nutritional Benefits of Meat

Meat greatly improves the overall protein quality of a diet by providing all essential amino acids necessary for growth, development, and metabolic processes (Geiker *et al*., 2021). It improves the bioavailability of

nutritionally important micronutrients, such as heme iron, zinc, vitamin B12, selenium, and the vitamins of the B-complex, which are often poorly bioavailable from diets based only on plants because of phytates and other antinutritional compounds (Giromini and Givens, 2022; Kavanaugh *et al*., 2025).

Red meat is an as an excellent source of vitamin B12 and iron that are important in preventing iron deficiency anemia among the vulnerable groups, including preschool children, pregnant women, and adolescent girls. Meat consumption supports cognitive development, muscling, and immune function because of its high biological value and nutrient density (Geiker *et al*., 2021; Leroy *et al*., 2023).

10.4.2 Health Risks of Excessive or Processed Meat Intake

While moderate meat consumption provides important nutritional benefits, excessive consumption of red and processed meat has been associated with an increased risk of several chronic diseases. It High consumption has been associated with cardiovascular diseases, type-2 diabetes, and certain cancers, which include colorectal cancer (Chung, Li and Liu, 2021; Micha *et al*., 2017).

Processed meats often contain preservatives, high sodium, and carcinogenic compounds; thus, their consumption enhances inflammatory responses, gut microbiome imbalances, and insulin resistance. Furthermore, overconsumption of such products increases the risks of ischemic heart disease, stroke, and other metabolic disorders, while replacing it with other protein sources such as fish, poultry, or plant-based proteins can help one reduce these risks while acquiring other essential nutrients (Giromini and Givens, 2022; Micha *et al*., 2017; WHO, 2023).

10.4.3 Meat and Noncommunicable Diseases: CVD, Cancer, and Obesity

High intake of red and processed meat is a characteristic of diets with a high correlation with an elevated risk of noncommunicable diseases. Processed red meats are known to be carcinogenic to colorectal cancer, in part, through heme iron-mediated lipid oxidation and carcinogenic compounds that result from processing/cooking (Farvid *et al*., 2021).

High consumption of red and processed meat also elevates the risk of type-2 diabetes and cardiovascular disorders. This is mediated through plaque formation in arteries, high sodium intake, and subsequent blood pressure elevation that disrupt metabolic homeostasis (Chung, Li and Liu, 2021; Micha *et al*., 2017). Recent studies emphasize frequency, portion size, and methods of processing as being important determinants of health risks from meat consumption (Giromini and Givens, 2022).

10.4.4 Role of Meat in Addressing Protein-Energy Malnutrition and Micronutrient Deficiencies

Meat will, therefore, play a critical role in addressing protein-energy malnutrition and micronutrient deficiencies in those underdeveloped and developing nations where economic constraints limit food choices and access to high-quality protein. Consumption of meat results in improvements in brain function, physical growth, and overall health while preventing deficiencies in bioavailable iron, zinc, and vitamins (Geiker *et al*., 2021).

The nutrient-rich profile of meat, thus, makes it an effective tool in combatting anemia and supporting total well-being throughout the life continuum, from child development into later adult nutrition (Leroy *et al*., 2023).

10.5 Dietary Recommendations and Guidelines

10.5.1 WHO and National Dietary Guidelines

WHO has classified processed meat as carcinogenic and red meat as likely carcinogenic, mainly due to their relation with colorectal cancer, among other health risks. In this respect, WHO recommends limiting both the intake of processed and red meat. However, moderate inclusion of meat in the diet can

serve to ensure a nutrient-dense dietary intake, including all essential nutrients often less bioavailable from plant-based diets (WHO, 2023). Accordingly, national dietary guidelines reflect similar recommendations. The UK National Health Service recommends limiting the intake of red and processed meat to no more than approximately 70 g per day for individuals who consume larger amounts, while encouraging the inclusion of alternative protein sources (NHS, 2024). The European Food-Based Dietary Guidelines recommend no more than 300 g of red meat and sausages per week, advising the consumption of meat one to two times per week while limiting the consumption of processed products (European Commission, 2022). Similarly, the Australian Dietary Guidelines recommend consuming lean meats as part of a balanced diet while limiting processed meat because of its associated health risks. The ICMR–NIN Dietary Guidelines for Indians recommend including meat, fish, poultry, eggs, and plant protein sources in appropriate amounts to meet daily protein requirements.

10.5.2 Recommended Intake Levels of Red and White Meat

General recommendations for red meat intake range from 350 to 500 g of cooked meat per week, based on evidence supporting a reduced risk of colorectal cancer. (WCRF, 2025). White meat, particularly poultry, is generally considered a healthier alternative to red meat and is not subject to the same intake restrictions in most dietary guidelines because of its lower associated health risks. Overall protein intake should meet about 0.8 g per kilogram of body weight per day, sourced from a combination of meat, fish, dairy, and plant-based proteins, ensuring a balanced dietary profile (American Heart Association, 2024).

10.5.3 Risk–Benefit Balance in Meat Consumption

Incorporating meat into the diet yields significant added benefits, providing highly bioavailable nutrients, including heme iron, vitamin B12, and zinc, with increased importance in places where deficiencies are common (Giromini and Givens, 2022). On the other hand, excessive intake of red and processed meats contributes to increased risk of colorectal cancer, arterial plaque buildup, CVDs, and type-2 diabetes. These negative health consequences are highly related to substances created during meat processing, like nitrosamines, and saturated fat contained in some meats (Micha *et al.*, 2017). Adding homemade meals and alternative protein sources will improve amino acid and lipid profiles, gut microbiome health, and digestion and lower the risk of diet-related diseases, yet still allow individuals to gain from the essential nutrients coming from meat.

The benefits, risks, and sustainability considerations of meat consumption are summarized in Figure 10.2, highlighting both nutritional advantages and broader environmental and ethical factors.

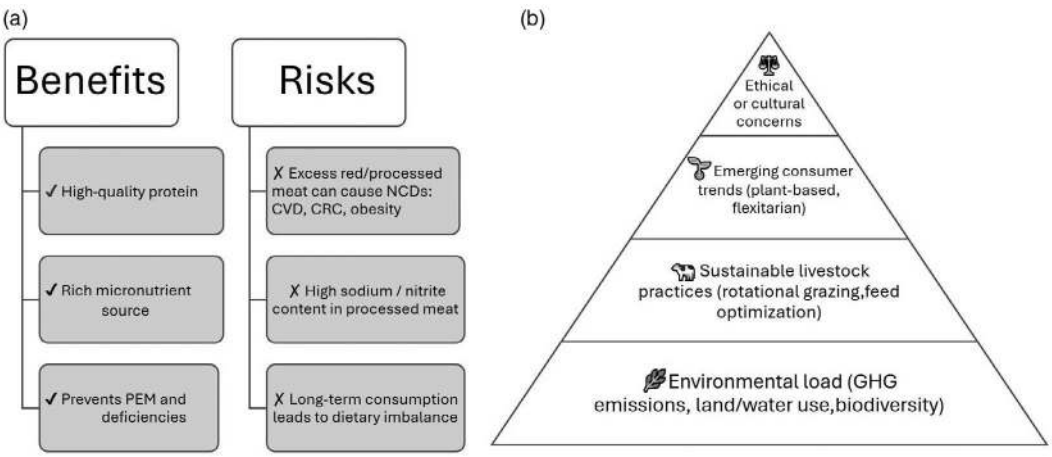

FIGURE 10.2 Health implications, sustainability, and ethical dimensions associated with meat consumption. (a) Health implications of meat. (b) Sustainability and ethical dimensions.

10.6 Emerging Trends and Consumer Perspectives

10.6.1 Flexitarian and Plant-Based Dietary Shifts

Meat is a rich source of high-quality protein, essential vitamins, and minerals; however, it also contains higher amounts of saturated fat compared to unsaturated fatty acids, and its processing can result in the generation of harmful compounds. High consumption of meat and processed meat is associated with cardiovascular diseases, type 2 diabetes, certain cancers, and environmental impacts such as increased greenhouse gas emissions (Zahari *et al*., 2022). These raise concerns that have provoked dietary pattern shifts toward increasing interest in plant-based diets allowing moderate inclusions of animal foods that balance health and environmental objectives. A flexitarian diet has become the most popular diet both in developed and developing nations because it reduces meat, dairy, and egg intake strategically without removing the food items from the diet, unlike vegetarian or vegan diets (Dagevos, 2021). Flexitarian diets recognize the nutritional value of meat combined with ethical, environmental, and health considerations (Dagevos, 2021; Derbyshire, 2017). Definitions of flexitarian diets vary, with exclusion of red meat but inclusion of poultry and fish, and restriction to specific species of fish (Derbyshire, 2017; Sheen, Lim and Forde, 2023).

Plant-based foods, including whole grains, legumes, nuts, fruits, and vegetables, are associated with reduced chronic disease risks of heart diseases, diabetes, and cancer, as well as lower environmental impact and ethical benefits. However, social, cultural, economic, religious, regulatory, and allergen-related factors continue to limit the widespread adoption of plant-based diets (Abe-Inge *et al*., 2024). Increasing consumer awareness about the sustainability, animal welfare, and health of foods has encouraged innovation in plant-based foods that have been associated with reduced obesity, hypertension, kidney and cardiovascular diseases, total mortality, and decreased environmental footprint (Carey *et al*., 2023; Yang *et al*., 2025).

10.6.2 Alternative Protein Sources and Meat Analogues

The market for alternative protein sources has grown rapidly in response to increasing consumer concerns about the health and environmental impacts of conventional meat production and consumption and plant-based protein sources have important potential for substitution into a wide variety of traditional protein sources while offering a large potential for growth in developing regions (Ishaq *et al*., 2022). Meat analogue products are designed to mimic the texture, taste, appearance, and colour of meat without containing animal-derived ingredients (Zahari *et al*., 2022). Research and industries have developed various alternative proteins and their analogs that are nutritionally and functionally similar to conventional meat. The alternatives were grouped into several classes, including plant-based, animal-based, microorganism-based, and insect-based.

Analogues made from plants utilize proteins sourced from cereal grains, legumes, soy, and oilseeds, along with water, lipids, fiber, and other ingredients added and then processed by extrusion, wet spinning, or thermo-extrusion to produce fibrous, meat-like products such as chunks, strips, patties, sausages, nuggets, and steak alternatives (Ishaq *et al*., 2022; Zahari *et al*., 2022). Many of these products provide all essential amino acids, contain lower levels of saturated fat, and are cholesterol-free; hence, they can be among the best healthy alternatives and sustainable protein sources. Mycoproteins obtained from fermentation, done by fungi, are rich in protein, vitamins, and minerals. Insect-based meat analogues are derived from crickets, mealworms, ants, and black soldier flies and are indeed nutrient-dense; however, there are some challenges concerning acceptance due to perceived safety and perception issues. Cultivated (in vitro) meat, produced from animal stem cell cultures, offer meat-like tissue with minimal animal involvement and lower ecological impact (Kumar *et al*., 2021).

10.6.3 Labeling, Perception, and Consumer Awareness

Nutritional concerns, animal welfare, environmental sustainability, and food safety are key factors influencing consumer perceptions of meat and its alternatives. Although sensory qualities like taste and texture are still relevant, the level of awareness related to fat content and health implications has increased

the demand for high-quality, well-produced meat products derived from ethical production methods (de Araújo *et al*., 2022). However, consumer acceptance of alternative proteins remains limited because of unfamiliarity with these products. However, informative labeling, innovation in marketing, and consumer education increase awareness, enable informed choices, and support consistent adoption of plant-based and alternative protein products (Baig *et al*., 2025).

10.7 Sustainability and Ethical Considerations

10.7.1 Environmental Impacts of Meat Production

Because of increasing population and rising income levels, global meat production has grown significantly over the years, enhancing demand for land, water, and energy. The meat industry, together with dairy production, involves significant environmental degradation in terms of deforestation, greenhouse gas emissions, water pollution, biodiversity loss, and soil degradation. Livestock emit large amounts of methane during digestion, and poorly treated manure releases methane, nitrous oxide, and carbon dioxide to produce a very high contribution to climate change. Methane's effect as a strong greenhouse gas makes meat production one of the main contributors to global warming, where a unit increase in meat consumption is associated with a 0.91% rise in greenhouse gas emissions (Oleinikova *et al*., 2025). It fuels biodiversity loss, with forests and grasslands being transformed into pastures, hence destroying the habitats and causing species extinction. Moreover, water required for livestock feed production reduces overall water availability. Application of eco-efficient livestock systems and zero-deforestation policies can contribute to mitigating these environmental impacts.

10.7.2 Sustainable Livestock Management Practices

Livestock production must be managed sustainably to meet the growing demand for animal-source foods while minimizing environmental impacts. Resource efficiency and ecological protection are enhanced by rotational grazing, precision feeding, and integrated crop–livestock systems (Henchion *et al*., 2021). Proper animal feeding and manure management reduce methane emissions, while silvopastoral systems—a combination of trees, grass, and livestock—provide shade, high-quality feed, and increase carbon storage, thus supporting both productivity and biodiversity (Yulianti, Muchtar and Amruddin, 2024). Other technological innovations in precision livestock farming include IoT sensors and automated feeding systems that make real-time monitoring possible on animal health and behavior to optimize efficiency and productivity. Animal welfare, especially proper nutrition, shelter, and minimizing discomfort, is another important aspect of sustainability. There exist several strategies for waste management in livestock production that incorporate anaerobic digestion, composting, and nutrient recycling for converting by-products into useful resources. Increasing consumer awareness of environmental and ethical concerns has created new opportunities in markets for animal products raised sustainably. Sustainable livestock management is essential for balancing food production with environmental conservation.

10.7.3 Ethical and Cultural Dimensions of Meat Consumption

Meat consumption is closely related to culture, prosperity, and social behavior. With a growing population, meat production has to be increased, but there are also growing concerns about unethical treatment in raising animals. In addition, contemporary meat production focuses on ethical standards, quality, safety, and environmental sustainability. Acceptable meat is expected to be acceptable based on cultural expectations for taste, texture, and nutritional value, and thus cultural acceptability ranks alongside safety and nutrition as an important consideration (Hansen *et al*., 2021). There is a growing demand by consumers for meat from animals raised humanely, which includes proper housing and nutrition and minimal pain at the time of slaughter. Ethical meat production also involves environmental responsibility, including reducing pollution and conserving natural resources such as land, biodiversity, and water. This integrated approach helps ensure that meat production aligns with societal values, animal welfare principles, and sustainability goals.

10.8 Future Perspectives

10.8.1 Innovations in Sustainable Meat Production

For centuries, meat has been one of the most valued sources of protein and vital nutrients in human culture. Because of its nutritional and cultural value, it is rather difficult to alter consumption habits. With increasing demand, advanced, environment-friendly methods of raising and processing meats are needed. This can be achieved by breeding genetically improved animals, with faster growth rates, higher slaughter weight, and optimal carcass composition, instead of increasing livestock numbers. In precision livestock farming, electronic tags, sensors, and real-time monitoring of animal health, feed intake, and environmental parameters are deployed, enabling increased productivity while considering animal welfare (Vaintrub *et al.*, 2021).

Other emerging technologies for enhancing meat quality and shelf life include high-pressure processing, pulsed light, electron beam, plasma, intelligent packaging, and modified atmosphere packaging (Singh *et al.*, 2020). Besides traditional meats, plant-based meat alternatives and cultured meat are being developed as sustainable options. Cultivated (cultured) meat, produced from animal stem cell cultures, has the potential to reduce environmental impacts, greenhouse gas emissions, and animal use. Therefore, cultured meat provides a promising direction to be followed for a more sustainable food system (Castellani *et al.*, 2025). Companies such as Beyond Meat and Impossible Foods produce plant-based products designed to mimic the taste, texture, and appearance of conventional meat.

10.8.2 Nutritional Optimization and Fortification of Meat Products

Though plant-based foods—cereals, legumes, nuts, and meat alternatives—offer health benefits like lower saturated fat, cholesterol, and higher fiber, vitamins, and phytonutrients, some nutrients in plant-based foods are less bioavailable than those in animal-source foods. Animal-derived foods provide high-quality protein, long-chain polyunsaturated fatty acids, and essential vitamins and minerals such as B12, iodine, selenium, calcium, iron, and zinc (Grasso *et al.*, 2023).

Fortification of plant-based meat alternatives with nutritional micronutrients found in animal-based meat will ensure nutritional adequacy as well as sustainability of the planet. In this regard, studies show that replacing 30% of all animal-sourced foods may reduce environmental impact but still keep nutrient intake adequate, whereas full replacement may result in reduced intake of essential micronutrients such as zinc, calcium, vitamin B12, and vitamin A (Seves *et al.*, 2017). In addition, enrichment strategies for conventional meat have been the addition of antioxidants and dietary fiber, and the reduction of undesirable components like sodium, nitrates, nitrites, and *N*-nitrosamines (Ursachi *et al.*, 2020). Added to meat, plant-based ingredients like vegetables, semolina, and soy oil produced a nutrient-rich product with increased protein content, unsaturated fatty acids, vitamins, minerals, and dietary fiber (Borisenko *et al.*, 2021).

10.8.3 Integration of Health, Environment, and Consumer Behavior

Although meat is an excellent source of essential nutrients, excessive consumption of red and processed meat has been associated with an increased risk of chronic diseases, including cardiovascular disease, type 2 diabetes, and colorectal cancer. At the same time, livestock production contributes substantially to greenhouse gas emissions, land-use change, and biodiversity loss. Public awareness about health and environmental implications of meat consumption is urgently needed. Policymakers, nutritionists, and health professionals should work collaboratively to educate consumers and promoting responsible and balanced meat consumption. A holistic approach includes informative labeling, education campaigns, and the promotion of fortified or alternative protein products to guide individuals toward dietary choices that optimize human health and reduce environmental impact.

10.9 Conclusion

The nutritional profile of meat underscores its long-recognized value as a staple part of human diets. As a concentrated source of high-quality protein, essential amino acids, B-complex vitamins, especially vitamin B12, and highly bioavailable minerals, including iron and zinc, meat can play an important role in improving nutritional status, especially among the most vulnerable groups of people. Yet, excessive intakes are related to high saturated fat and cholesterol intake and are linked with noncommunicable diseases. Alongside ethical and environmental concerns, changes in consumer attitudes and growing interest in plant-based alternatives and diversified dietary patterns have occurred. Understanding how species, anatomical cut, production systems, and methods of processing affect meat's nutritional profile is important for making informed choices. The nutritional benefits of meat must balance with public health imperatives through moderation, promotion of leaner meats produced sustainably, and complementary plant-derived foods. Sustainable diets require coordination of health goals, environmental stewardship, cultural practices, and economic realities. This chapter emphasizes responsible consumption strategies for promoting individual well-being and planetary health.

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11

Genetically Modified (GM) Meat versus GM Feed: Scientific, Technological, Health, and Socioeconomic Perspectives

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11.1 Introduction

The global agri-food system is facing unprecedented and interrelated challenges, including rapid population growth, climate change, the depletion of natural resources, and rising demands for sustainable food production. These pressures highlight the limitations of conventional agricultural practices and pose significant risks to long-term food security (Food and Agriculture Organization of the United Nations, 2018). In response, enhancing agricultural productivity while reducing environmental impacts has become a central objective of modern food systems. Within this context, biotechnology—and particularly genetic engineering—has emerged as a key technological driver in contemporary agriculture and animal production. Advances in genetic engineering have enabled the development of crops and livestock with improved resistance to biotic and abiotic stress, increased productivity, and more efficient resource use, thereby supporting the transition toward resilient and sustainable agri-food systems (Aziz *et al*., 2022; Malo, 2023; Zilberman, Holland and Trilnick, 2018).

Genetically modified organisms (GMOs) have been the subject of intense scientific, political, and public debate for more than three decades. A central distinction within this debate concerns genetically modified (GM) feed and GM meat. Although both involve the application of genetic technologies, they differ fundamentally in terms of biological intervention, regulatory treatment, ethical implications, and consumer acceptance.

GM food became an object of controversy in the United States and Europe. GMOs face consumer fears about safety, contamination, allergenicity, toxicity, and unnaturalness.

It all started with genetic engineering with insertion of genes into microorganisms and safety concerns with recombinant DNA technology (Berg *et al*., 1975). Genentech had inserted genes for insulin production into Escherichia *coli* in 1977 (Goeddel *et al*., 1979).

A synthetic Humulin was produced after five years.

As reported in 2012, most of the world's insulin is produced by GM strains of yeast or *E. coli*, making it available for diabetics (Aggarwal, 2012).

Transgenic plant started their production in the 1970s and in 1982, a tobacco plant resistant to the antibiotic kanamycin was produced (Fraley *et al*., 1983). Commercialization of GM crops started in 1992, when Chinese farmers planted virus-resistant tobaccos (James, 1997).

Calgene Flavr Savr tomato was launched in 1994 and was advertised as a product with an extension of shelf life due to the addition of a gene that slowed pectin degradation (Winerip, 2013).

By 2016, 26 countries actively plant GM crops with the major GM plantation in areas covered by the United States (39%) followed by Brazil (27%), Argentina (13%), Canada (6%), and India (6%) (ISAAA, 2017).

Despite the high public acceptance in the United States for GMOs being 73% (Hoban, 1997), the European support was lower.

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Anti-GMO activists tried to pressurize foodservice firms (Schurman and Munro, 2010), and as a result products intended for processing or animal consumption rose. Ron Herring (2010) reported that America's processed and packaged food industries use ingredients from the processing of GE feed crops such as soybean oil, corn starch, or corn syrup.

The late-1990s increase in GM planting in the United States showed an increase from 1.7 million hectares to 39.9 million hectares from 1996 to 1999 for planted GM crops (Mohorčich and Reese, 2019).

A softer regulatory approach and different institutional handling of agricultural biotechnology compared to Europe was reported by Sheingate (2006, 2009).

GMO opposition rose from 1996 to 1999 by double digits (Bernauer, 2016).

Europe today allows for legal cultivation of a GM strain of Bt corn in Spain, despite the wide growth in the United States.

This chapter provides a comprehensive and comparative analysis of GM feed and GM meat, examining their scientific foundations, technological development, health and environmental impacts, ethical considerations, and socioeconomic consequences.

11.2 Scientific Background of Genetic Modification

11.2.1 Definition and Classification of GMOs

GMOs are organisms whose genetic material has been intentionally altered using modern biotechnology techniques in ways that do not occur naturally through mating or conventional recombination (WHO, 2014; EFSA, n.d.).

GMOs are broadly classified as follows:

- GM plants, including climate-resilient and nutrient-enhanced crops.
- GM microorganisms, widely used in biomanufacturing, vaccine production, and synthetic biology.
- GM animals, developed for improved productivity, welfare, and disease resistance.

11.2.2 Evolution of Genetic Engineering Technologies

Genetic engineering has advanced significantly since the early recombinant DNA era. While early methods relied on random transgene insertion, the last decade has seen a shift toward programmable nucleases and high-fidelity genome-editing tools. Since 2020, the field has been transformed by innovations such as CRISPR-Cas12a, Cas13, prime editing, and CRISPR-associated transposase systems, which enable more accurate and versatile genome modifications (Anzalone, Koblan and Liu, 2020; Chen and Liu, 2023).

CRISPR-Cas9 remains a foundational technology; however, newer CRISPR systems offer enhanced specificity, alternative PAM recognition, and reduced off-target activity (Zhang *et al*., 2023). Prime editing, introduced in 2019, has undergone rapid refinement and is now capable of performing precise insertions, deletions, and base substitutions with minimal genomic disruption and without the induction of double-strand breaks (Anzalone, Koblan and Liu, 2020; Chen and Liu, 2023).

Base editing technologies have also expanded considerably, with studies demonstrating efficient single-nucleotide modifications in animal and livestock species while avoiding double-strand DNA cleavage, thereby reducing unintended genomic alterations (Rees and Liu, 2018; Xu *et al*., 2024). Emerging CRISPR-associated transposase systems further extend the genome-engineering toolkit by enabling targeted DNA integration through RNA-guided mechanisms, representing a promising but still developing frontier in the field (Anzalone, Koblan and Liu, 2020).

In animal biotechnology, post-2020 applications include the following:

- *Heat-tolerant cattle* engineered through targeted edits to the prolactin receptor gene (PRLR), demonstrating improved thermotolerance and production traits (Cuellar *et al*., 2024; Pozzebon, Guldbrandtsen and Sandøe, 2024).

- *Gene-edited (GE) sheep with enhanced muscle growth* using CRISPR/Cas9-mediated knockout of the myostatin (MSTN) gene, resulting in increased muscle mass and growth performance (Crispo *et al*., 2015).
- *Disease-resistant poultry* developed by CRISPR/Cas9 editing of viral receptor genes, conferring resistance to avian leukosis viruses in commercial chicken lines (Kheimar *et al*., 2021; Koslová *et al*., 2018).

These developments blur the traditional distinction between "transgenic" and "gene-edited" organisms, prompting updated regulatory discussions in the European Union, the United States, and Asia regarding how post-2020 GE livestock should be classified and governed (Zhang and Ricroch, 2023).

11.3 GM Feed: Production and Global Adoption

11.3.1 GM Crops Used for Animal Feed

GM feed is predominantly derived from large-scale cultivation of GM crops, especially soybean, maize, canola, and cottonseed. These crops form the backbone of global feed supply chains due to their high protein and energy content. Recent global adoption data indicate that GM crops continue to dominate international feed markets. According to the GM Crop Area Review 2024/2025, approximately 74.9% of global soybean area and 33.7% of global maize area are planted with GM varieties, while GM cotton and GM canola account for 78.4% and 24.3% of their respective global planted areas (CropLife Vietnam, 2025). In major exporting countries such as the United States, Brazil, and Argentina, adoption rates for GM soybean and GM maize exceed 90% of planted area, making GM varieties the dominant source of feed ingredients in global commodity markets (International Service for the Acquisition of Agri-Biotech Applications, 2018).

The primary traits engineered into GM feed crops include herbicide tolerance, insect resistance (Bt traits), and improved yield stability, including drought tolerance and enhanced nutrient-use efficiency. Herbicide tolerance enables simplified weed management and supports reduced tillage practices, while Bt traits decrease crop losses and reduce reliance on chemical insecticides. These traits have been extensively developed and deployed in major GM crops such as maize and soybean and are well documented in comprehensive reviews of genetically engineered crops (Aziz *et al*., 2022).

Recent meta-analyses and long-term field data demonstrate that GM crop adoption contributes to greater resilience under climate stress, improved harvest consistency, and reduced environmental impacts, particularly through decreased pesticide use and enhanced resource efficiency (Brookes, 2022; Pellegrino *et al*., 2018). As global livestock production continues to expand, GM feed crops have become essential for meeting the growing demand for high-quality, affordable feed ingredients, given their widespread cultivation and role in global feed supply chains (FAO, 2023).

11.3.2 Role of GM Feed in Modern Livestock Production

GM feed plays a central role in modern livestock systems by enhancing feed efficiency, lowering production costs, and stabilizing feed supply chains. Economic analyses of GM crop adoption demonstrate significant benefits in reducing input costs and increasing productivity for livestock producers, particularly in regions dependent on imported soybean meal (Brookes and Barfoot, 2014, 2020).

Empirical research highlights several key benefits of GM feed use:

- Reduced pesticide application, due to Bt- and herbicide-tolerant traits lowering chemical inputs (Klümper and Qaim, 2014).
- More predictable feed quality, with consistent nutrient profiles and significantly reduced mycotoxin contamination in GM maize (Gomes, Weber and Luciano, 2024).
- Higher productivity per unit of land, supporting sustainable intensification of livestock production (van Eenennaam and Young, 2014; OECD & FAO, 2023).

These advantages have led to widespread integration of GM feed into intensive livestock systems across North and South America, Asia, and increasingly parts of Africa. As global demand for animal protein continues to rise, GM feed remains a cornerstone of efficient, scalable, and resilient livestock production.

11.4 Metabolism of GM Feed in Food-Producing Animals

A central question in the safety evaluation of GM feed is whether recombinant DNA or transgenic proteins can survive digestion and appear in edible animal products. Over the past five years, multiple studies have consistently shown that GM-derived DNA and proteins are rapidly degraded in the gastrointestinal tract of livestock and do not transfer into meat, milk, eggs, or other tissues (Salisu *et al.*, 2020; Van Eenennaam and Young, 2017). Recent reviews further support this conclusion. Salisu *et al.* (2020) conducted a comprehensive analysis of feeding trials in cattle, poultry, and swine and concluded that transgenic DNA fragments are extensively hydrolyzed during digestion, with no intact recombinant sequences detectable in blood, muscle, or milk. Similarly, Goodman (2024) emphasized that after nearly three decades of GM feed use, no study has demonstrated the presence of functional recombinant DNA or proteins in animal-derived foods, reinforcing the long-term safety record.

Industry-wide assessments also align with these findings. de Vos and Swanenburg (2018) reported that GM feed ingredients behave identically to conventional feed in terms of digestion, nutrient absorption, and metabolic fate, with no evidence of bioaccumulation or gene transfer. Moreover, Siddiqui *et al.* (2024) noted that numerous feeding studies using GM crops revealed no biologically relevant differences in animal performance, health, or the composition of products such as meat and milk compared with conventional diets. Together, these studies confirm the scientific consensus that GM feed is metabolized like any other plant-based feed, with recombinant DNA and proteins fully degraded before absorption. Regulatory bodies such as the European Food Safety Authority (EFSA) have repeatedly concluded that approved GM crops for food and feed are as safe as their conventional counterparts, with no adverse nutritional or toxicological effects identified under assessed conditions (European Food Safety Authority (EFSA), 2023, 2024).

11.5 GM Meat: Direct Genetic Modification of Food Producing Animals

11.5.1 Objectives of Genetic Modification in Animals

Unlike GM feed, which influences livestock indirectly through nutrition, GM meat and genome-edited livestock originate from animals whose genomes have been directly modified to express desirable phenotypes. The primary objectives of genetic modification in livestock include enhanced growth performance, increased resistance to infectious diseases, improved feed efficiency, and broader adaptability to environmental stressors. Recent reviews emphasize that genome-editing technologies such as CRISPR-Cas systems have expanded the range of traits that can be targeted with precision, enabling modifications that would be difficult to achieve through conventional breeding alone (Popova, Bets and Kozhevnikova, 2023; Rodriguez-Villamil, Beaton and Krisher, 2024).

A central focus of current livestock genome editing research has been on targeting specific regulatory loci to enhance production traits. For example, the myostatin (MSTN) gene is a well-established negative regulator of muscle growth, and its disruption via CRISPR-Cas9 has been shown to produce cattle with increased muscle mass and improved growth characteristics in vivo, illustrating the potential for precise genome edits to achieve phenotypes that would be difficult to obtain through conventional selection alone (Gim *et al.*, 2022).

In addition to growth traits, gene editing is actively being studied for disease resistance. Recent work demonstrates that CRISPR/Cas9 editing of host genes in pigs can confer full resistance to severe livestock pathogens such as classical pestiviruses, offering a novel genetic approach to immunological resilience in production animals (Crooke *et al.*, 2025).

Gene editing tools also hold potential for improving feed efficiency and environmental sustainability in livestock systems. Although direct genetic modification of enteric methane production has not yet reached practical implementation, genome editing is being explored for traits that could improve nutrient utilization and resilience to environmental stress, which may contribute indirectly to lower resource use and reduced emissions (Rodriguez-Villamil, Beaton and Krisher, 2024).

Collectively, these approaches reflect a shift in genetic modification objectives from traditional productivity gains toward more holistic outcomes that include improved health, productivity, and sustainability in livestock production systems (Rodriguez-Villamil, Beaton and Krisher, 2024).

11.5.2 Examples of GM Animals

One of the most widely recognized examples of GM meat is AquAdvantage salmon, a GM Atlantic salmon engineered to grow to market size in roughly half the time of conventional salmon. This accelerated growth is achieved through the insertion of a growth hormone gene from Chinook salmon, regulated by a promoter from ocean pout, enabling continuous expression and improving production efficiency with reduced resource use. Regulatory evaluations confirm that the salmon's composition, nutritional profile, and allergenicity are comparable to non-GM salmon, and that food from AquAdvantage salmon is as safe as food from conventional Atlantic salmon (Health Canada, 2016; US Food and Drug Administration, 2015).

Beyond aquaculture, several experimental GE livestock models have been developed using CRISPR-based technologies:

- *Cattle Resistant to Bovine Tuberculosis:* A CRISPR/Cas9 nickase approach has been shown to insert the NRAMP1 gene into cattle genomes, resulting in transgenic cows with increased resistance to *Mycobacterium bovis* infection and reduced off-target effects (Gao *et al.*, 2017).
- *Pigs Resistant to PRRS:* Gene editing of the CD163 receptor has produced pigs that are resistant to porcine reproductive and respiratory syndrome virus (PRRSV), with edited animals showing resistance in challenge trials (Whitworth *et al.*, 2016; Burkard *et al.*, 2017).
- *Chickens with Reduced Susceptibility to Avian Influenza:* Research using CRISPR/Cas9 to edit the ANP32A gene family in chickens demonstrates proof-of-concept for reducing influenza A virus replication (Idoko-Akoh *et al.*, 2023).
- *GE Goats with Altered Milk Composition:* CRISPR/Cas9 has been used to knock out the β-lactoglobulin (BLG) gene in goats, resulting in goats that produce milk-lacking BLG, a major milk allergen (Zhou *et al.*, 2017).
- *Gene Editing for Muscle Traits in Small Ruminants:* CRISPR/Cas9 disruption of the MSTN gene in goats has been shown to cause increased body mass and heritable mutations, demonstrating potential for precision breeding in ruminants (Wang *et al.*, 2018).

Despite these scientific advances, commercial availability of GM meat remains extremely limited. Regulatory frameworks for GM animals are significantly more stringent than those for GM crops, requiring extensive genomic, toxicological, and welfare assessments. Public opposition, ethical concerns, and trade uncertainties further slow commercialization.

11.5.3 New Genomic Techniques and Animals

New genomic techniques (NGTs) have been applied to current or near-market animals for food, feed and other agricultural uses (hence referred to as NGT animals).

According to EFSA Panel on Genetically Modified Organisms (GMO) (2025), no novel hazards have been identified that are linked to either the modification process or the newly introduced trait, when SDN-1, SDN-2, and comparable techniques (e.g. base editing or prime editing) were compared to established genomic techniques (EGTs) or conventional breeding.

SDN-1, SDN-2, and SDN-3 are classifications for different types of site-directed nuclease (SDN) (gene editing) techniques, primarily in plants. Edits have been categorized by how they are made and whether foreign DNA is involved, which impacts regulatory status. SDN-1 involves small changes (indels) via cell repair (NHEJ) without adding new DNA, often exempt from GMO rules. SDN-2 uses a short DNA template for precise, small edits (like point mutations) but is sometimes regulated as GMO. SDN-3 inserts larger DNA fragments (like a whole gene) using a template, generally considered a GMO (https://biotech.co.in/sites/default/files/2022-02/FAQ%20about%20gene%20edited%20plants.pdf).

Targeted mutagenesis was considered (e.g., SDN-1 or SDN-2 to induce nucleotide modification, insertion, deletion, or inversion) and targeted insertion of a DNA cassette encoding a transgene, intragene, or cisgene of interest (e.g.: SDN-3) (EFSA Panel on Genetically Modified Organisms (GMO), 2025).

Farmed animals—mammals, birds, fish, and invertebrates—bred to obtain food, feed, and other agricultural product were considered in this mandate of EFSA, and identified by Parisi and Rodríguez-Cerezo (2021) and Van Eenennaam (2023).

The Commission's study on NGTs published in April 2021 covered the use of NGTs in plants, animals, and microorganisms, and in the agricultural, food, medicinal, and industrial sectors (https://food.ec.europa.eu/document/download/5135278b-3098-4011-a286-a316209c01cd_en?filename=gmo_mod-bio_ngt_eu-study.pdf). The study was supported by a report of the Commission Joint Research Centre (Broothaerts *et al*., 2021).

Development of NGT animals involves ex vivo modification of either somatic cells, germ cells, or early-stage embryos from genetically elite donor animals through the introduction of NGT reagents using various methodologies. Founder offspring production at the pre-commercial stages uses species-specific methods. In mammals, edited embryos are implanted into a uterus, while in fish, they are incubated in water.

Advanced pre-commercial development will include breeding and trait characterization (EFSA Journal, 2025).

11.5.4 GE Beef and Pigs

Gene editing, a genetic engineering method, involves editing an organism's native DNA (Genetic Literacy Project, 2017; Karavolias, 2022) by circumventing existing negative connotations associated with GMOs (removing genes and introducing them into organisms).

These gene-editing tools, like CRISPR/Cas9 (clustered regulatory interspersed short palindromic repeats/CRISPR-associated protein 9), may lead to sustainability of agricultural systems, spanning produce, grains, and livestock (Karavolias *et al*., 2021).

Of course, unwanted changes in an organism's genome have been reported along with toxicity concerns with regard to CRISPR but at low rates (Movahedi *et al*., 2023; Tavora *et al*., 2022).

Promising opportunities for livestock industries have been provided by this technology (Martin-Collado *et al*., 2022).

Gene editing can be used in livestock production to mitigate abiotic stresses caused by climate change, confer disease resistance, increase yields in cattle, sheep, goat, and pig production by increasing animal muscle mass, and increase the nutritional value of livestock (Karavolias *et al*., 2021; Trott *et al*., 2022; Zhao *et al*., 2019). Increased livestock productivity while using less resources and decreasing production costs is another target of this technology (Dace, 2021; Pixley *et al*., 2022).

FDA made its first low-risk determination for marketing food products from CRISPR GE beef cattle, known as PRLR-SLICK cattle (FDA, 2022). These cattle have a short, slick hair coat that enables them to better withstand heat, hence, they are less likely to experience stress from extreme temperatures (FDA, 2022).

Few studies have investigated how consumers will respond to it with limited insights into consumers' perceptions (Paudel *et al*., 2021; Strobbe *et al*., 2023; Yang and Hobbs, 2020). Considering this, Gatica-Arias *et al*. (2019) found that consumers would be more willing to consume them if CRISPR foods had a higher nutritional value and were cheaper than conventional foods.

Moreover, consumers would be more willing to accept GE foods when compared to GM foods (Bašinskienė and Seinauskiene, 2021; Muringai, Fan and Goddard, 2020; Ortega, Lin and Ward, 2022;

Son and Lim, 2021; Strobbe *et al.*, 2023). This might depend on whether they see this as an improvement over genetic modification from a health and environmental perspective (Paudel *et al.*, 2021).

Additionally, acceptance of GE crops when compared to GE livestock might be higher (Kato-Nitta *et al.*, 2021).

Parrella *et al.* (2024) used structural equation modeling, aiming to determine how key psychological and social factors influence US consumers' attitudes toward gene-edited beef from GE cattle. Results indicate that knowledge, subjective social norms, and perceived benefits positively influenced attitudes, while perceived risks and food technology neophobia negatively influenced attitudes.

Behavioral intentions were positively influenced by subjective social norms, perceived benefits, and attitudes, while influenced intentions were negatively affected by perceived risks and food technology neophobia.

11.5.5 Animal Welfare Considerations

Animal welfare is a central ethical concern in the development of GM animals. While many genetic modifications aim to improve animal health, reduce disease burden, or enhance resilience to environmental stressors, others raise concerns regarding unintended physiological effects, behavioral changes, or long-term impacts on well-being. Recent welfare assessments emphasize that gene editing must be evaluated not only for intended outcomes but also for potential off-target edits, developmental abnormalities, and metabolic disruptions, which may affect overall welfare (Mehra and Kumar, 2022).

For example, edits that increase muscle mass—such as MSTN knockouts—may inadvertently affect mobility, birthing ease, or metabolic balance. Similarly, immune-enhancing edits must be evaluated for potential autoimmune responses or altered pathogen interactions. Welfare concerns also extend to the reproductive performance of GM animals, as some edits may influence fertility or gestation.

Regulatory agencies therefore require multigenerational studies, behavioral assessments, and physiological monitoring before approving GM animals for food production. Frameworks for evaluating GE livestock increasingly prioritize welfare protection by advocating that edited animals should not experience greater suffering than their non-edited counterparts and call for welfare indicators to be integrated into assessment protocols (Shriver, 2020).

Ethical debates also focus on the broader implications of modifying sentient beings. Some scholars argue that gene editing can enhance welfare by reducing disease and improving resilience, while others caution that technological interventions may normalize intensive production systems and obscure underlying welfare issues. Systematic reviews of the ethical literature highlight a wide range of reasons for and against genome editing in nonhuman animals, including concerns about animal welfare, intrinsic value, and social acceptability (De Graeff *et al.*, 2023). Public perception research consistently shows that consumers weigh animal welfare considerations heavily when forming attitudes toward GE livestock, with acceptance increasing when edits are perceived to improve welfare but decreasing when they are seen to primarily serve production traits without welfare benefits (Yunes *et al.*, 2021).

Overall, while genetic modification offers significant potential to improve animal health and sustainability, ensuring robust welfare protection remains essential for both ethical and regulatory acceptance.

11.6 Comparative Analysis: GM Feed versus GM Meat

11.6.1 Level of Biological Intervention

The fundamental distinction between *GM feed* and *GM meat* lies in the biological target and depth of intervention. GM feed involves the genetic modification of plants, which are then consumed by animals whose genomes remain unchanged. In contrast, GM meat originates from animals whose genomes have been directly edited, resulting in heritable modifications that persist across generations. Genome editing technologies such as CRISPR-Cas9 enable precise modifications in animal genomes and have been widely reviewed for their transformative potential in both research and agricultural biotechnology (Bruce, 2017; Urban *et al.*, 2025).

Scientific analyses emphasize that genome editing in animals represents a higher-order biological intervention because it can alter multiple regulatory pathways governing traits such as immunity, growth, and metabolism, and these changes are directly embedded in the animal's germline and passed on to subsequent generations (Bruce, 2017; Urban *et al*., 2025). These interventions carry complex implications that differ fundamentally from the compositional changes found in GM plants.

This distinction has major implications for risk assessment. While GM feed is evaluated primarily for compositional equivalence and environmental impact, animals with heritable genomic modifications require comprehensive multilevel evaluation. Such assessments include genomic stability, unintended genomic alterations, welfare outcomes, and potential ecological effects if animals escape or interbreed with wild populations. The National Academies of Sciences, Engineering, and Medicine report on heritable genetic modification in food animals highlights that hazards such as unintended edits, changes in phenotype, or pleiotropic effects must be carefully considered in risk analyses (National Academies of Sciences, Engineering, and Medicine, 2025).

Moreover, ethical and regulatory frameworks must address the welfare and long-term ecological impacts of edited animals beyond the direct food safety concerns typical of GM plant evaluations. Analyses on gene editing in farm animals indicate that welfare considerations and regulatory consistency under EU law demand frameworks sensitive to the unique ethical questions posed by genome editing technologies (Cimadori, Di Concetto and Grieger, 2025). In addition, European perspectives on gene editing emphasize the need for harmonized regulatory approaches that balance innovation with animal welfare and consumer protection (Gil, 2024).

Consequently, the biological complexity of GM meat—stemming from direct genomic editing with heritable outcomes—places it under more stringent regulatory and ethical scrutiny compared to GM feed.

11.6.2 Regulatory and Commercial Status

GM feed is widely approved and commercially integrated across global livestock systems. Many countries have authorized GM crops for food and animal feed, and databases tracking such approvals list hundreds of GM crop events with established use in feed markets, particularly in the Americas, Brazil, and Argentina where adoption rates are high (International Service for the Acquisition of Agri-Biotech Applications, 2026). Regulatory frameworks in major markets are mature and supported by long histories of risk assessment and safety evaluations, facilitating international trade and widespread use of GM feed (Wray-Cahen, Hallerman and Tizard, 2024).

In contrast, GM meat remains subject to intensive and protracted regulatory oversight. Approval processes for GM animals require extensive genomic characterization, welfare assessments, and environmental risk evaluations. The AquAdvantage Salmon, a genetically engineered Atlantic salmon designed for faster growth, is one of the few GM animals that has received commercial authorization following detailed regulatory review (Table 11.1). Approved first by the US Food and Drug Administration and later assessed in Canada, AquAdvantage Salmon faced rigorous evaluation of safety, effectiveness, and environmental impact, including containment measures to prevent escape and breeding in the wild (US Food and Drug Administration, 2015; Government of Canada, 2016).

As a result, the regulatory landscape for GM animals remains highly restrictive relative to GM crops, with approvals geographically limited and commercial adoption slow. This reflects the significantly higher evidentiary thresholds, regulatory complexity, and ethical concerns associated with animal biotechnology compared to plant biotechnology (Wray-Cahen, Hallerman and Tizard, 2024).

From a commercial perspective:

- *GM Feed:* A fully established component of industrial livestock production with extensive international trade.
- *GM Meat:* Remains largely confined to research programs, pilot trials, and niche approvals such as AquAdvantage Salmon, with commercialization limited by stringent regulation and market access challenges.

11.6.3 Consumer Perception

Consumer perception constitutes a critical differentiating factor between GM feed and GM meat, influencing both regulatory decision-making and commercial viability. While GM feed is indirectly linked to food production and typically not visible to end consumers, GM meat involves the direct consumption of GM animals, which is widely perceived as a more ethically and biologically intrusive application of biotechnology. Empirical studies and cross-national surveys consistently indicate that public acceptance of genetic modification in animals is substantially lower than acceptance of genetic modification in plants, even when both are intended for food production (Ipsos MORI & Food Standards Agency, 2021; Koralesky *et al*., 2023).

This differential acceptance is primarily associated with concerns regarding animal welfare, perceived unnaturalness, and uncertainty about long-term ecological and health impacts. Research shows that consumers tend to evaluate genetic modification in animals more critically than in crops, reflecting stronger ethical sensitivities and a higher perceived level of risk. Notably, lower acceptance levels persist even in cases where genetic modification is framed as delivering potential benefits, such as improved animal health or reduced disease burden (Ipsos MORI & Food Standards Agency, 2021).

Beyond the intrinsic characteristics of technology, institutional trust and governance factors play a central role in shaping consumer attitudes. Higher levels of trust in regulatory authorities, transparent risk assessment procedures, and clear labeling practices are associated with increased acceptance of biotechnology applications, whereas skepticism toward institutions and regulatory oversight correlates with resistance to GM meat in particular (Koralesky *et al*., 2023). These dynamics help explain why regulatory approval does not automatically translate into market acceptance.

Regulatory approvals for GM animals represent formal authorizations issued by competent national authorities following comprehensive evaluations of food safety, environmental risk, genomic stability, and animal welfare (Table 11.1). However, such approvals are jurisdiction-specific and do not imply broad societal acceptance. As a result, consumer perception remains a key constraining factor for the commercialization of GM meat, reinforcing the contrast with GM feed, which benefits from lower visibility, longer market presence, and higher levels of public acceptance.

TABLE 11.1

Officially Approved Genetically Modified Animals

GM Animal	Trait/Modification	Developer	Type of Approval	Official Regulatory Reference
AquAdvantage Salmon	Growth-enhanced salmon (opAFP-GHc2 construct enabling continuous GH expression)	AquaBounty Technologies	Commercial food production	US FDA (2015). New Animal Drug Application (NADA 141–454): AquAdvantage Salmon. Center for Veterinary Medicine
AquAdvantage Salmon	Growth-enhanced salmon	AquaBounty Technologies	Commercial food production	Health Canada (2016). Novel Food Information: AquAdvantage Salmon
GalSafe Pig	α-gal–free pig for allergy-safe meat and biomedical use	Revivicor/ United Therapeutics	Food use + medical use	US FDA (2020). Freedom of Information Summary: NADA 141–542—GalSafe Pigs
EnviroPig	Phytase expression to reduce phosphorus excretion	University of Guelph	Research approval only (withdrawn 2012)	Environment Canada (2009). CEPA Environmental Release Assessment for Enviropig
GloFish (Zebrafish)	Fluorescent coloration (GFP/RFP genes)	National University of Singapore	Commercial ornamental use	US FDA (2003). Statement on Genetically Engineered Fluorescent Ornamental Fish
Fluorescent Medaka & Tetra	Fluorescent coloration	Taikong Corp. & Academia Sinica	Commercial ornamental use	Taiwan Council of Agriculture (2012–2015). Approval Notices for GM Fluorescent Ornamental Fish

(Continued)

TABLE 11.1 ***(Continued)***

Officially Approved Genetically Modified Animals

GM Animal	Trait/Modification	Developer	Type of Approval	Official Regulatory Reference
GE Mosquito (OX513A)	Self-limiting gene for mosquito population suppression	Oxitec Ltd.	Environmental release	CTNBio (2014). Technical Opinion No. 3024/2014: Approval of OX513A Aedes aegypti
GE Mosquito (OX5034)	Next-generation self-limiting strain	Oxitec Ltd.	Environmental release	CTNBio (2020). Approval of OX5034 *Aedes aegypti*
GE Mosquito (OX5034)	Next-generation self-limiting strain	Oxitec Ltd.	Experimental use permit (field trials)	US EPA (2020). Experimental Use Permit for Oxitec OX5034 Mosquito
GE Silkworm	Enhanced silk production / recombinant protein expression	Sericulture Research Institute of China	Industrial use (not food)	Ministry of Agriculture and Rural Affairs of China (2018). Approval of Genetically Engineered Silkworm for Industrial Use
GE Carp	Growth-enhanced carp	Chinese Academy of Sciences	Conditional pilot-scale aquaculture	Ministry of Agriculture and Rural Affairs of China (2024). Conditional Approval Notice: Growth-Enhanced GE Carp

11.7 Implications for Human Health

11.7.1 Food Safety and Nutritional Equivalence

Extensive scientific evidence demonstrates that animal products derived from livestock fed with GM feed are nutritionally equivalent to those produced using conventional feed. Over the past two decades, multiple systematic reviews and long-term feeding studies have consistently shown that the use of GM crops such as maize and soybean in animal diets does not result in biologically meaningful differences in animal health, performance, or the composition of meat, milk, and eggs, compared with non-GM feed (Rodler *et al.*, 2018; Snell *et al.*, 2012).

Comprehensive literature reviews further indicate that recombinant DNA and proteins derived from GM feed are extensively degraded during digestion and are not detected at functionally relevant levels in animal-derived food products. Consequently, no significant differences in nutrient composition or food safety parameters have been identified between products obtained from animals fed GM versus non-GM diets, supporting the conclusion of nutritional and safety equivalence (Van Eenennaam and Young, 2014). This body of evidence has provided the scientific basis for the widespread regulatory acceptance of GM feed across multiple jurisdictions.

In contrast, the safety assessment of GM meat is inherently more complex. Unlike GM feed, which affects animals indirectly through dietary exposure, GM meat originates from animals whose genomes have been intentionally modified, necessitating evaluation of potential unintended effects such as altered gene expression, metabolic changes, or pleiotropic outcomes. Regulatory authorities, therefore, require comparative safety assessments that include molecular characterization, phenotypic evaluation, and compositional analysis relative to conventional animal products. The European Food Safety Authority has issued detailed guidance outlining these requirements for GM animals, emphasizing food safety, animal health, and animal welfare considerations (European Food Safety Authority (EFSA), 2012).

Similarly, regulatory frameworks in the United States treat intentional genomic alterations in animals under a risk-based approach that requires assessment of molecular stability, potential off-target effects, and the safety of edible tissues. Guidance issued by the US Food and Drug Administration underscores the need for comprehensive data packages to ensure that intentional genomic alterations do not adversely affect food safety or nutritional composition (US Food and Drug Administration, 2024).

Consequently, while the scientific consensus strongly supports the nutritional equivalence and safety of animal products derived from GM feed, GM meat requires additional layers of evaluation to address uncertainties associated with direct genomic modification. This distinction underpins the more stringent regulatory scrutiny applied to GM animals compared with GM feed.

11.7.2 Allergenicity and Toxicological Concerns

Allergenicity and toxicological effects remain central components of human health risk assessments for both GM feed and GM meat. For GM feed, regulatory and scientific bodies agree that evaluating the potential allergenic risk of GM crops relies on a weight-of-evidence approach, which combines amino acid sequence homology screening, in vitro digestibility tests, and consideration of exposure and history of safe use, because no single test can definitively predict allergenicity (EFSA GMO Panel, 2022).

Systematic reviews of available evidence indicate that commercially approved GM foods and feeds do not show increased allergenicity relative to their non-GM counterparts. These reviews conclude that, although some genetically engineered proteins may share structural features with known allergens, there is no consistent evidence that consumption of GM products increases the risk of food allergy in humans or animals (Dunn *et al.*, 2017).

Similarly, toxicological assessments of GM feed have not identified adverse effects that are reproducibly linked to genetic modification per se. Reviews of animal feeding studies have found that parameters such as growth, organ histopathology, serum biochemistry, immune response, and gastrointestinal microbiota in livestock-fed GM diets fall within normal biological ranges and do not indicate biologically meaningful adverse effects (Snell *et al.*, 2012; van Eenennaam and Young, 2014). These findings have been integrated into risk assessment frameworks used by major regulatory agencies and are reflected in contemporary reviews of GM crop safety (EFSA GMO Panel, 2022).

For GM meat, allergenicity and toxicology assessments also require evaluation of whether the genetic modification introduces novel proteins or affects the expression of endogenous proteins in edible tissues. To date, no approved GM animal product has demonstrated increased allergenic or toxicological risk compared to its conventional counterpart. For example, the regulatory assessment of the AquAdvantage salmon by the US Food and Drug Administration concluded that this GM Atlantic salmon is as safe and nutritious as non-GM salmon, with no evidence of differences in allergenicity or toxicological endpoints (US Food and Drug Administration, 2015).

Nevertheless, long-term human epidemiological data on GM meat are limited due to the restricted commercialization of GM animals. Accordingly, regulators continue to adopt a case-by-case evaluation strategy, requiring comprehensive premarket testing, ongoing post-market monitoring, and transparent risk communication to ensure that any unintended effects—such as off-target genomic alterations or novel peptides—are identified and assessed appropriately (EFSA GMO Panel, 2022; European Food Safety Authority, 2012).

11.8 Environmental Impacts

11.8.1 Environmental Effects of GM Feed

The environmental impacts of GM feed are closely tied to the ecological performance of the GM crops from which these feed ingredients are derived. Over the past decade, research has shown that GM feed crops—particularly herbicide-tolerant soybean and insect-resistant (Bt) maize—can contribute to reduced pesticide use, lower soil disturbance, and greater agricultural efficiency. Recent analyses confirm that Bt crops continue to significantly reduce insecticide applications, thereby lowering chemical runoff and improving soil and water quality (Ngongolo and Mmbando, 2025).

However, environmental concerns persist. One major issue is the evolution of herbicide-resistant weeds, which has been documented in regions with intensive glyphosate-tolerant crop cultivation. Evidence shows that repeated reliance on a single herbicide mode of action accelerates resistance development, leading to increased herbicide use over time (Heap and Duke, 2018; Schütte *et al.*, 2017). Additionally,

the widespread adoption of GM feed crops has contributed to monoculture expansion, which can reduce landscape heterogeneity and indirectly affect biodiversity through habitat simplification.

GM feed may also influence the environmental footprint of livestock production indirectly. Improved feed conversion ratios (FCR) associated with GM feed crops can reduce the amount of land, water, and fertilizer required per unit of animal protein produced. Broader sustainability assessments indicate that integrating GM feed into livestock systems can contribute to more efficient resource use and lower environmental emissions per kilogram of meat produced (Hallerman *et al*., 2024).

11.8.2 Environmental Risks from GM Animals

The environmental risks from GM animals for meat production extend beyond the "escape" concerns of aquatic species to include systemic shifts in agricultural inputs, waste management, and climate-related adaptations. Growth-enhanced and high-yield traits in GM livestock, engineered to improve feed conversion efficiency, may reduce land requirements for grazing but can also intensify industrial farming systems. Such intensification increases manure concentration, elevating nitrogen and phosphorus loads and heightening the risk of soil and water eutrophication. In addition, genome-edited livestock may exhibit unintended physiological or metabolic changes, as discussed in recent evaluations of GE animal applications (Dolezel *et al*., 2025).

11.8.2.1 Environmental Resilience and Land-Use Changes

Applications to create climate-resilient livestock, such as slick-haired cattle engineered for improved heat tolerance, enable animals to maintain productivity under warming climatic conditions. While these traits can reduce heat stress and support adaptation, they also introduce environmental risks by enabling livestock production to expand into regions that were previously unsuitable for intensive ranching. Such expansion can alter land-use patterns, increase pressure on natural habitats, and intensify deforestation risks. These concerns align with established environmental risk assessment principles for GM animals, which emphasize indirect ecological effects and broader ecosystem interactions (EFSA GMO Panel, 2013).

11.8.2.2 Disease Resistance and Ecosystem Overspill

GE pigs resistant to porcine reproductive and respiratory syndrome virus (PRRSV) represent one of the most advanced applications of genome editing in livestock. The deletion of the CD163 receptor's scavenger–receptor cysteine-rich domain 5 has been shown to confer complete resistance to PRRSV-1 infection, demonstrating a major breakthrough in disease-resistant breeding (Burkard *et al*., 2018). Broader reviews of genome editing in pigs and poultry highlight how such traits could substantially reduce disease burden and antibiotic use in intensive systems (Proudfoot, Lillico and Tait Burkard, 2019).

As commercialization progresses, economic analyses suggest that widespread adoption of PRRS-resistant pigs could significantly reshape global pork markets and production structures (Lusk, 2025). However, increased disease resistance may also enable higher stocking densities and more intensive housing systems. Such conditions can alter pathogen–host dynamics and may create selective pressures that favor the evolution of more virulent or persistent pathogen strains, raising concerns about long-term ecosystem and spillover risks.

11.8.2.3 Mitigation of Methane and Greenhouse Gases

An emerging mitigation pathway involves the genetic engineering of cattle or their rumen microbiota to reduce enteric methane emissions. Recent research reviews the use of CRISPR/Cas9 tools to edit key methanogenic microbial pathways within the rumen, offering a potential long-term reduction in methane production (Khan, 2024). Evidence also indicates that host genomic variation influences methane emissions, suggesting that genetic selection or editing of host genomes could be an effective strategy for mitigation (Martínez-Álvaro *et al*., 2022). Genome-wide association studies have identified specific bovine

genomic variants associated with methane yield, providing targets for future breeding or editing efforts (Arikawa, Mota and Fonseca, 2025). Large interdisciplinary initiatives, such as those at UC Davis and the Innovative Genomics Institute, are actively exploring gene-editing approaches to engineer climate-friendly rumen microbiomes (UC Davis/IGI, 2023–2025).

11.9 Regulatory Frameworks Governing GM Feed and GM Meat

11.9.1 European Union Regulatory Approach

The European Union maintains one of the world's most stringent regulatory systems based on the Precautionary Principle. While GM feed from authorized crops is permitted under strict traceability and labeling rules, GM meat faces major regulatory barriers (Directive, 2001; Regulation, 2003). Any GM animal intended for the food chain must undergo EFSA's premarket risk assessment, which requires applicants to submit a complete scientific dossier covering safety, environmental impact, and animal welfare (EFSA Panel on Genetically Modified Organisms (GMO), 2025; European Commission, 2024). As of 2024, no GM meat is authorized for sale in the EU, and the Community GMO Register lists only plant-based GM events for food and feed use.

11.9.2 US Regulatory Approach and Global Regulatory Diversity

The United States utilizes a product-based regulatory model, focusing on the safety of the final food product rather than the process used to create it. Following the landmark 2015 approval of AquAdvantage Salmon, the US Food and Drug Administration has accelerated authorizations, including GalSafe pigs and genome-edited "slick-haired" cattle (FDA, 2015; 2020; 2022). This model is characterized by flexibility and a reliance on post-market environmental monitoring to manage long-term risks.

Regulatory landscapes vary significantly by region (Figure 11.1). Canada, Brazil, and Argentina have streamlined approvals for GM feed and are developing frameworks for GE livestock (Health Canada, 2022). Meanwhile, China has increased investment in agricultural biotechnology as part of broader food-security strategies, although regulatory transparency and approval pathways differ from Western models. In contrast, many nations in Africa and Asia maintain restrictive policies due to trade dependencies with the EU (FAO, 2021; Xingru *et al*., 2024).

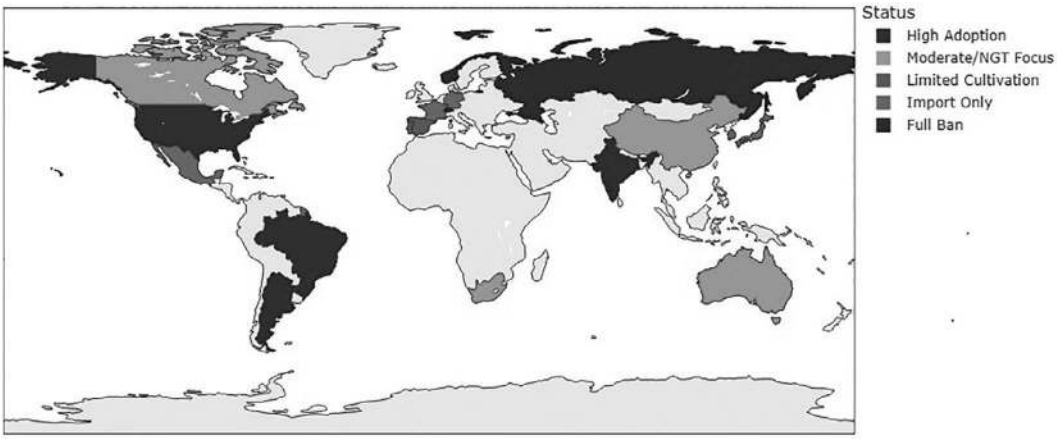

FIGURE 11.1 Global regulatory landscape and adoption of GM plants (2025). *High adoption:* The United States, Brazil, Argentina (product-based model); *Moderate/NGT focus:* China, Canada (emerging GE hubs); *Import only:* EU, Japan (domestic restrictions, high feed imports); *Full bans:* Areas where the precautionary principle remains absolute. (*Data:* FAO GM Foods Platform, PG Economics, ISAAA briefs (n.d.).)

11.9.3 Risk Assessment of GM Feed versus Risk Assessment of GM Meat

11.9.3.1 GM Feed

Risk assessment of GM feed focuses on compositional equivalence, molecular characterization, and animal health outcomes. A comprehensive systematic review of GM food and feed consumption—including studies involving livestock—found no consistent evidence of adverse health effects associated with approved GM products (Shen *et al*., 2022).

Regulatory and policy analyses further support the safety of approved GM feed ingredients, emphasizing that existing risk-assessment frameworks and oversight mechanisms are adequate to ensure animal health and feed performance when GM feedstuffs are properly evaluated (Hallerman *et al*., 2024).

11.9.3.2 GM Meat

In contrast, assessing GM meat is more complex because it involves direct modification of the animal's genome, which introduces additional biological, welfare-related, and ecological considerations. Current scientific and regulatory frameworks emphasize three major domains of risk assessment.

- *Off-Target Effects:* Ensuring genomic integrity is central to evaluating GM meat. Although livestock-specific whole-genome sequencing studies remain limited, high-impact CRISPR research demonstrates that gene editing can induce large deletions, rearrangements, and unintended genomic alterations, underscoring the need for comprehensive off-target screening in GE animals (Kosicki, Tomberg and Bradley, 2018). Additionally, mosaicism—where different cells carry different edits—remains a documented challenge in GE livestock, further highlighting the need for rigorous genomic characterization (Salvesen, Grupen and McFarlane, 2024).
- *Animal Welfare:* Gene edits that alter growth, muscle development, or disease resistance must be evaluated for potential welfare impacts. Ethical and scientific analyses argue that welfare protection must be a primary criterion in GE livestock, requiring careful assessment of whether modifications introduce pain, chronic stress, or developmental abnormalities (Shriver, 2020).
- *Ecological Escape and Population-Level Risks:* Ecological risk-assessment frameworks highlight the need to evaluate escape, introgression into wild populations, and long-term population effects. Recent global analyses of animal-biotechnology governance emphasize that GE animals may pose ecological risks if engineered traits alter fitness, reproduction, or survival, and therefore require robust population-level modeling and regulatory oversight (Hallerman *et al*., 2024).

11.10 Labeling, Traceability, and Consumer Rights

Labeling is the primary point of international divergence. In most jurisdictions, products from animals raised on GM feed (milk, meat, eggs) do not require labeling because the GM DNA is degraded during digestion and is not present in the final product (European Food Safety Authority, 2007). Conversely, GM meat products are subject to explicit requirements. In the United States, the National Bioengineered Food Disclosure Standard, which became fully effective in 2022, requires "Bioengineered" (BE) labels for such products. Research indicates that consumer trust depends heavily on transparent science communication and the perceived benefits (e.g., sustainability or animal welfare) of the genetic modification (Martin-Collado *et al*., 2022; United States Department of Agriculture, Agricultural Marketing Service, 2022).

11.11 Public Perception, Ethics, and Science Communication

Public attitudes toward genetic modification (GM) differ significantly between feed and meat. GM feed is often perceived as an indirect application, whereas GM meat involves direct modification, triggering

complex emotional and cultural reactions. Recent consumer studies confirm that acceptance of GM animals remains lower than for GM crops, even when modifications promote sustainability (Fan *et al.*, 2021; Sendhil *et al.*, 2022). Concerns are focused on naturalness, animal integrity, and trust in biotechnology firms. Effective science communication must address these value-based concerns rather than focusing solely on technical data (Fan *et al.*, 2021). Research emphasizes that transparency regarding ethical safeguards and societal benefits can improve understanding, although not always acceptance. Ethical evaluations now utilize proportionality frameworks, questioning whether the benefits (e.g., environmental resilience) justify the intervention (Sandøe and Christiansen, 2020). Some scholars argue that gene editing is ethically superior to traditional transgenics when it directly improves animal welfare, such as creating disease-resistant livestock (Wray-Cahen *et al.*, 2022).

11.12 Socioeconomic Impacts and Global Food Security

While GM feed has stabilized global supply chains and reduced costs, it has also contributed to market consolidation and dependency on multinational seed corporations (Brookes and Barfoot, 2020). GM meat offers the potential for enhanced growth and resilience, yet it risks widening the technological divide between high-income and low-income regions. International trade dynamics are increasingly complicated by regulatory heterogeneity, as countries with restrictive policies may block imports of GM-derived animal products, affecting global price stability (Fajardo *et al.*, 2023; Turnbull, Lillemo and Hvoslef Eide, 2021). Van Eenennaam *et al.* (2021) modeled three case studies (mastitis-resistant dairy cattle, PRRS-resistant pigs, and AquAdvantage salmon) and found that 5–10-year regulatory delays can impose billions of dollars in opportunity costs and reduce global food security. Such delays also deter investment and public interest research, slowing the deployment of welfare-improving and disease-resistant innovations.

11.13 Future Directions and the Technological Innovation Effect

Advancements in CRISPR-Cas9, base editing, and prime editing are fundamentally blurring the distinctions between traditional GMOs and conventional breeding (Sprink, Wilhelm and Hartung, 2022). Current regulatory debates (2024–2025) emphasize a transition toward "risk-proportionate" oversight models, prioritizing the characteristics of the final product over the transgenic process (European Commission, 2023). Future adoption of these technologies is predicated on Welfare-Centric Edits, such as PRRS-resistant pigs or heat-tolerant cattle, which enhance public acceptance by providing clear benefits to the animal (Wray-Cahen *et al.*, 2022). Furthermore, Transparent Governance, utilizing blockchain-based traceability, is expected to be the standard for ensuring consumer choice and trust (Kamilaris, Fonts and Prenafeta Boldú, 2019).

11.13.1 Analysis of the Technological Adoption & Complexity Index (TACI) and Graphical Trends

The graph provided in Figure 11.2 utilizes TACI to quantify the evolution of these innovations. The values for the past (2010–2024) were formulated by synthesizing historical market penetration data from various sources (FAO GM Foods Platform, PG Economics) and regulatory milestones, such as the FDA approval of AquAdvantage Salmon. The trend shows "isolated adoption", where GM plants achieved high saturation while animals and microbiota remained in developmental stages due to rigid "process-based" barriers. The current trend (2025–2028) indicates a sharp upward trajectory in complexity and synergy. This shift signifies that we are moving away from single-species modification toward Integrated Bio-Systems. The rapid rise of the GM Microbiota curve is particularly significant; it reflects a global response to the Global Methane Pledge (2021), where engineering the rumen environment is now prioritized as a primary climate mitigation tool (Beauchemin *et al.*, 2020).

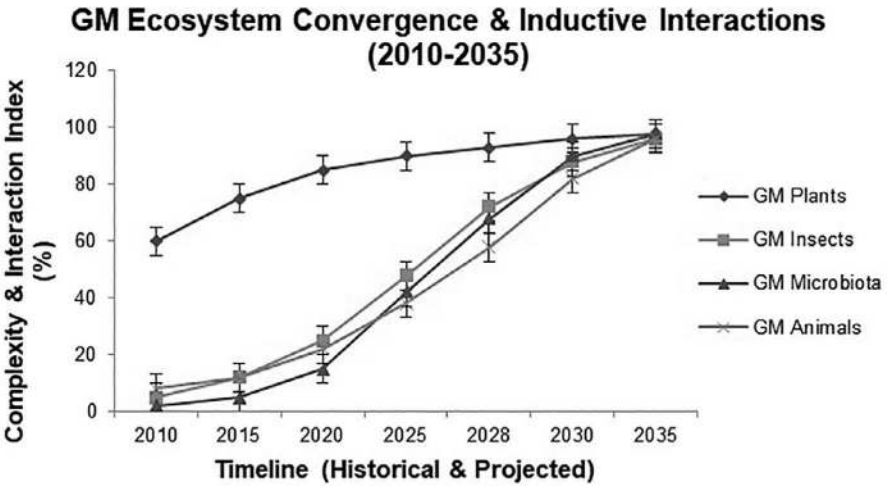

FIGURE 11.2 TACI and emergence of the inductive nexus (2010–2035). TACI indicative for the transition from isolated adoption, characterized by stand-alone GM plants and single-trait GM animals, to a phase of multispecies convergence.

11.13.2 Expectations: The Inductive Expression Nexus

Looking toward the future (2028–2035), a Nexus Point is predicted where GM results from technological advances converge (Figure 11.2). It is expected in the era of Inductive Expression, a breakthrough where a GM animal's traits are not "always on" but are instead "triggered" by external signals. In this context, heat-tolerance or growth genes in an animal are induced by specific metabolites produced by GM rumen microbiota in response to signaling molecules found in GM feed. The emergence of the Inductive Expression Nexus is increasingly supported by the integration of GM insects and insects reared on GM plant substrates. Utilizing CRISPR-Cas9 technology, species such as *Hermetia illucens* are being engineered as biological "reactors" to express enhanced lipid profiles and antimicrobial peptides (Kou *et al.*, 2024; Sui *et al.*, 2024). Furthermore, safety analyses confirm that insects effectively bioconvert GM plant biomass, such as Bt-maize, into high-quality protein without the transfer of intact transgenes to the animal host (Oliveira *et al.*, 2026). Within this framework, GM insects act as a biological bridge, delivering specific metabolic "inducers" that activate context-aware gene switches in GM livestock, thereby optimizing feed conversion and sustainability. The significance of this analysis is that it provides a roadmap for multispecies synchrony. By 2030, the "Technological Innovation Effect" will mean that a GM animal is no longer an isolated genomic island, but a responsive node in a context-aware ecosystem. This synergy addresses the primary limitations of previous GM generations, such as metabolic burden and environmental containment, by allowing for precise, environmentally gated trait expression.

11.14 Conclusions

The comparison between GM meat and GM feed reflects two divergent trajectories in agricultural biotechnology. GM feed is now a globally integrated input supported by mature regulatory frameworks, whereas GM meat remains constrained by ethical concerns, welfare considerations, and stricter oversight due to direct genomic alteration of animals.

Post–data analysis indicates an emerging inductive expression nexus projected for 2030–2035, in which cross-species biological signaling begins to link these domains. In this context, traits such as thermo-tolerance or growth efficiency may be modulated by metabolic cues from engineered rumen microbiota or by bioactive proteins originating from GM plants or insects, creating coordinated multispecies expression systems.

This transition from isolated organism-level modification to interacting engineered species requires regulatory approaches that evaluate ecosystem-level risk rather than focusing solely on production methods. Transparent traceability architectures and long-term, multi-generational monitoring will be essential to ensure biosystem stability. Ultimately, aligning GM feed and GM meat within coherent, risk-proportionate governance will support sustainable and ethically robust food production systems.

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12

Bovine Spongiform Encephalopathy (BSE) in Meat: Risks, Detection, and Management

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12.1 Introduction

Transmissible spongiform encephalopathies (TSEs) are a group of uniformly fatal neurodegenerative diseases identified in at least 12 different animal species (Hillerton, 1998). These diseases progress slowly, lack an immune response, and are characterized by the accumulation of abnormal protein aggregates, primarily within the central nervous system (CNS) (Aguzzi, 2006). Unusual proteins, called prion protein (PrP), cause all these TSEs (Prusiner, 1982, 1998). Inoculation with these PrP or sometimes merely the ingestion of tissue containing PrP transmits the disease to a new host (Cuillé, 1936; Dawson, Wells and Parker, 1990; Gajdusek, 1977; Gordon, 1946; Marsh and Hanson, 1979; Pattison *et al.*, 1972). Other notable TSEs include scrapie in sheep (Detwiler and Baylis, 2003), transmissible mink encephalopathy in mink (Marsh and Hadlow, 1992), chronic wasting disease (CWD) in cervids (Williams, 2005), kuru in humans (Gajdusek and Zigas, 1959), sporadic Creutzfeldt–Jakob disease (CJD) in humans and bovine spongiform encephalopathy (BSE) in cattle (Belay, 1999; Sy, Gambetti and Wong, 2002). BSE is the only TSE known to be transmissible from animals to humans (Lasmezas *et al.*, 1996; Will *et al.*, 1996). BSE, commonly known as "mad cow disease", is a prion disease of cattle that was first identified in the United Kingdom in 1986 and formally described in 1987 (Wells *et al.*, 1987). By 1988, over 2,000 cases had been recorded; BSE became a notifiable disease in June that year, and the number of reported cases increased dramatically, from approximately 60 cases a month to 50–60 cases a week, after notification had been introduced (Kimberlin and Wilesmith, 1994). The epidemic peaked in 1992–1993, with more than 184,500 confirmed cases in the UK, but since then, it has declined markedly (Harman and Silva, 2009; Nathanson, Wilesmith and Griot, 1997). BSE is considered a zoonosis (Smith and Bradley, 2003), as experimental studies have shown that it can be naturally transmitted via the oral route in cattle and sheep, making contaminated food the most likely source for humans, especially since many infected cattle have entered the human food chain (Smith and Bradley, 2003). However, the exact mode of transmission to humans remains unclear (Smith and Bradley, 2003). BSE typically occurs in adult animals of either sex, usually those that are 4–5 years old (Wilesmith *et al.*, 1988). The disease is thought to have originated from scrapie-infected sheep products used in cattle feed (Southwood, 1989). The incidence of BSE-affected herds of either type increases progressively with herd size; the larger the herd is, the more feed is needed, and the greater the chances of buying an infected batch (Kimberlin and Wilesmith, 1994). Importantly, there is no evidence for direct horizontal transmission of BSE between cattle (Hoinville, Wilesmith and Richards, 1995).

The disease has now been confirmed in native-born cattle in 25 countries worldwide, including Asia and North America (Harman and Silva, 2009). The incubation period of BSE is dose-dependent, with as little as 0.5–1 g of infected brain tissue sufficient to infect calves orally (Brewer, 1999). It is a neurological disease involving pronounced changes in mental status, abnormalities in posture and movement,

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and sensation, and is characteristically progressive and fatal (Wilesmith *et al*., 1988). Pathologically, the disease produces distinctive lesions in the CNS, characterized by bilaterally symmetrical vacuolation of neuronal cell bodies and gray matter neuropil, similar to scrapie (Kimberlin and Wilesmith, 1994; Wells *et al*., 1987). Experimental studies have confirmed transmission to cattle through brain homogenates, albeit with prolonged incubation periods of one to two years (Dawson, Wells and Parker, 1990). On average, the natural incubation period is of 4–5 years, indicating that the impact of feed bans on disease incidence is not immediate (Kimberlin and Wilesmith, 1994; Winter *et al*., 1989). Currently, no diagnostic test exists for live animals, as the infection triggers no detectable immune response; thus, BSE can be confirmed only once clinical signs appear (Kimberlin and Wilesmith, 1994).

BSE belongs to the scrapie family of prion diseases, and while the exact biochemical nature of the agent remains unclear, its biological behavior is better understood (Wilesmith and Wells, 1991). Extracts of BSE brains contain abnormal fibrils very similar to scrapie-associated fibrils (SAFs). These fibrils derive from a normal host-encoded protein, PrP, that has undergone abnormal posttranslational modification. The fibrils obtained from BSE-affected brains are made up of the same modified host protein. The presence of SAF is another characteristic feature of TSEs, which also indicates an infectious etiology for BSE (Kimberlin and Wilesmith, 1994). Knowledge from related scrapie diseases provides insight into the potential course of the BSE epidemic (Wilesmith and Wells, 1991).

Therefore, BSE has a significant effect on the global cattle trade, animal health, and public health (Smith and Bradley, 2003). The outbreak resulted in significant economic losses for farmers and heightened public concern about the potential risk of transmission to humans through beef or milk (Matthews, 1990). Despite progress, significant research gaps and limitations remain. The infectious agents are highly resistant to destruction, remain undetectable until clinical signs or brain lesions appear, and have very long incubation periods, which make early control extremely challenging. Moreover, the absence of an immune response has prevented the development of serological tests for live cattle, limiting the ability to detect infections before clinical onset, making BSE a major veterinary problem (Van Keulen *et al*., 2000). Although advances in postmortem diagnostic techniques have improved the sensitivity and speed of detection, these methods are restricted to dead animals and cannot prevent disease spread in herds. Therefore, further research is needed to develop live animal diagnostic tools, understand the biochemical nature of the infectious agent, and strengthen surveillance and feed control measures to prevent recurrence and eventually eradicate BSE (Wilesmith and Wells, 1991). Hence, this chapter aims to provide an overview of BSE, covering their origin, epidemiology, diagnosis, control measures, and research gaps, with emphasis on their implications for animal health, food safety, and public health.

12.2 Etiology

A misfolded form of the widely expressed glycoprotein called prion protein (PrP) causes BSE. The PrP-encoding gene (PRNP) encodes PrP, which is a common element found in vertebrate cell membranes (Castle and Gill, 2017). Stanley Prusiner and others discovered the etiologic agent of TSEs more than 25 years ago. They reported that the pathogenic entity was proteins that could spread without the use of nucleic acids. Prions are the names given to these proteins (Prusiner, 1982, 1998). A combination of the words "proteinaceous" and "infectious" was used to characterize its distinct characteristics. (Aulić, Bolognesi and Legname, 2013).

PrP^{C} is the normal form (normal prion protein), whereas PrP^{Sc} is the infectious, disease-causing type (abnormal and misfolded prion protein) (the "Sc" stands for scrapie). Although the amino acid sequences of the two isoforms are the same, their three-dimensional structures (conformations) are different (Colini Baldeschi *et al*., 2022; Imran and Mahmood, 2011). PrP^{C} tends to aggregate when it adopts its misshapen state, or PrP^{Sc}, forcing its abnormal structure onto otherwise harmless PrP^{C} molecules. Therefore, prions serve as corrupting seeds that start a series of PrP aggregation and misfolding events (Jucker and Walker, 2018). Fish, amphibians, birds, mammals, and yeast all have PrP^{C} (Pastore and Zagari, 2007). The spleen, lymph nodes, kidney, pancreas, salivary glands, adrenal glands, liver, thymus, and bone marrow are among the many organs in animals that express the protein, which is strongly expressed in the neurological system (Tichopad, Pfaffl and Didier, 2003). Several mouse strains that lack PrP^{C}

expression show only slight, nonfatal differences in their physiological and locomotor activities compared with those of wild-type mice, indicating that the physiological purpose of PrP^C is still unknown (Nico *et al*., 2005).

An external infectious prion isoform transforms a negative PrP^C into a replica of the contagious prion isoform during the course of a prion illness. In a sort of chain reaction, this newly created isoform can then transform additional native PrP^Cs, causing the infectious prion isoform to multiply and spread the illness (Cohen, Pan and Huang, 1994; Eigen, 1996; Harper and Lansbury, 1997). Certain prion disease strains, including scrapie and BSE strains, exhibit unique disease traits. The strains differ in histology, clinical symptoms, the time required for an animal to incubate after experimental infection, and the patterns of protein deposition in the brain and lymphoid tissues. For example, in the case of scrapie, some strains proliferate preferentially in the CNS, whereas others are characterized by substantial infectivity in lymphoid organs (Scialò *et al*., 2019).

BSE is known to exist in three different strains. One form of prion, known as classical BSE (C-BSE), is responsible for the human vCJD epidemic that accompanied the BSE outbreak that began in the UK and spread to other countries (Ritchie, Peden and Barria, 2021). Atypical strains, also known as H (high)- and L (low)-BSE, are rare and usually occur in cattle that are 8–20 years old (Masujin *et al*., 2016). They appear to appear at random and without warning. Standard sterilizing methods used to prepare surgical tools and supplies are notoriously ineffective in inactivating prions (Sakudo, Yamashiro and Onodera, 2022). PrP^{Sc} is resistant to gamma irradiation, UV irradiation at 254 nm, 70% alcohol treatment, and conventional autoclaving (121 °C for 20 minutes). A variety of methods, such as strong autoclaving (134 °C for 8–18 minutes) in conjunction with detergents and hydrogen peroxide gas plasma treatment, can inactivate PrP^{Sc} (Sakudo, Anraku and Itarashiki, 2021). The infectiousness of prions can be decreased by various processes that alter or hydrolyze proteins. While PrP^C is protease-sensitive and soluble in nondenaturing detergents, PrP^{Sc} is insoluble in detergents and contains a protease-resistant core (Yuan *et al*., 2006).

12.3 Prion Biology

The prion protein-encoding gene (PRNP), located on chromosome 20 in humans, encodes PrP^C, a normal cellular form of the prion protein that is a kind of glycoprotein prominently found on the surface of host neurons (Olech, 2023; Toldrá, 2009). It is commonly attached to the plasma membrane through a glycosylphosphatidylinositol (GPI) anchor. In mammals, PrP^C is encoded by a single gene that produces a protein of approximately 250 amino acids, featuring an N-terminal signal peptide followed by five octapeptide repeats rich in proline and glycine, which bind copper. Additionally, the protein includes a highly conserved central hydrophobic domain (HD), two glycosylation sites, a disulfide bond, and a hydrophobic C-terminal region that signals for GPI anchor attachment (Sarnataro, Pepe and Zurzolo, 2017). The N-terminal signal peptide (amino acids 1–22) serves as the primary signal directing PrP^C to the endoplasmic reticulum (ER). This segment is recognized by signal recognition particles (SRPs), which facilitate the targeting of the ribosome–nascent chain complex to ER membrane receptors. Upon docking, protein synthesis resumes, and the PrP polypeptide is cotranslationally translocated into the ER. The structural integrity of this N-terminal signal peptide is essential for the proper import of PrP^C and the formation of its correct topological isoforms. When the import signal is inefficient or defective, PrP^C may accumulate abnormally in the cytosol, ultimately disrupting cellular functions and impairing cell viability (Figure 12.1) (Heller *et al*., 2003).

12.3.1 Prion Protein Misfolding and Aggregation

The normal cellular PrP^C is involved in the development of TSEs, a group of fatal neurodegenerative diseases affecting both humans and various animal species. Under these conditions, PrP^C can undergo a conformational change into its abnormal, disease-associated form, known as PrP^{Sc}. Although the exact process by which the PrP^C transforms into the disease-associated PrP^{Sc} isoform remains unclear, the most widely accepted theory suggests that direct physical contact between PrP^C and PrP^{Sc} is necessary to initiate this conversion. Some research, particularly in transgenic mouse models, also indicates that an

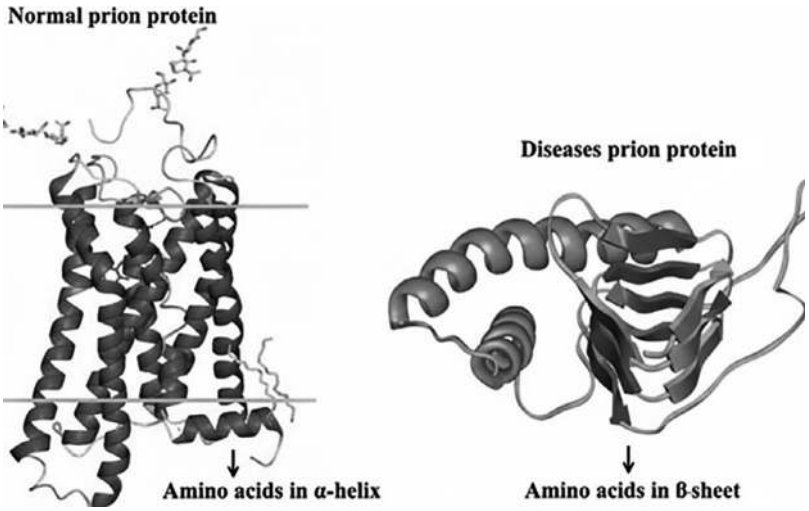

FIGURE 12.1 Schematic representation of the conformational changes in the prion protein. The normal cellular isoform (PrP^{c}) is rich in α-helices, whereas the pathological, misfolded isoform (PrP^{sc}) has a high β-sheet content, leading to aggregation and neurotoxicity. (This schematic was generated via an AI tool based on the structural concepts described by Vázquez-Fernández *et al.*, 2016.)

additional host factor, often referred to as "protein X", may facilitate this transformation (Telling *et al.*, 1995). The conversion is thought to occur either at the plasma membrane, where endogenous PrP^{C} meets incoming PrP^{Sc}, or shortly after internalization within cellular compartments such as endolysosomes or recycling vesicles (Sarnataro, Pepe and Zurzolo, 2017). The prion hypothesis suggests that sporadic or spontaneous forms of prion disease occur when the PrP^{C} undergoes a conformational change, either randomly or due to a somatic mutation in the PRNP gene, into the abnormal, disease-causing form (PrP^{Sc}). This misfolded protein then acts as a template, triggering the conversion of additional PrP^{C} into PrP^{Sc}. In acquired forms of the disease, PrP^{Sc} is introduced from an external source and initiates the same misfolding process in the host (Aguzzi, Sigurdson and Heikenwaelder, 2008; Prusiner, 2004).

This misfolded variant is insoluble, partially resistant to protease digestion, and capable of self-propagation by converting normal PrP^{C} into more PrP^{Sc}. The misfolded prion protein PrP^{Sc} has a strong propensity to form polymers, leading to the development of amyloid aggregates that accumulate predominantly in the brain. This abnormal protein buildup also occurs in the lymphoreticular system and is associated with spongiform changes, such as neuronal vacuolation, ultimately leading to neuron death. After a prolonged incubation period, affected individuals begin to exhibit progressive neurological decline, which invariably ends in death (Prusiner and DeArmond, 1994). PrP^{Sc} is highly resilient, showing strong resistance to proteases, nucleases, and radiation. When treated with proteinase K, PrP^{Sc} yields a smaller, protease-resistant core fragment known as PrP^{res}, which is typically 27–30 kDa in size (Bolton, McKinley and Prusiner, 1982). Notably, PrP^{C} and PrP^{Sc} share an identical amino acid sequence but differ in their posttranslational folding and biochemical properties. PrP^{C} exists as a soluble, monomeric protein that is readily degraded by proteinase K, whereas PrP^{Sc} forms insoluble, protease-resistant aggregates. Spectroscopic analyses have revealed structural differences: PrP^{C} is rich in α-helices (approximately 42%) and contains very few β-sheets (approximately 3%), whereas PrP^{Sc} has a significantly greater β-sheet content (approximately 45%) and a reduced α-helical structure (approximately 30%) (Pan *et al.*, 1993).

12.3.2 Mechanism of the Pathogenic Cascade

Following oral exposure to the C-BSE agent, the exact route by which prions cross the intestinal lining is not fully defined, but M cells (Heppner *et al.*, 2001), specialized epithelial cells in the gut and

tonsils, are believed to transport prions from the intestinal lumen into underlying tissues. Within the first eight months post-infection (mpi), abnormal prion protein (PrP^{Sc}) accumulates in tangible body macrophages (TBMs) located in gut-associated lymphoid tissues such as the ileocecal junction, jejunum, and Peyer's patches (Terry *et al*., 2003). By 6–10 mpi, prions are also detected in the palatine tonsils. A peak in infectivity occurs at 12 mpi in the distal ileum, associated with increased PrP^{Sc} levels in follicular dendritic cells (FDCs) and TBMs, followed by additional peaks at 24 mpi and at 32–40 mpi in the jejunum and ileum. During intestinal infection, prions access the enteric nervous system (ENS) and spread through the mesenteric nerves to the coeliac–mesenteric ganglia. They then reach the thoracic spinal cord via the sympathetic nervous system (splanchnic nerves) and the brainstem via the parasympathetic pathway (vagus nerve) (Iwamaru *et al*., 2010). PrP^{Sc} subsequently spreads throughout the central and peripheral nervous systems, including the cranial medulla, cauda equina, dorsal root ganglia, and trigeminal and cervical ganglia. Prion presence has also been confirmed in the adrenal glands and sciatic nerve. Between 42 mpi and 84 mpi, PrP^{Sc} accumulates in the muscle spindles of various skeletal muscles, such as the masseter, triceps brachii, intercostals, and semitendinosus (Okada *et al*., 2014).

A time-limited intraspecies transmission study involving a Japanese case of L-type BSE revealed that PrP^{Sc} was initially detected in nerve roots and subsequently in peripheral nerves, as determined by Western blot (WB) analysis. The findings showed that after the brain becomes affected, nearly all examined peripheral nerve tissues progressively test positive for PrP^{Sc} over time, while no prion presence is detected in lymphoid tissues. This pattern suggests that L-type BSE prions primarily replicate within the CNS and then spread outward along nerve pathways (Iwamaru *et al*., 2010). Currently, understanding the pathogenesis of atypical BSE remains challenging due to limited data, as most information on PrP^{Sc} distribution comes from cattle in the late clinical stage. Experimental transmission studies have shown that in both H- and L-type BSE, PrP^{Sc} accumulates in CNS tissues, peripheral nerves and ganglia, muscle spindles, adrenal glands, and the retina. However, unlike C-BSE, atypical cases have shown no PrP^{Sc} presence in lymphoid or gastrointestinal tissues (Costassa *et al*., 2016).

12.3.3 Species Barrier and Cross-Species Transmission Dynamics

Among the TSEs in animals, scrapie is the most well-known. First identified more than 200 years ago in the UK, the term "scrapie" generally refers to TSEs affecting sheep and goats. However, the exact number and nature of the prion strains responsible for the disease remain unclear. To date, three separate prion strains have been identified in sheep. Two of these strains, SSBP/1 (derived from the scrapie-infected Cheviot sheep brain pool) (Dickinson *et al*., 1968) and CH1641 (isolated from a Cheviot sheep in the UK during the 1970s) (Foster and Dickinson, 1988), have been consistently maintained through transmission in their natural hosts. The third type is the atypical scrapie strain (Simmons *et al*., 2007). The newly identified atypical form of scrapie has been detected in European sheep and goat populations through active surveillance programs that use rapid biochemical methods to detect PrP^{res} in brain tissue. Studies have shown that both cattle and transgenic mice expressing bovine PrP^{C} are susceptible to scrapie isolates from the United States and Europe (Béringue, Vilotte and Laude, 2008). However, none of the resulting disease patterns resemble those of BSE, providing no support for the theory that BSE originated from a scrapie agent. For human health, there is currently no epidemiological evidence linking scrapie to human prion diseases. The worldwide distribution of sporadic CJD remains relatively uniform, regardless of whether a country has reported scrapie cases or is considered scrapie-free (Ladogana *et al*., 2005).

Strong evidence suggests that a single dominant prion strain caused a BSE outbreak in cattle. To date, BSE remains the only animal prion disease confirmed to be transmitted to humans, resulting in variant Creutzfeldt–Jakob disease (vCJD). Over two decades since its emergence in the UK, the outbreak has been largely controlled across most of Europe. This proactive surveillance has also revealed rare molecular variants, possibly representing new prion strains different from BSE. These atypical cases have mostly been found in older cattle, suggesting the potential presence of sporadic TSE forms in the species (Biacabe *et al*., 2008). Cross-species transmission of C-BSE has been documented under natural conditions in exotic ungulates, including goats and cats. Experimental studies have also shown that BSE

can be transmitted to pigs, sheep, and goats (Foster, Hope and Fraser, 1993). This raise concerns that the BSE agent may be present in sheep and goat populations, potentially creating an additional risk of human exposure. When orally exposed to BSE, goats and sheep develop clinical and pathological signs that are indistinguishable from those of scrapie (Olech, 2023).

CWD is a prion disorder affecting both wild and farmed cervids, including mule deer, white-tailed deer, Rocky Mountain elk, and, more recently, moose (Sigurdson, 2008). Initially identified in Colorado in 1967, CWD has since spread widely across North America, including Canada. While its exact origin remains unclear, many pathological features of CWD resemble those observed in sheep scrapie. Evaluating the risk of cross-species transmission to other farm animals that may come into contact with cervids (such as cattle and sheep), wildlife scavengers (such as raccoons), and humans, particularly hunters and those who consume venom, is especially important (Béringue, Vilotte and Laude, 2008).

12.3.4 Classic versus Atypical Prion Strains and Their Zoonotic Potential

Three distinct forms of BSE have been identified. The most prevalent BSE is C-BSE, which was initially detected in Great Britain (GB) in 1986 and is associated primarily with widespread outbreaks of the disease. In 2004, two additional atypical variants were discovered independently in France and Italy (Biacabe *et al.*, 2004; Casalone *et al.*, 2004). These atypical forms are categorized into L-type (low) and H-type (high) forms on the basis of the relative position of the unglycosylated PrP^{res} band on WB analysis, which is lower or higher, respectively, than that of C-BSE. The L-type is also referred to as bovine amyloidotic spongiform encephalopathy (BASE), characterized by PrP-positive amyloid plaques in the brain, which are absent in classical cases (Table 12.1). Although L- and H-type BSEs are significantly rarer than the classical form, they have been documented in multiple countries, including several countries across Europe, as well as in the United States, Canada, and Japan (Hagiwara *et al.*, 2017). The inclusion of bovine-derived materials from animals affected by atypical BSEs in food or feed production could present a health risk to humans. Certain laboratory-based transmission studies have suggested that L-type BSEs may have zoonotic capabilities, potentially exceeding those observed in the C-BSE variant (Kong *et al.*, 2008; Mestre-Francés *et al.*, 2012).

TABLE 12.1

Distinguishing Features of Classical versus Atypical BSE

Feature	Classical BSE (C-Type)	Atypical BSE (H- and L-Type/BASE)
Origin and discovery	First identified in 1986 (UK), linked to contaminated feed with BSE-infected sources	Detected in 2004 (Italy, France) Occurs sporadically in older cattle
Transmission and zoonosis	Easily spreads via the oral route (to animals and humans) In humans, there are causes of vCJD	Poor oral transmission No human cases confirmed, but L-type may carry zoonotic potential
Global presence	Reported in over 20 countries Incidence declining with strict controls	Very rare, but it may appear anywhere, even in the absence of C-BSE cases
Clinical signs	Marked by behavioral changes, heightened sensitivity, hind limb incoordination, weakness, and weight loss	Shows signs like dullness, drooping head, inactivity, and reduced nervousness
Molecular and biochemical traits	PrP^{Sc} is highly resistant to digestion, exhibiting a typical 3-band WB pattern	PrP^{Sc} is more digestible L-type has a lower, and H-type has a higher, unglycosylated band on WB than classical
WOAH risk status	Included in official risk status assessments	Not considered in official risk classification

Source: Modified from Olech, 2023.

12.4 Epidemiology and Risk Factors

12.4.1 Origins of the Epidemic: Feed Contamination and Recycling of MBM

Before the detection of BSE, scrapie in sheep and goats was first described as TSE (Ness, Aiken and McKenzie, 2023). BSE was first diagnosed in GB in November 1986, when a cow with neurological signs was referred to the Central Veterinary Laboratory (CVL) of the Ministry of Agriculture, Fisheries and Food (MAFF) at Weybridge, Surrey. Clinical and pathological investigations of cows identified the disease as a spongiform encephalopathy characterized microscopically by the presence of sponge-like alveolar structures in the animal's brain tissue (Dealler and Lacey, 1991; Wells *et al*., 1987). The disease was subsequently confirmed in the general meeting of the World Organization for Animal Health (WOAH, formerly Office International des Epizooties, OIE) in 1988 (Yoshikawa, 2008).

The actual origin of BSE remains unclear; however, various hypotheses have been proposed (Figure 12.2). The disease in cattle is thought to have originated and amplified by the use of supplementary cattle feed containing meat and bone meal (MBM) contaminated by a scrapie-like agent derived from sheep (Alarcon *et al*., 2023; Cummins *et al*., 2001). MBM, a high-protein meal, is produced by the rendering process, principally from tissues discarded by abattoirs and butchers, along with carcasses from fallen stock. Rendering involves cooking animal residues, which enables the separation and collection of the melted fat fraction (tallow), while the remaining solids (greaves) are crushed to form MBM (Taylor *et al*., 1997). MBM has been widely used globally as a recycled feed ingredient because of its high content of undegradable proteins, which effectively increase milk yield and daily weight gain in cattle. Unfortunately, a portion of the MBM becomes contaminated with transmissible prions, causing BSE in cattle (Takahashi, 2005). Subsequent epidemiological studies conducted in 1988 and 1989 demonstrated that the rapid spread of the epidemic in the cattle population of GB was most likely caused by the ingestion of MBM from infected cattle (Donnelly *et al*., 1997).

12.4.2 Geographical Distribution and Outbreak Trends

At first, BSE was considered an issue limited to the UK, but it soon became clear that countries importing cattle, cattle products, or MBM were also at risk. Since then, BSE has been detected in cattle across most European nations and, more recently, in several countries beyond Europe (Smith and Bradley, 2003). BSE is likely spread from the UK, primarily through the export of live cattle and contaminated feed (Fox and Peterson, 2002). Moreover, rendering practices similar to those in the UK were also used in some European countries, which could have facilitated the spread of BSE (Smith and Bradley, 2003).

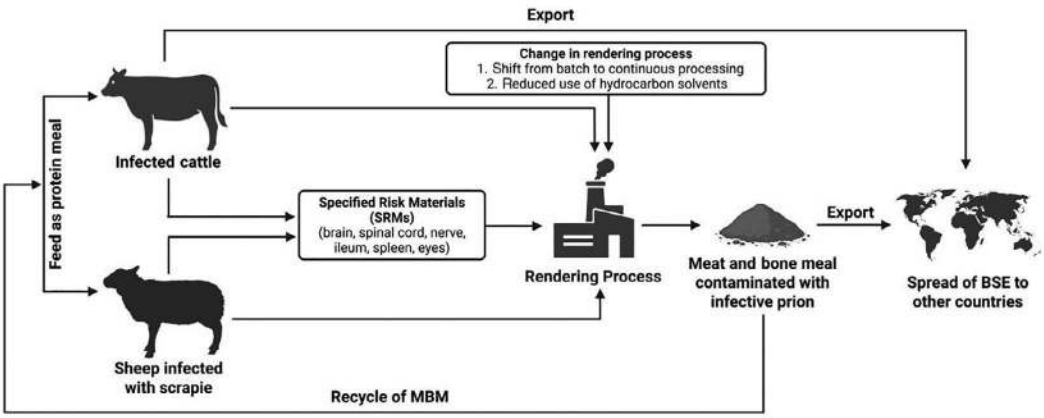

FIGURE 12.2 Origin and spread of BSE epidemics.

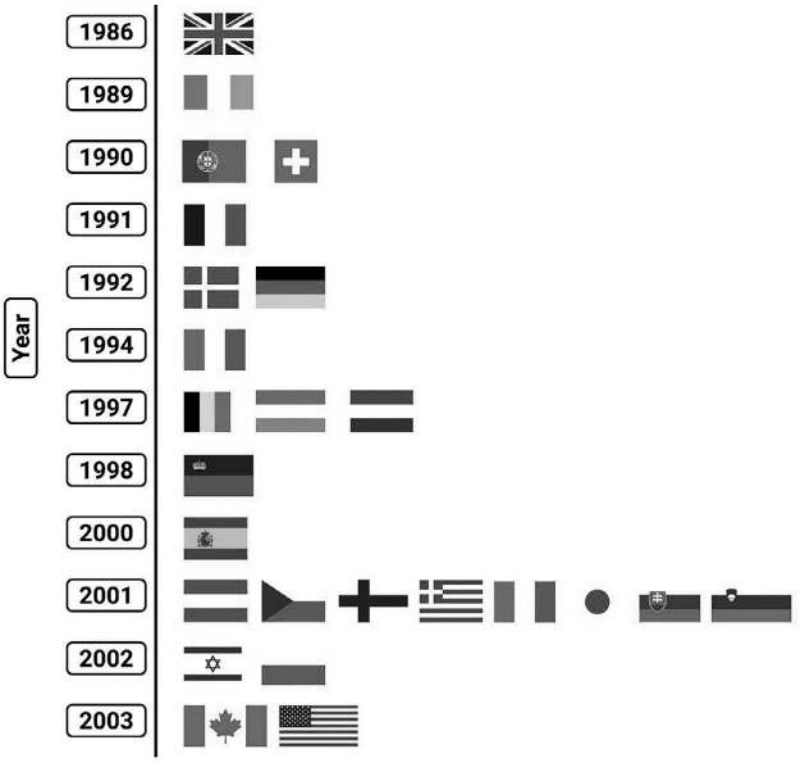

FIGURE 12.3 Chronology of the first reported BSE cases in different countries. (Smith and Bradley, 2003; USDA, 2025a.)

C-BSE originated in the UK and subsequently spread to at least 28 other countries, primarily Europe, with sporadic cases also reported in Asia (Japan), the Middle East (Israel), and North America. To date, over 115 million cattle have been tested in Europe, confirming more than 185,000 cases in the UK, 7,891 cases across Europe, and 60 cases worldwide in countries such as Brazil, Canada, Israel, and Japan (Casalone and Hope, 2018). The chronology of the first reported BSE cases across countries is shown in Figure 12.3.

Similarly, Table 12.2 outlines the significant BSE outbreak events and the diagnostic methods used to detect them, whereas Figure 12.4 illustrates the global BSE risk status map.

12.4.2.1 BSE Transmission to Humans (vCJD Cases)

Naturally, many exported animals infected with BSE are not detected and subsequently enter the food chain for both humans and animals, facilitating the spread of the disease (Fox and Peterson, 2002). In particular, concern over potential human exposure to BSE through contaminated food emerged after the first few cases of vCJD were identified in the UK (Corona *et al.*, 2017). By April 1, 2013, a total of 176 cases of vCJD had been documented in the UK (Figure 12.5) (Chen, Wang and Wu, 2013).

Research based on biological and molecular strain typing has clearly demonstrated that BSEs and the vCJD agent are the same or at least have similar pathogenicity for humans and for macaque monkeys, to which both agents have been transmitted (Collee, Bradley and Liberski, 2006). Therefore, BSE is a zoonotic TSE that poses a significant risk to both human and animal health (Corona *et al.*, 2017).

TABLE 12.2

Timeline of BSE Outbreaks

Year	Country	Events	Total Cases	Detection Methods	References
April 24, 2012	USA	USDA confirmed the country's fourth BSE case in a cow tested at a rendering facility in central California	1	Samples were first tested at the California Animal Health and Food Safety Laboratory, then sent to the NVSL on April 20 for confirmation. APHIS reported the positive result on April 24	USDA, 2012
March 13, 2006	USA	USDA found a cow with BSE in Alabama	1	A western blot performed at the USDA's NVSL in Ames, IA, confirmed the cow's infection	AVMA, 2006
June 30, 2005	USA	12-year-old beef cow born in Texas was confirmed with BSE by USDA	1	Western blot test	Cooper, 2023; CIDRAP, 2005
January 2004	Britain	143 people in Britain have been infected with vCJD, and 180,000 cattle have been diagnosed with BSE	143 cases of vCJD, 180,000 cases of BSE	–	CFS, 2025
December 23, 2003	USA	BSE confirmed in a dairy cow from Washington state, imported from Canada	1	–	CFS, 2025
May 20, 2003	Canada	An 8-year-old cow in Alberta tests positive for BSE, the first confirmed case in North America	1	Western immunoblotting technique	Stack *et al.*, 2004
August 2002	Canada	A Canadian man dies from vCJD after contracting the disease in Britain	1	Canadian and UK experts confirmed the diagnosis of vCJD through autopsy	Wilkins, 2002
April 2002	USA	A 22-year-old British woman living in Florida confirmed the first case of vCJD in the United States	1 case of vCJD	Western blot and immunohistochemistry	CDC, 2002
September 2001	Japan	First outbreak of BSE in Japan	1	The specimen was submitted to the Veterinary Laboratories Agency in England and diagnosed with BSE infection	Giles, 2001; Nakao, 2001
July 1997	Britain	21 vCJD victims in Britain have been confirmed	21 vCJD cases	–	CFS, 2025
August 1996	Britain	A 20-year-old vegetarian, Peter Hall, died of vCJD	1 vCJD cases	–	Reuters, 1996
March 1996	Britian	10 cases of CJD in people aged under 42. The UK government first acknowledged that BSE may transmit to humans as variant CJD, leading to the culling of approximately 4.5 million cattle	10 vCJD cases	–	CFS, 2025
1993	Britain	120,000 cattle have been diagnosed with BSE in Britain	120,000	–	CFS, 2025
Early 1990s	Britain	Five types of antelope die in British zoos from TSEs that had been fed commercial cattle feed	5 TSEs cases	–	CFS, 2025
1988	Britain	421 cattle have been diagnosed with BSE in Britain	421	–	CFS, 2025
1986	Britain	First detection of BSE in Britain. The exact cause remains unclear, although it is suspected that feeding cattle with rendered material from scrapie-infected sheep may have contributed to the disease	1	Microscopic examination	CFS, 2025; Dealler and Lacey, 1991

Source: CFS, 2025.

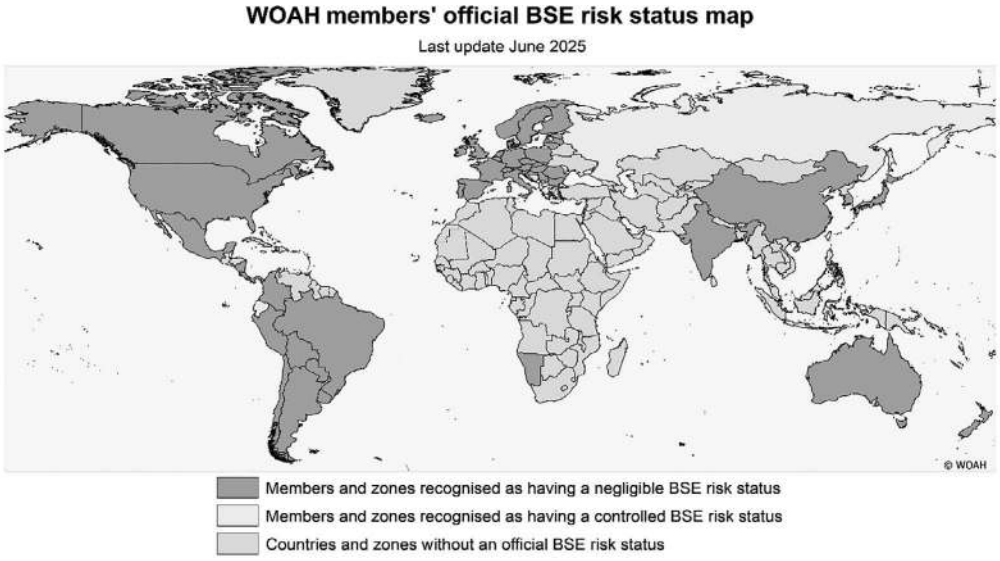

FIGURE 12.4 BSE risk status map of the world. (WOAH, 2025a.)

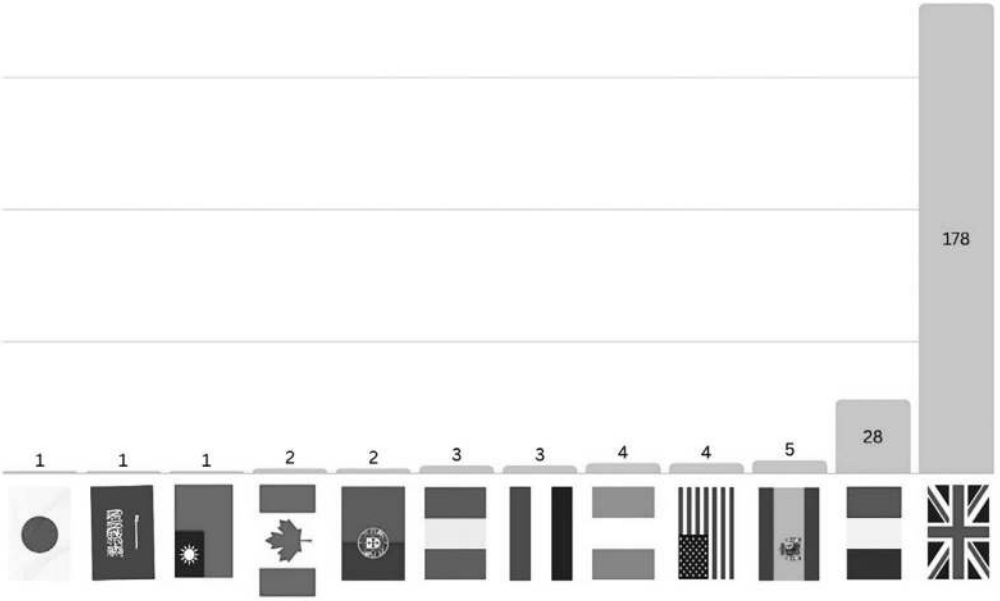

FIGURE 12.5 Cases of vCJD worldwide (1995–2024). (From EuroCJD, 2025.)

12.4.3 High-Risk Practices: Ruminant Feed, Rendering Methods, and Specified Risk Materials (SRMs)

Although the exact origin of BSE is uncertain, epidemiological studies have been conducted by Wilesmith *et al.* (1988). In the early stage of the BSE epidemic in GB, a crucial role was played in understanding BSE. These studies demonstrated that MBM, produced from BSE-infected cattle, was the primary vehicle of transmission (Wilesmith *et al.*, 1988; Wilesmith, Ryan and Atkinson, 1991; Yamamoto *et al.*, 2006). Despite feed consumption patterns differing significantly between farms and geographical areas,

it is generally accepted that almost all cattle born in the 1980s in GB were given protein supplements containing MBM at some point in their lives (Donnelly *et al*., 1997). Moreover, calves are separated from their mothers shortly after birth, reared initially on milk substitutes and then on a diet of hay and concentrates that often contain MBM (Smith and Bradley, 2003). Thus, all age groups are at risk of infection (Donnelly *et al*., 1997).

MBM is produced by rendering waste parts from various species, including sheep and cattle, that are unsuitable for human consumption. During rendering, the raw materials were cooked via different methods to evaporate water as steam, after which tallow (fat) was separated through centrifugation or pressing. The remaining solid residue, known as greaves, was then ground to produce MBM (Smith and Bradley, 2003). In the late 1970s, modifications to the rendering process to recover nutritional and commercial products from abattoir waste were believed to have reduced its effectiveness in inactivating prion-infected offspring. A survey of all rendering plants in the UK in 1988 revealed two major changes in the industrial process: a shift from batch to continuous processing and a reduced use of hydrocarbon solvents to maximize tallow extraction (Corona *et al*., 2017). This change in practice specifically halted the solvent extraction of tallow, which may have allowed up to ten times more infectious prions to survive the rendering process (Fox and Peterson, 2002). This subsequently resulted in contamination of MBM, and the continued recycling of BSE-infected cattle material through this system may have sustained the spread of the disease (Casalone and Hope, 2018). Shortly after recognizing MBM as the main transmission route, UK authorities prohibited the feeding of ruminant-derived protein to other ruminants, leading to an 80% reduction in infection rates among cattle born the following year (Harman and Silva, 2009).

12.4.3.1 Specified Risk Materials (SRMs)

The distribution of BSE agents in infected cattle is highly uneven. In natural infections, infectivity is largely confined to the brain, spinal cord, retina, and third eyelid. An experimental study following oral administration of BSE revealed early infectivity in the ileum and tonsils. CNS tissues, including the brain, associated ganglia, spinal cord, and dorsal root ganglia, become infected approximately three to six months before clinical signs. During the clinical stage, infectivity is also detected in the sternal bone marrow. In contrast, tissues such as the mammary gland, milk, skeletal muscle, liver, kidney, reproductive organs, fetal blood, and placenta show no detectable infectivity (Smith and Bradley, 2003).

The specified risk material (SRM) refers to the parts of an animal that carry the highest risk of BSE infectivity. At slaughter, these tissues are separated from other waste and bone material. The SRM includes the brain, spinal cord, trigeminal ganglia, dorsal root ganglia, ileum, spleen, and eyes. In Europe, a volume of SRM generated from all ruminants slaughtered for human consumption must be safely disposed of by law to prevent entry into the food and feed chains (Cummins *et al*., 2002). The removal of SRM is believed to eliminate infectious doses by 99.4%. Thus, if SRM is completely and reliably removed, the possibility of meat being contaminated with BSE prions can be reduced dramatically (Onodera and Kim, 2006).

12.4.4 Atypical BSE Occurrence and Surveillance Implications

As a result of appropriate containment measures, such as the prohibition of animal-derived MBM in the UK (1996) and Europe (2001), cases of C-BSE have rapidly decreased (Comoy *et al*., 2008; Daikai and Yamamoto, 2022). However, BSE surveillance testing of cattle for abnormal PrP in Europe and North America has led to the detection of two distinct atypical forms of BSE, classified as H-type and L-type BSE (Comoy *et al*., 2008). These atypical BSE prions were first identified in France and Italy in 2004 (Table 12.3) (Corona *et al*., 2017). Two main patterns have been identified: the L-type, resembling the initial Italian case and characterized by a lower molecular weight than the C-BSE, and the H-type, first detected in France, which has a higher molecular weight than the typical BSE (Brown *et al*., 2006). L-type BSE is also referred to as BASE because of the characteristic presence of PrP-positive amyloid plaques in the brain (Corona *et al*., 2017).

TABLE 12.3

Atypical BSEs (H-Type/L-Type) in Recent Years

Country	Year	Atypical BSE Detections (H/L)	References
EU-27 and Northern Ireland (XI)	2023 (948,165 cattle tested)	Five atypical cases in 2023 (Four H-type: two in Spain, one in France, and one in Ireland One L-type in the Netherlands	EFSA, 2024
US	2023	One atypical BSE case in a 5-year-old beef cow at a slaughter plant in South Carolina	CIDRAP, 2023; USDA, 2025a, 2025b
UK	2024 and 2025	One atypical case in Scotland (December 2024) and one atypical case in Essex (May 2025)	BVA, 2025

The origins of atypical BSEs remain unclear, but the most widely accepted hypothesis is that they occur spontaneously in cattle, comparable to most cases of sporadic CJD in humans (Casalone and Hope, 2018). Atypical BSE is detected infrequently and is primarily found in cattle aged 8 years or older, resulting in slaughter with few or no signs of disease (Casalone and Hope, 2018; Comoy *et al.*, 2008). Most atypical BSE cases occur without any identifiable infectious source, suggesting that the disease may arise sporadically when protein quality control mechanisms fail to maintain proper folding and prevent misfolding homeostasis (Dudas and Czub, 2017). Since most cases are detected in fallen stock with no clinical suspicion, atypical BSEs may be less virulent than C-BSEs and potentially harmless to humans (Corona *et al.*, 2017). However, more recent studies suggest that experimental inoculation of the BASE strain into transgenic and inbred mice may lead to natural progression into the C-BSE strain (Comoy *et al.*, 2008; Dudas and Czub, 2017). Moreover, a bioassay study demonstrated that the L-BSE agent can be transmitted orally between cattle when brain tissue from infected animals is administered to healthy cattle (Daikai and Yamamoto, 2022).

Since 2001, a total of 44 L-type and 60 H-type BSE cases have been reported in Europe, according to the EU BSE databases. The global prevalence of atypical BSE remains uncertain due to the lack of official surveillance programs and systematic reporting in many countries; however, cases have been reported in the United States, Canada, Brazil, and Japan (Casalone and Hope, 2018). Atypical BSE cases have primarily been detected through active surveillance in countries that test large numbers of slaughtered cattle and fallen stock. Maintaining high levels of surveillance is crucial to identifying any potential reintroduction, reemergence, or circulation of prion diseases within the cattle population. However, active BSE surveillance is costly, and many countries have reduced testing in recent years. This highlights the continued importance of passive surveillance, which was highly effective in identifying BSE cases during the early years of the epidemic (Boujon, Serra and Seuberlich, 2016).

12.5 Surveillance and Regulatory Frameworks

Following the confirmation that BSE could be transmitted to cattle (Wilesmith *et al.*, 1988), the UK implemented its first formal control measures through BSE Order 1988 (SI 1988/1039), which came into effect on June 21, 1988 (Alarcon *et al.*, 2023). This legislation classified BSE as a notifiable disease and required affected farms to implement movement restrictions. Farmers were responsible for cleaning and disinfecting their premises and equipment. The order also established policies on slaughter and compensation, along with a ban on feeding ruminant-derived MBM to cattle.

12.5.1 International Surveillance Standards (WOAH Type A/B)

A robust BSE surveillance program must encompass every step of the process. This means being able to identify and follow up on cattle that show signs linked to BSE, collect and test samples from those animals or their carcasses, and ensure that the results are reported clearly—regardless of where or when the case

TABLE 12.4

Examples of Indicators for Designing and Assessing BSE Surveillance

Risk Group	Example Reference Indicators
Bovines with neurological signs suggestive of BSE	• Common local diseases causing neurological signs in adult cattle • Estimated prevalence of these conditions • Recent % of cases showing BSE-like signs • Number of reported BSE suspects
Cattle showing signs at ante-mortem inspection	• Main reasons for rejection at slaughter inspection • % of adults rejected before slaughter due to clinical signs
Cattle unable to stand or walk (downer cows)	• List of local causes of recumbency in cattle over 4 years old • % of such cases on farms relative to adult stock
Cattle found dead (fallen stock)	• % of adults found dead on the farm • % found dead during transport • % found dead at markets or abattoirs

Source: WOAH, 2025.

occurs (Table 12.4). According to Article 11.4.20 (point 3) of the terrestrial code (WOAH, 2025a, 2025b), a reliable system must be built on continuous training and awareness, an effective reporting and notification network, accurate laboratory testing, and clear, well-documented procedures to guide every action.

12.5.2 Country Case Studies

BSE was initially identified in GB in 1986, with later reviews indicating clinical cases as early as 1985 (Wilesmith *et al*., 1988). The disease was notifiable in the country in 1988 and was subsequently associated in 1996 with a novel form of vCJD in humans (Will *et al*., 1996). To date, the UK has reported a total of 183,325 BSE cases in cattle, including atypical forms, and 178 confirmed human cases of vCJD, with an annual human incidence in 2020 of 1.98 cases per million. BSE has since been identified in 25 countries worldwide. In 2004, cases of the atypical form of the disease were reported in Italy and France (Biacabe *et al*., 2004; Casalone *et al*., 2004). BSE cases in cattle born after the strengthening of the feed ban on July 31, 1996, in GB are classified as BARB cases (born after the reinforced ban). To date, 184 BARB cases have been confirmed in the UK, including 6 identified as atypical BSE. Since these animals were not supposed to have been exposed to prohibited feed, their origin has generated considerable interest and debate regarding possible causes. The most recent C-BSE cases were reported in Aberdeenshire, Scotland, in October 2018, and in Somerset, in September 2021 (Alarcon *et al*., 2023). Consequently, Scotland was downgraded from a BSE negligible risk to a controlled risk status according to the WOAH standards (WOAH, 2022), whereas the 2021 case prevented England and Wales, which currently have a controlled risk status, from applying for a negligible risk classification.

12.5.2.1 UK Epidemic Control

In response to growing public concern during the late 1980s as the BSE epidemic escalated, the UK government took several necessary steps to address the crisis and ensure food safety. An independent expert committee known as the SEAC (Spongiform Encephalopathy Advisory Committee) was established to provide the government with sound scientific advice on TSE-related issues (Toldrá, 2009). In parallel, the UK introduced and reinforced a range of control measures to reduce the risk of BSE-contaminated meat entering the human food chain. These actions aimed to reduce the risk to an acceptable level, balancing feasibility and cost, while acknowledging that the risk could not be eliminated. In January 1998, the UK launched the BSE Inquiry to examine the emergence of BSE and vCJD, as well as the government's response up to March 20, 1996, evaluating its adequacy on the basis of the knowledge available at the time (TNA, 1996). To further strengthen food safety oversight, the UK Food Standards Agency was formed in 2000 with a mandate to protect public health by ensuring that TSE-related food controls are scientifically grounded and effectively minimize the risks associated with consuming beef and sheep meat (FSA, 2000).

In the case of animals, the emergence of the BSE epidemic in the UK was attributed to the use of MBM produced from the rendered carcasses of infected cattle, which introduced infectious prions into cattle feed (TNA, 1996). In response, the UK government introduced a ban in 1988 that prohibited the use of MBM in ruminant feed. Although this measure significantly reduced the risk of infection, contamination of pig and poultry feed with MBM persisted, allowing further cases to occur. To mitigate this, the ban was expanded in August 1996 to cover all farm animals. The EU subsequently enforced a comprehensive ban in 2001 (Toldrá, 2009). Under these regulations, the use of mammalian proteins in ruminant feed and the inclusion of mammalian MBM in any livestock feed are strictly prohibited.

12.5.2.2 US EPA and FDA Feed Bans Policies

The United States Environmental Protection Agency (US EPA) does not directly regulate animal feed; however, it plays an indirect role in BSE control through environmental regulations. For example, the EPA guidelines on sustainable food management, such as the reduction of waste food and its potential usage in animal feed, are most relevant (EPA, 2025). These guidelines aim to ensure that any food scraps or by-products used in animal feed do not pose environmental or health risks, thereby indirectly supporting the objectives of the BSE feed ban.

In 1992, the US Food and Drug Administration (FDA) started monitoring medical products and other regulated goods made from cattle from nations where BSE was present. In 1997, the FDA prohibited the inclusion of most mammalian-derived proteins in feed for cattle and other ruminants to prevent potentially infectious tissues from entering their diet (GAO, 2005). Under feed-ban regulation, the US FDA mandates that companies must (1) clearly label any feed or feed ingredients containing or potentially containing most mammalian proteins (referred to as prohibited material) with a warning stating, "Do not feed to cattle or other ruminants"; (2) implement measures to prevent mixing or cross-contamination when handling both prohibited and nonprohibited feed materials; and (3) keep detailed records to track feed and ingredients containing or possibly containing prohibited material from receipt to final use or disposal (Colloton, 2001).

12.5.3 Specified Risk Material (SRM) Definitions and Policies

In 1989, the UK authorities issued a directive requiring the elimination of specific tissues identified as carrying almost all the infectious risk. These were termed SRMs, referring to specific tissues from cattle and, in some cases, small ruminants that are most likely to contain prions. These infectious agents cause BSE. It includes the brain, spinal cord, tonsils, thymus, spleen, and small intestine. Their exclusion from both the food chain and animal feed represents a critical measure for controlling the spread of BSE (Smith and Bradley, 2003). From that point onward, slaughterhouses were mandated to remove bovine brain tissue. The routine method involves sawing the deboned head into two halves and manually extracting the brain for disposal, whereas the skull, which still contains minor remnants of brain matter and the eyes, is processed by rendering plants. However, it was not until 1995 that the entire skull was formally listed as an SRM (Collee and Bradley, 1997). By October 2005, SRM definitions differed between countries, with age thresholds influencing classification. The strictest regulations were applied in GB and Portugal, where the whole head (except the tongue) was considered SRM once the animals reached 6 months of age. In these same countries, the spinal cord, thymus, and spleen were also categorized as SRMs from six months onward (Vařechová, 2015).

12.6 Risk to Meat Safety and Human Health

12.6.1 Meat Contamination Pathways: Central Nervous System Tissues, Mechanical Recovery, and Cross-Contamination

Figure 12.6 illustrates potential pathways for meat contamination that ultimately lead to vCJD. Infected cattle serve as the primary reservoir, with CNS tissues being the primary source of prions. During slaughter and processing, transmission can occur through carcass splitting, leading to sawdust and surface contamination, captive-bolt stunning, embolization of brain tissue into muscles and organs, cross-contamination

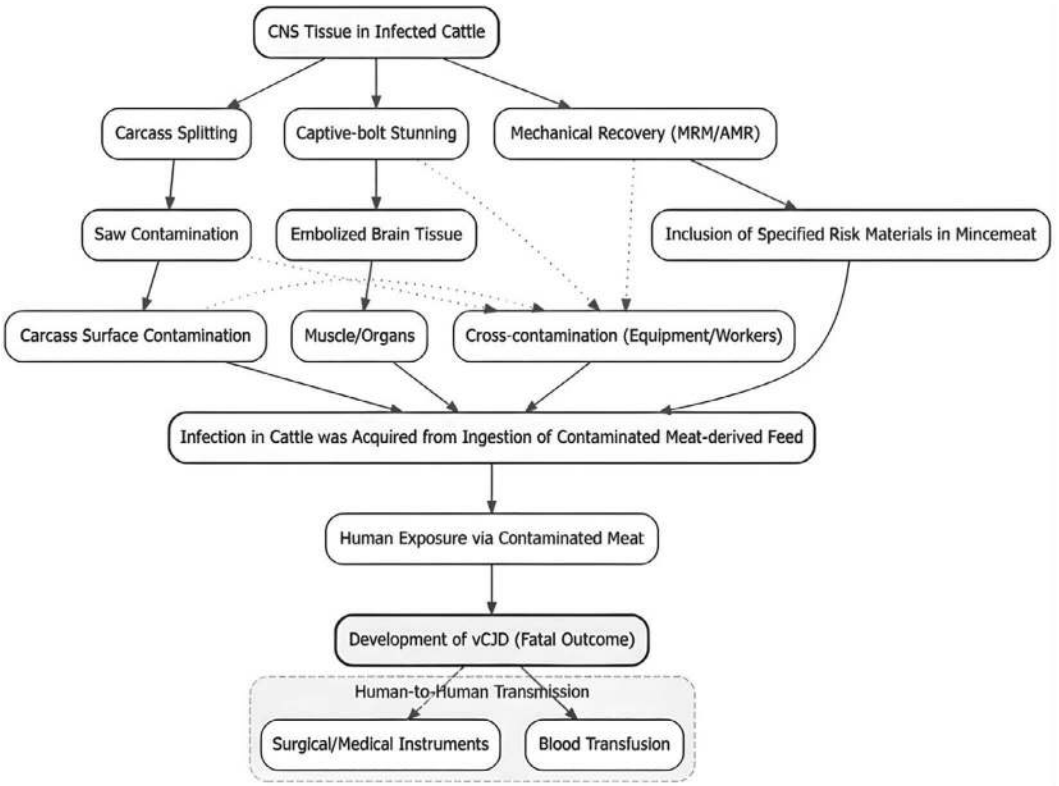

FIGURE 12.6 Meat contamination pathways and how they enter humans and cause vCJD.

via equipment and workers, and mechanical meat recovery (MRM/AMR), which may introduce SRMs into minced meat. These processes can lead to contaminated beef and meat products, which, when consumed by humans, provide a pathway for prion exposure and the subsequent onset of vCJD, a fatal neurodegenerative disorder. In addition, secondary transmission between humans has been documented through contaminated surgical instruments and blood transfusions, emphasizing critical control points within meat production and healthcare systems where preventive measures are vital to safeguarding public health.

12.6.2 Specified Risk Materials (SRMs)

SRMs represent the cornerstone of regulatory strategies to reduce the risk of BSE transmission via meat. In this section, we explore what SRMs are and the scientific basis for concern.

12.6.2.1 What Are the SRMs?

Specific risk materials are those tissues that are known to accumulate high levels of infectious agent responsible for BSE: misfolded prion protein. These tissues are hazardous because they are resistant to standard meat processing, cooking, and many disinfection procedures. Ingestion or exposure to these tissues is considered the primary route by which the disease can cross into the human population (US Department of Agriculture, 2025).

12.6.2.2 Which Tissues Are SRMs and How Risk Varies with Age and Species

The definition of SRMs varies among regulatory authorities, but it generally encompasses specific tissues determined by the animal's species and age.

12.6.2.2.1 Key SRM Tissues in Cattle

Key SRM tissues include brain, skull, eyes, spinal cord, dorsal root ganglia, trigeminal ganglia, tonsils, distal ileum, and portions of the vertebral column (Bowling *et al.*, 2007). Many regulations set age thresholds for the removal of certain SRMs because of prion accumulation:

- In the *United States*, in cattle aged ≥30 months, SRMs comprise the brain, skull, eyes, trigeminal ganglia, spinal cord, vertebral column (with exclusions), and dorsal root ganglia. Regardless of age, the tonsils and distal ileum are considered SRMs (Bowling *et al.*, 2007).
- In the *European Union*, for bovines older than 12 months, SRMs include the skull (excluding the mandible), brain, eyes, and spinal cord, whereas for all ages, the intestines from the duodenum to the rectum and the mesentery are included (The European Parliament and the Council of the European Union, 2013).

12.6.2.2.1.1 Sheep and Goats SRM definitions commonly encompass the skull with the brain and eyes, spinal cord, and tonsils in animals exceeding a defined age, such as the eruption of permanent incisors, or those legally considered older (US Department of Agriculture, 2025).

12.6.3 Survival of Prions during Meat Processing and Cooking

BSE prions are unusually resistant to standard decontamination methods. Conventional processes such as cooking, pasteurization, or sterilization are often ineffective, and even thorough boiling or frying cannot reliably destroy these proteins (Team, 2025). BSE prions retain transmissibility despite autoclave treatment at 133 °C for 20 minutes (Schreuder *et al.*, 1998), 134 °C for as long as 2 hours (Fernie *et al.*, 2007; Giles *et al.*, 2008), or even 150 °C for 20 minutes (Matsuura *et al.*, 2013). Industrial rendering, which typically involves heating animal carcasses at approximately 140 °C for 1 hour, has been reported to lower prion infectivity by only approximately 35-fold; however, the abnormal prion protein (PrP^{Sc}) still retains its capacity to replicate and spread (Yoshioka *et al.*, 2013). More intense dry-heat treatments appear to be considerably more effective, as studies, including those conducted in Japan, have shown that BSE seeding activity persists after heating at 150–200 °C for 20 minutes, whereas exposure at 400 °C or higher for the same duration eliminates transmissibility (Matsuura *et al.*, 2020). Although high-pressure processing coupled with heat (120–130 °C at 600–700 megapascals for 5 minutes) leads to an estimated 2-log, or 100-fold, reduction in infectivity, it falls short of achieving complete prion inactivation (Brown *et al.*, 2016). As demonstrated by Schreuder *et al.* (1998) in the Netherlands, pressure-cooking rendering conditions (e.g., 20 minutes at 133 °C) achieve only partial inactivation of BSE, since infectivity is reduced but not completely eliminated (Schreuder *et al.*, 1998).

12.6.4 Zoonotic Transmission and Human Disease

Since its identification in the 1980s, BSE has been regarded not only as a major animal health concern but also as a zoonotic threat, given its ability to cross species barriers and cause disease in humans. The principal human disorder associated with BSE is vCJD, which was first detected in the UK during the mid-1990s in unusually young patients with a distinct clinical subtype of CJD. Converging lines of epidemiological, neuropathological, and molecular evidence have confirmed a causal relationship between dietary exposure to BSE-contaminated bovine products and the occurrence of vCJD in humans (Torres *et al.*, 2016).

12.6.4.1 Routes of Exposure and Transmission

Human infection with BSE primarily occurs through the consumption of prion-contaminated bovine tissues, particularly CNS material and other specified risk tissues that inadvertently enter the food chain.

Both regulatory investigations and laboratory studies have provided compelling epidemiological and molecular evidence that vCJD in humans is caused by the same prion strain responsible for C-BSE in cattle (Lee *et al.*, 2013). The routes are as follows:

- The primary route of BSE transmission to humans is through the consumption of meat or meat products derived from infected cattle, particularly those containing CNS tissues (Houston and Andréoletti, 2018).
- vCJD can also be transmitted through blood, and prion infectivity has been detected in lymphoid organs as well as in blood components (Ironside and Head, 2004).
- Prions are transmitted during medical procedures through contaminated surgical instruments or grafts, which poses a significant concern since they retain infectivity and show remarkable resistance to most conventional sterilization methods (Pauli, 2005).

12.6.4.2 Clinical Manifestation

Prion diseases are a group of rare, invariably fatal neurodegenerative disorders that affect both humans and animals. These diseases are characterized by the accumulation of misfolded prion proteins in the brain, leading to progressive neuronal damage and characteristic clinical symptoms.

12.6.4.2.1 Common Clinical Features

The clinical presentation of prion diseases is typically characterized as follows:

- *Rapidly Progressive Dementia:* A swift decline in cognitive functions, including memory loss, confusion, and impaired judgment.
- *Cerebellar Ataxia:* Difficulty in coordination and balance, leading to unsteady gait and clumsiness.
- *Myoclonus:* Sudden, involuntary jerking movements of muscles or muscle groups.
- *Visual and Auditory Disturbances:* These include hallucinations and visual impairments.
- *Behavioral and Psychiatric Symptoms:* These include depression, anxiety, and personality changes (Verity *et al.*, 2019; Zerr *et al.*, 2009).
- *Absence of Systemic Abnormalities:* Unlike many other neurological disorders, prion diseases do not typically present with systemic abnormalities such as fever or inflammation.

12.6.4.3 Disease Progression and Prognosis

Rapid progression characterizes prion diseases once clinical symptoms appear. The duration from onset to death is usually short, often ranging from several months to a year, depending on the specific prion disease and individual factors (Sikorska *et al.*, 2012).

12.7 Detection and Diagnosis in Meat

Following the identification of a new variant of CJD, a range of detection techniques has been developed to identify central nervous tissue (CNT) in meat products (Toldrá, 2009). These efforts aim to support regulatory food safety inspections by identifying the presence of potentially harmful CNTs, especially those related to BSE, and thus mitigate human exposure risks associated with TSEs. Among the established detection tools are immunochemical methods, including WB analysis targeting neuron-specific enolase (NSE-WB) (Lücker *et al.*, 1999, 2000) and enzyme-linked immunosorbent assays (ELISAs) that detect glial fibrillary acidic protein (GFAP) (Schmidt *et al.*, 1999). These approaches have been validated through multiple ring trials and are recognized for their efficiency and reliability in identifying CNT

contamination in processed meat products. Immunohistochemistry has also proven to be a viable option for detecting CNTs in such contexts (Wenisch *et al*., 1999).

12.7.1 Clinical Observation Limits

In BSE, the incubation period exceeds five years, which is long compared with the typical lifespan of cattle, so most infected animals are slaughtered before showing clinical signs, creating a hidden risk of disease spread (Donnelly *et al*., 2002). In C-BSE (C-type), affected cattle exhibit behavioral changes, increased sensitivity, unsteady hind limbs, general weakness, and a gradual decline in body condition. In contrast, atypical BSE (H-type and L-type/BASE) is often characterized by dullness, lowered head carriage, reduced activity, and an overall lack of nervousness (Olech, 2023). BSE is a neurological disorder; therefore, clinical observation alone is insufficient for detection. Consequently, laboratory testing remains the essential diagnostic method.

12.7.2 Postmortem Confirmatory Tests

With the implementation of mandatory active surveillance programs in the EU, developing rapid diagnostic tools for BSE has become a top priority (Table 12.5). To date, the EU has authorized rapid assays that detect the PrP^{res}, the only dependable molecular marker for prion diseases (Vidal *et al*., 2005). These tests have all been validated via postmortem brain tissue, specifically samples taken from the medulla oblongata at the level of the obex.

TABLE 12.5

Comparison of Diagnostic Methods for Prion Detection

Method	Sample/ Matrix	Sensitivity/ Specificity)	Detection Stage/Notes	Caveats	References
Rapid ELISA/ IHC	Brain/CNS tissue	99–100% (for C-BSE in the brain)	Postmortem (end stage)	• Rapid screening ELISA and IHC are standard in BSE surveillance • EU-approved rapid tests also detect atypical forms • For IHC: immunohistochemistry is the gold standard in confirmatory diagnosis of BSE postmortem • In practice, false negatives may occur in early or low-load cases, and sensitivity depends on sampling of optimal sites (obex, medulla) • Additionally, fixation and antigen retrieval affect IHC sensitivity	Safar *et al*., 2005; Hagiwara *et al*., 2017
WB	Brain tissue homogenate	100% (for confirming protease-resistant PrP)	Postmortem, confirmatory	• WB is the "gold-standard" confirmatory test for PrP^{Sc} in brain homogenates after protease digestion (detection of protease-resistant core). However, sensitivity depends on the amount of PrP^{Sc} present • Very low levels may go undetected • Some rapid tests combine immunoblot with chemiluminescence (BSE surveillance) to improve detection	Carra *et al*., 2009; Lukan, Vranac and Čurin Šerbec, 2013

(Continued)

TABLE 12.5 ***(Continued)***

Comparison of Diagnostic Methods for Prion Detection

Method	Sample/ Matrix	Sensitivity/ Specificity)	Detection Stage/Notes	Caveats	References
PMCA	Blood, CSF, saliva (research)	Extremely high (fg-level favorable)	Preclinical/ research	• PMCA was developed to amplify minute quantities of PrP^{Sc} seeds • It has been used to detect prions in peripheral tissues in prion disease models and vCJD contexts • In one pilot/review, PMCA achieved 89% sensitivity and 100% specificity in blood from experimentally infected animals • In comparison of sheep BSE blood samples, two PMCA assays reached 100% sensitivity (versus RT-QuIC at 61%) when samples were collected ~26 months before onset • Such extreme sensitivities (fg-level) are observed in optimized lab settings, often with many amplification cycles • real-world robustness, preclinical sensitivity in natural disease, and cross-strain performance are more limited • Additionally, PMCA has limitations in detecting sporadic CJD prions (versus vCJD) in peripheral samples	Giaccone and Moda, 2020; Thomas *et al.*, 2024; Wang, Pritzkow and Soto, 2023
RT-QuIC	Blood, CSF, other fluids (research/ pilot)	Very high (100% in some models)	Preclinical/ pilot evaluation	• RT-QuIC (real-time quaking induced conversion) is a seed amplification assay widely used in prion diagnostics • It has been adapted for CSF, nasal brushings, skin, and other applications • In a comparative study on BSE-infected sheep blood, RT-QuIC (with bead capture) showed 100% specificity (no false positives) and was less sensitive than PMCA in detection • In human prion diagnosis, RT-QuIC on CSF shows high sensitivity (90–97%) and 100% specificity for sporadic CJD • (One caution: detection of BSE prions in sheep blood two years before onset was reported (preclinical detection) in a model setting • "100%" is often a best-case figure in controlled experiments • Real sensitivity in heterogeneous real disease may be lower	Thomas *et al.*, 2019, 2022

(Continued)

TABLE 12.5 ***(Continued)***

Comparison of Diagnostic Methods for Prion Detection

Method	Sample/ Matrix	Sensitivity/ Specificity)	Detection Stage/Notes	Caveats	References
Aptamer biosensors	Blood, tissue (research)	Not yet fully quantified	Preclinical/ research	• Aptamers (DNA, RNA, or peptide ligands) have been selected to bind PrP/PrP^{Sc} for biosensor applications • Aptamer-functionalized gold nanoparticle (aptasensor) for the prion protein achieved detection down to 0.07 nmol/L (70 pM) in a buffer/model system • Another review discusses aptamer selection for PrP and potential diagnostic uses, but without definitive sensitivity/specificity in biological fluids • More recently, a proof-of-concept for an aptamer-enhanced isothermal amplification method for prion protein detection was published, demonstrating a sensitivity of 10 pM in a spiked matrix. Thus, aptamer biosensors remain at the development stage	Gilch and Schätzl, 2009; Macedo and Cordeiro, 2017; Ramos *et al.*, 2025; Zhang *et al.*, 2014

12.7.2.1 Histopathology and Immunohistochemistry

Histopathology was the first diagnostic method for TSEs, enabling detection of CNS lesions. Typically, the medulla at the level of the obex is sampled and fixed in 4% formaldehyde (or 10% formal saline/ buffered formalin) for three to five days to prevent autolysis. The tissues were then treated with 98% formic acid to reduce prion infectivity, embedded in paraffin, sectioned at 5 µm, and stained with hematoxylin and eosin (HE) (Olech, 2023). Under a light microscope, vacuolation of the gray matter neuropil (spongiform change) and bilaterally distributed neuronal vacuolation are the most common histological features observed in BSE-affected CNS tissue. The highest levels of vacuolar changes in BSE occur in specific brainstem regions at the obex, including the solitary tract nucleus, the spinal tract nucleus of the trigeminal nerve, and the dorsal nucleus of the vagus nerve, making these sites standard for histological diagnosis. Intraneuronal vacuolation can also be observed occasionally; however, vacuolated neurons alone, without neuropil vacuolation, do not confirm BSE (Fix and Garman, 2000; Gavier-Widén *et al.*, 2005).

Immunohistological techniques combine the detection of specific antigens with microscopic morphological analysis. For example, examining morphological features can help distinguish between central and peripheral nervous system tissues, mainly when antibodies with low specificity are used. Additionally, micromorphological evaluation can identify non-CNS high-risk materials, such as lymphoid tissues or intestinal samples. Early immunohistological methods for detecting CNS tissues in heat-treated meat showed that NSE antibodies were effective, whereas GFAP antibodies were less effective (Wenisch *et al.*, 1999). Subsequent studies demonstrated that detection success depended on both heat treatment and the antibody/epitope used; anti-MBP antibodies showed superior applicability in one study, whereas anti-NF antibodies outperformed NSE, GFAP, MBP, and peripherin in another, allowing detection of as little as 1% CNS tissue and differentiation of nerve fibers via morphological criteria (Toldrá, 2009). The USDA currently uses an immunohistological GFAP-based procedure; however, the results have proven inconsistent. Other studies have indicated that specific anti-GFAP and anti-MBP antibodies can detect 8% of the bovine brain in heat-treated meat (Herde *et al.*, 2005).

For nonheated matrices, anti-synaptophysin antibodies were successfully applied, and anti-S100β immunostaining provided early evidence of brain tissue microembolization from captive bolt stunning (Anil *et al.*, 2001).

12.7.2.2 Western Blot, ELISA, and Rapid Assays

The WB method typically yields results faster than histology, but its use has been limited primarily to research settings. Several WB techniques have been developed, with some serving as screening tests and others for confirming suspected cases detected through active or passive surveillance. WB is highly versatile, as it can be performed on fresh, frozen, or autolyzed tissue samples (Olech, 2023). Western blotting involves preparing brainstem homogenates and digesting them with proteinase K. After ultracentrifugation, the pellet is dissolved in Laemmli buffer, denatured, and loaded onto SDS–PAGE gels. Denaturation exposes PrP^{Sc} for antibody binding. Proteins are then transferred to a PVDF membrane and detected via enzyme-labeled antibodies, with signals visualized via chemiluminescence (Hyperfilm ECL). Early "WOAH Western blot" protocols were lengthy, requiring multiple ultracentrifugation steps and substantial amounts of tissue (2–4 g). Modern methods utilize smaller samples (up to 0.5 g) and improved buffers, thereby eliminating the need for ultracentrifugation and reducing processing time (Gavier-Widén *et al.*, 2005; Stack *et al.*, 2004).

Astrocytic glial fibrillary acidic protein (GFAP), a significant component of astrocyte filaments, was first identified in 1999 as a marker for CNS detection in food control (Schmidt *et al.*, 1999). Initial methods employed a modified colorimetric GFAP-ELISA that combines polyclonal and monoclonal antibodies to detect CNS in mixtures with muscle and blood down to ~1 ng. This method was later improved to 0.2 ng using a fluorescent GFAP F-ELISA (Schmidt *et al.*, 2001). GFAP was absent in skeletal muscle and blood clots, with only trace amounts detected in the sciatic nerve, whereas the CNS contained significantly higher levels. A commercial GFAP assay became available in 2001 and was validated for heat-treated meat, showing good to excellent performance in comparison studies (Toldrá, 2009). GFAP-ELISA was officially adopted in Germany for food control in 2004. Later studies demonstrated the detection of non-heat-treated CNS, such as contamination of fresh meat, band saw blades, and advanced meat recovery products (Hossner *et al.*, 2006; Reddy *et al.*, 2006). Compared with commercial ELISA and immunohistochemical methods, GFAP F-ELISA demonstrated greater sensitivity and repeatability, all of which are widely used in the United States. However, some false positives occurred in blood samples from healthy cattle when the commercial GFAP-ELISA was used; these false positives were avoided when the laboratory-developed GFAP-ELISA, which became commercially available in 2004, was used (Kunath *et al.*, 2005). Today, GFAP-ELISA is considered the standard procedure for detecting CNS in fresh and heated meat products, as well as for monitoring CNS contamination on equipment surfaces.

In contrast to these protein-based methods, molecular techniques have emerged as alternative tools. One such method involves detecting messenger RNA (mRNA) from CNT-specific proteins, such as GFAP or myelin basic protein, via reverse transcription polymerase chain reaction (RT–PCR). This molecular strategy offers both high specificity and sensitivity, enabling the species-level identification of CNTs present within the meat matrix (Seyboldt *et al.*, 2003). This specificity is important, as only CNTs from cattle, sheep, and goats are legally classified as SRM and must be excluded from the human food chain. While CNTs from other species are legally permissible in meat production, their presence must be clearly labeled on product packaging. RT–PCR-based techniques have undergone partial validation through ring trial evaluations (Lücker *et al.*, 2010).

12.7.3 Advanced Amplification Techniques

In recent years, significant advances in diagnosis have been made through the development of highly sensitive seeding assays that amplify PrP^{Sc} detection. These methods enable reliable antemortem identification of prion diseases, help minimize the risk of iatrogenic transmission, and offer valuable biomarker tools for assessing future therapeutic interventions (Zanusso *et al.*, 2016), such as PMCA and RT-QuIC.

12.7.3.1 Protein Misfolding Cyclic Amplification (PMCA)

In 2001, Soto and colleagues introduced an innovative in vitro method known as protein misfolding cyclic amplification (PMCA), which enables the acceleration of prion replication in a test tube (Saborio, Permanne and Soto, 2001). PMCA proceeds through repeated cycles comprising two main steps: incubation and sonication. In the incubation step, the test material is combined with a PrP^{C} source and incubated at 37 °C to promote the formation of PrP^{Sc} aggregates or fibrils. Small amounts of PrP^{Sc}, referred to as seeds, originating from infected samples act as templates that convert PrP^{C} into the misfolded PrP^{Sc} form, extending the fibrils. During the subsequent sonication step, these fibrils are fragmented into smaller pieces, each serving as a new seed for further misfolding events. This repetitive process leads to an exponential increase in the number of seeds. Because the system is cyclic, it can continue for as many rounds as necessary to achieve the desired amplification level for detecting PrP^{Sc} in a sample. Following amplification, the material is treated with proteinase K, and the resistant PrP^{res} is identified via immunological techniques such as Western blotting or ELISA (Castilla *et al.*, 2006).

12.7.3.2 Real-Time Quaking-Induced Conversion (RT-QuIC)

An important objective in prion disease management is the earliest possible detection of infectious prion seeds. Seed amplification assays (SAAs), such as RT-QuIC, enable the amplification of prion seeds present at levels that would otherwise be undetectable in diagnostic samples (Vascellari, Orrù and Caughey (2022). Building on earlier amyloid seeding assays (Colby *et al.*, 2007), the RT-QuIC method pioneered by the Atarashi and Caughey groups (Atarashi *et al.*, 2011; Wilham *et al.*, 2010), achieves up to a trillion-fold amplification of prion seeds in multiwell plates by shaking cycles with a fluorescent readout. In this reaction system, prions in the test sample initiate the conversion of excess recombinant prion protein (rPrP) into amyloid fibrils, thereby enhancing the fluorescence of the dye thioflavin T (ThT). RT-QuIC has since been optimized for nearly all mammalian prions (Vascellari, Orrù and Caughey (2022). The reaction was carried out in 96–384-well plates in a fluorescence plate reader, where controlled cycles of shaking and incubation were performed. Like other seeded amyloid polymerization processes, positive RT–QuIC reactions display three distinct phases. The lag phase represents the time before fluorescence surpasses the set threshold, during which prion seeds undergo undetectable early growth. This is followed by the exponential phase, during which fibril elongation occurs alongside the creation of new seeding sites via fibril fragmentation and/or secondary nucleation. Finally, the plateau phase is reached once the rPrP substrate is depleted. In specific reactions, fluorescence decreases after peaking, possibly because fibril bundling alters ThT binding or the displacement of fibrils out of the optical path rather than the degradation of the ThT dye itself (Orrú *et al.*, 2016).

12.7.4 Sensitivity, Specificity, and Surveillance Role of Each Method

In BSE, various diagnostic methods differ in their sensitivity, specificity, and utility for surveillance. Histopathology and immunohistochemistry are highly specific but less sensitive in the early stages of infection, whereas Western blotting and ELISA are more sensitive for detecting abnormal prion protein. For more particular confirmation of prion proteins, advanced methods such as PMCA and RT-QuIC are widely used.

12.8 Management and Control Strategies

12.8.1 Feed Bans and Specified Risk Material (SRM) Removal

The BSE epidemic is widely attributed to the practice of feeding cattle contaminated with MBM derived from rendered ruminants already infected with prions (Brown, 2006). Recycling infectious material through MBM serves as a major amplification route, allowing the disease to spread extensively within

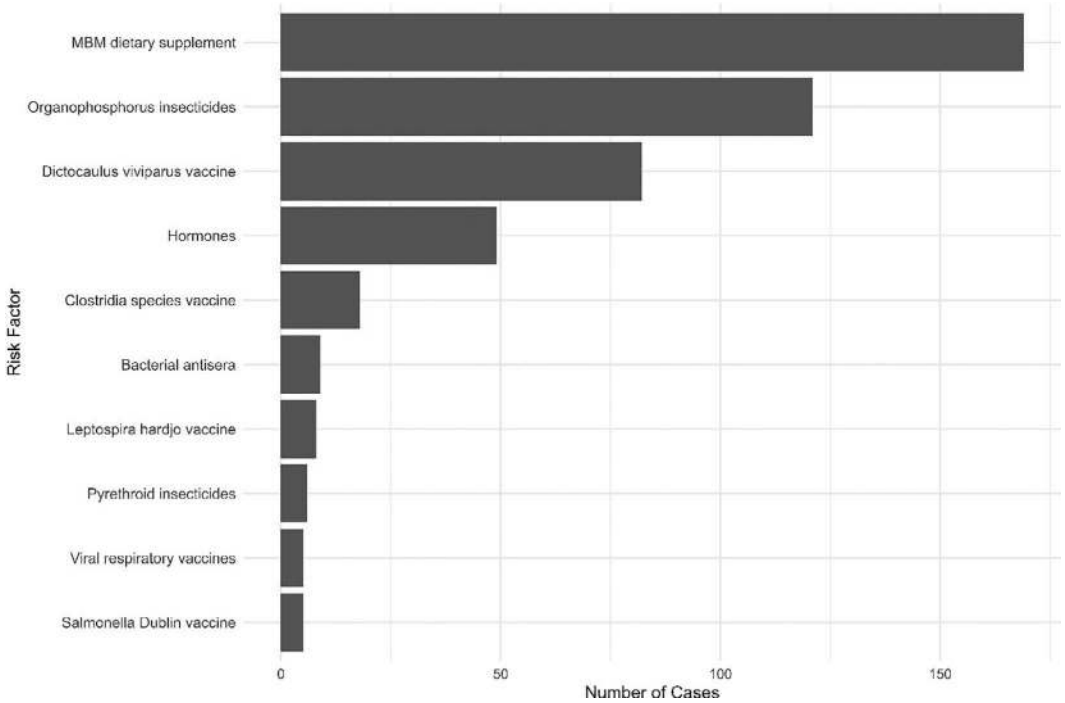

FIGURE 12.7 Risk factors among 169 early cases of BSE, UK, 1986. (Wilesmith, Ryan and Atkinson, 1991.)

cattle populations (Smith and Bradley, 2003). Evidence from multiple case–control studies further reinforced this link, identifying the routine inclusion of MBM as a dietary protein supplement commonly introduced at weaning as a significant risk factor for BSE transmission (Figure 12.7) (Nathanson, Wilesmith and Griot, 1997).

During the early 1980s, approximately 45 rendering plants in the UK produced MBM from slaughterhouse by-products such as offal. The process converts waste into tallow (fat) and defatted protein meal through a combination of mixing, steam heating, milling, and fat extraction using hydrocarbon solvents. However, energy-intensive solvent extraction became uneconomical in the 1970s because of rising fuel costs and narrowing profit margins between tallow and MBM. As a result, many plants discontinued solvent extraction, producing MBM with greater residual fat content (~1%), which may have resulted in limited prion inactivation during rendering (Nathanson, Wilesmith and Griot, 1997).

12.8.1.1 Feed Bans

Once contaminated MBM was identified as the principal source of infection in the BSE epidemic, the UK introduced a ban on ruminant feed in July 1988. This regulation prohibited the inclusion of ruminant-derived protein in feed intended for ruminants. However, MBM from ruminants is still permitted in the diets of pigs and poultry, as these monogastric animals are not considered susceptible to the BSE agent (Smith and Bradley, 2003). Although the effect of the ban was not immediate due to the long incubation period of the disease, typically approximately five years, its impact became evident over time. Most exposures occurred in young calves, but clinical signs did not manifest until years later. By 1992, a marked reduction in BSE incidence was observed, with case numbers declining by approximately 40% per year thereafter (Smith and Bradley, 2003).

The identification of contaminated MBM as a common source of infection strongly supported the causal hypothesis. Consequently, the feed ban represented both a decisive administrative action and a critical test of this hypothesis. The subsequent steady decline in BSE cases followed a trajectory predicted

TABLE 12.6

Cases of BSE by Year of Birth, UK, 1981–1992

Year	No. of Cases with Known Birth Year	Adjusted No. of Cases	% of Maximum
1981	50	72	0.1
1982	525	758	1.5
1983	3,480	5,028	9.9
1984	7,200	10,402	20.5
1985	10,150	14,664	28.8
1986	18,850	27,231	53.6
1987	35,200	50,853	100.0
1988	19,132	27,640	54.4
1989	9,458	13,664	26.9
1990	2,464	3,560	7.0
1991	490	708	1.4
1992	8	12	0.0

Source: From MAFF, 1995.

at the time of the ban, further confirming the role of the MBM in propagating the epidemic (Nathanson *et al.*, 1993). A mathematical back-calculation analysis by Anderson *et al.* (1996) reconstructed the dynamics of the outbreak, estimating that over 300,000 new infections occurred in 1988, decreasing to approximately 30,000 by 1991. These findings indicated that transmission did not halt immediately after the ban, as infections continued in cattle born up to 1991, although in progressively smaller numbers (Nathanson, Wilesmith and Griot, 1997). This pattern corresponds with epidemiological data showing a sharp decline in BSE cases across post-1988 birth cohorts (Table 12.6).

Residual infections after the ban likely resulted from contaminated feed manufactured before July 1988, which remained in circulation. Additional factors included cross-contamination within feed mills producing rations for both monogastric species (pigs and poultry) and ruminants and occasional misfeeding of cattle with feed formulated for nonruminants (Wilesmith, 1996). The risk of such contamination was greatest in northern and eastern England, where intensive pig and poultry production was concentrated, contributing to geographical variation in BSE risk among cattle born after the ban. Despite these residual exposures, the 1988 ruminant feed ban played a crucial role in curbing the BSE epidemic, providing compelling evidence that contaminated MBM was the primary driver of disease transmission and validating the effectiveness of feed-based control strategies.

12.8.1.2 SRM Removal

The infective agent of BSE is a misfolded prion protein that accumulates predominantly in specific tissues of infected cattle. These high-risk tissues include the brain, skull, spinal cord, trigeminal and dorsal root ganglia, eyes, tonsils, and spinal columns of cattle aged 30 months or older, as well as the distal ileum in cattle of all ages (Wagner and Wu, 2014). Collectively, these tissues are termed SRMs because they have the potential to harbor high concentrations of prions.

BSE is transmitted primarily through the oral route by feeding cattle MBM derived from infected ruminants containing prion-contaminated tissues. Therefore, eliminating SRM from the feed chain is essential to interrupt the cycle of infection and prevent further spread among ruminant populations (Wilesmith *et al.*, 1988). In recognition of SRM's critical role in disease propagation, the UK introduced a formal ban in 1989, ordering the removal and destruction of tissues that accounted for approximately 99% of infectivity, including the brain, spinal cord, tonsils, thymus, spleen, and small intestine (Smith and Bradley, 2003). This decisive action marked a significant milestone in the management and control of BSE, substantially reducing the risk of prion exposure across both the human and animal food chains.

12.8.2 Rendering Methods to Inactivate Prions: Slaughterhouse and Processing Hygiene

Significant regulatory measures have been put in place to prevent contamination and minimize exposure to BSE. These include strict EU directives on cattle and beef identification, surveillance of SRM, and prohibitions governing the operation of abattoirs, kennels, and incinerators. Additionally, a ban on feeding mammalian MBM to livestock is rigorously enforced to reduce transmission risks (Hillerton, 1998).

Prion infectivity is exceptionally resistant to conventional inactivation procedures that are effective against bacteria, viruses, and parasites. Studies have shown that prions remain infectious after exposure to sterilizing radiation, formalin, UV light (2,500 nm), extreme pH, organic solvents (such as methanol, hexane, and petroleum ether), 0.1 μm filters, and autoclaving at 134 °C for 60 minutes (Brown *et al*., 1990; Haig *et al*., 1969; Taylor *et al*., 1995). Furthermore, prions show remarkable resistance to enzymatic degradation by proteases, amylases, and nucleases, and their stability in tissues, liquid waste, and contaminated surfaces poses substantial challenges for complete decontamination (Taylor, 2004). The degree of resistance may also vary depending on the prion strain (Peretz *et al*., 2006; Taylor, 2004).

In laboratory and surgical settings, when TSEs are suspected, the use of disposable instruments is strongly recommended, followed by incineration of all contaminated materials (Taylor, 2003). Among chemical disinfectants, sodium hypochlorite (16,500 ppm available chlorine) effectively destroys infectivity in BSE-infected brain homogenates after 120 minutes of exposure. In contrast, sodium dichloroisocyanurate and 2 M NaOH at room temperature fail to achieve complete inactivation (Taylor *et al*., 1995; Taylor and Fernie, 1996). Complete prion inactivation has been observed with 1 M NaOH at 55 °C and saturated phenol, whereas exposure to iodine, hydrogen peroxide, formaldehyde, urea, or psoralen has little or no effect (Brewer, 1999; Brown *et al*., 1982, 1990).

Importantly, prion-contaminated materials should never be allowed to dry on surfaces, as desiccation increases adhesion and complicates removal (Taylor *et al*., 1998). Aldehyde-based disinfectants (e.g., formaldehyde and glutaraldehyde) are contraindicated since they stabilize prion proteins through cross-linking. BSE infectivity has even been shown to persist for two years in tissues preserved in 10% formalin (Fraser *et al*., 1992). Similarly, steam cleaning is discouraged since high heat may enhance prion binding to surfaces, making them more difficult to remove (Brown *et al*., 1982). Autoclaving at 121 °C for 60 minutes significantly reduces prion infectivity but does not eliminate it. Even prolonged exposure at higher temperatures (>140°C) may not achieve complete inactivation, particularly in high-titer materials. Similarly, conventional rendering processes (112–122 °C for 20–57 minutes) have also proven inadequate for the complete inactivation of BSE (Brown *et al*., 1982, 1990; Marsh, 1990; Taylor *et al*., 1995).

More effective inactivation can be achieved via the use of protein denaturants such as guanidine salts or through incineration at 1,000 °C (Brown *et al*., 2004). Extended autoclaving at 134 °C for 4.5 hours, especially when combined with sodium hydroxide, significantly enhances prion destruction (Ernst and Race, 1993). Certain phenolic disinfectants have been shown to reduce infectivity markedly, and under specific conditions, even mild solutions such as 5% SDS can be beneficial (Lemmer *et al*., 2004; Peretz *et al*., 2006). In line with WHO guidelines, best practices for prion decontamination in medical and veterinary facilities emphasize thorough cleaning, the use of effective chemical treatments, and the incineration of contaminated materials (Harman and Silva, 2009). The European Commission's Scientific Veterinary Committee recommends rendering at 133 °C for at least 20 minutes to improve MBM safety, although even this approach cannot guarantee the complete elimination of TSE agents (Brewer, 1999).

Field evidence demonstrates the environmental persistence of TSEs. On scrapie-infected farms, reintroduced sheep develop disease even after disinfection and a two-year fallow period, and a similar persistence of CWD has been observed in endemic regions such as Colorado (Georgsson and Sigurdarson, 1995; Williams and Young, 1992). These findings underscore that TSE agents can survive in soil and local ecosystems, suggesting that absolute eradication may be unattainable and reinforcing the need for stringent hygiene measures in slaughterhouses and rendering plants.

12.8.3 Traceability, Culling, and Compensation Mechanisms

Effective control of BSE requires robust systems for traceability, targeted culling, and compensation to ensure compliance and transparency. Initially, reliance on passive reporting of clinical cases was

recognized as insufficient, as it often led to underreporting of the true extent of the disease owing to weaknesses in surveillance systems. To address this, surveillance was strengthened by introducing objective diagnostic tests for cattle at abattoirs, providing more accurate data and increasing consumer confidence that meat comes from animals free of detectable BSE. However, because infection often occurs early in life and prions can be detected only in the brain a few months before symptoms appear, some infected cattle can still test negative (Smith and Bradley, 2003).

To improve disease control, individual animal identification systems, including ear tags, herd registers, and cattle passports, have been introduced. These systems allow authorities to trace the origin and movement of animals and identify herds at risk of exposure. Once BSE infection was suspected or confirmed, infected and high-risk cattle were culled to prevent further transmission. The UK implemented several key control measures between 1986 and 1997: declaring BSE a notifiable disease, banning ruminant-derived protein in animal feed, destroying clinically affected animals, prohibiting the consumption of milk from affected cows, removing SRMs from the food chain, culling cattle over 30 months of age, and being most likely to be incubating for infection (Brewer, 1999). To ensure farmer cooperation, compensation schemes were introduced to reimburse owners for culled animals. This financial support helped encourage timely reporting, compliance with movement restrictions, and participation in surveillance programs, which are critical components in managing and ultimately reducing BSE prevalence (Nathanson, Wilesmith and Griot, 1997).

12.8.4 Emergency Preparedness and Risk Communication

BSE is not a highly contagious disease. Although vaccination is not currently a viable prevention strategy due to the absence of a protective immune response, its spread can be effectively managed through surveillance, targeted testing, and strategic culling (Kimberlin, 1993). In 1999, Swiss veterinary authorities conducted targeted testing of at-risk cattle, including fallen stock, emergency slaughter, and adult cattle at abattoirs, using rapid assays to detect the misfolded prion protein (PrP^{Sc}) in brain tissue. Several infected animals were identified through these tests, even in the absence of clinical signs, highlighting the importance of active surveillance in understanding BSE occurrence and risk across cattle populations in the EU.

Currently, there is no test for live animals, as prion concentrations gradually increase during the incubation period, and infected cattle typically show no clinical signs until late in the disease. Definitive diagnosis requires the detection of BSE-associated prions in brain tissue, specifically from the obex region of the midbrain (Harman and Silva, 2009). Modern high-throughput immunoassays, including ELISA, WB, and lateral flow immunoassays, are used in postmortem surveillance and can detect prions several months before histopathological changes appear (Espinosa *et al*., 2007; Grassi *et al*., 2008; Safar *et al*., 2002; Wells *et al*., 1998). The EU has approved 12 rapid tests for BSE screening, some of which are also used in the United States, all with equivalent sensitivity for detecting BSE prions (Deslys *et al*., 2001; Harman and Silva, 2009).

In addition to surveillance, strategic culling remains a key component of emergency preparedness. Many more cattle were culled than initially proposed under EU cull schemes, and cohort-based strategies that prioritized older animals were projected to eliminate BSE from the UK by the mid-1990s (Hillerton, 1998). Complementing surveillance and culling, risk communication ensures that farmers, veterinarians, and the public are well informed about BSE risks, preventive measures, and feed safety practices, thereby maintaining transparency, compliance, and public confidence.

12.9 Challenges and Emerging Issues

12.9.1 Global Regulatory Harmonization

The international community has broadly adopted WOAH standards for BSEs, but significant divergences remain (Table 12.7). For example, the EU formally aligned its BSE risk categories with the WOAH system in 2007 (Bradley, Collee and Liberski, 2006). Major trading partners (the United States, Canada, and Japan) are now recognized as "negligible risk" by WOAH, but each follows its own rules (Jordan, 2017). In feed regulations, North America harmonized early: since 1997, Canada and the United

TABLE 12.7

Comparison of BSE Regulatory Measures in Major Regions

Region	WOAH BSE Status	Feed Ban (Mammalian Protein)	SRM Removal	Notable Trade Measures	References
EU	Officially negligible	• 1994 ban on cattle/sheep/goats • 2001 ban on all farmed animals	Comprehensive SRM removal (including spinal cord from all cattle >12 m)	• Historically, one of the strictest regimes • Some non-EU import bans persisted (China's beef ban)	Boulanger *et al.*, 2015; Krivko and Smutka, 2021
US	Officially negligible (WOAH)	• 1997 ban on ruminants (harmonized with Canada) • 2008 enhanced feed rule	Remove brain, spinal cord (SRMs) from cattle >30 months (since 2004)	• Following the 2003 case, 58 countries banned US beef (loss $3 billion) • Gradually reopened markets (Japan required <21 months of beef until 2019)	Onodera and Kim, 2006
Canada	Officially negligible (WOAH)	1997 ban on ruminants (harmonized with the United States)	SRM removal rules are generally broader than those in the United States	• Resumed exports to Japan/Taiwan (2019) and Australia (2022) after extended bans • China only lifted the Canadian beef meal ban in 2024	GOC, 2025
Japan	Officially negligible (WOAH, 2013)	• 2001 ban (after the first BSE) • Strictly enforced testing in feed mills	Intensive SRM removal in cattle (including spleen, etc.)	• Imposed strict age limits on imports (20 months), longer than WOAH minimum • Banned Canadian beef (2001–2013), and US beef (2003–2005, 2006) • Now largely reopened under negotiated terms	USDA, 2023

States have banned all mammalian protein in ruminant feed (Lewis, Krewski and Tyshenko, 2010). However, Canada removed a broader list of SRMs at slaughter than did the United States. EU followed its own timeline, banning mammalian proteins from cattle in 1994 and from all farmed animals by 2000, with comprehensive SRM removal in cattle (Russell, 2008). Japan instituted feed bans only after its first BSE case in 2001, after which more SRMs were added (Onodera and Kim, 2006).

The risk classification and trade rules also differ. Japan achieved negligible status only in 2013 (Onodera and Kim, 2006) and has long maintained an import age limit (≤20 months) on foreign beef, stricter than the WOAH's guideline of ≤30 months (Kumagai, Daikai and Onodera, 2019). China, South Korea, and others have often kept bans on negligible-risk imports (China has only recently lifted its ban on Canadian beef and bone meal) (Tyshenko and Krewski, 2010). In 2023, the WOAH updated its BSE Code so that any single BSE case (classical or atypical) no longer forced a country to lose its official risk status (Hassan *et al.*, 2024). Despite these efforts to harmonize, some governments remain cautious: one analysis noted that "ethical concerns, unclear scientific evidence and public health issues easily mobilize domestic publics and put pressure on governments" to enact stricter controls than international standards do (Neyer, 2000).

12.9.2 Atypical BSEs: Detection, Surveillance, and Unknown Zoonotic Risk

Atypical BSEs (H-type and L-type) are thought to arise sporadically in older cattle rather than from feed exposure. These cases typically occur in asymptomatic cattle aged 8 years or older and are only discovered through active surveillance at slaughter (Comoy *et al.*, 2008). The detection of atypical BSEs

poses scientific challenges, as abnormal prion proteins exhibit different biochemical characteristics, which initially raised concerns about test sensitivity (Dudas and Czub, 2017). In practice, however, standard EU-approved rapid tests and confirmatory assays have proven capable of detecting known atypical strains with similar accuracy as C-BSE. Novel findings from "reactive" brain samples have prompted investigations into potentially new prion types, but their significance is not yet clear (Dudas and Czub, 2017).

Surveillance protocols focus on high-risk animals. The WOAH guidelines recommend targeted testing of fallen stock, emergency slaughters, and older slaughtered cattle to identify atypical BSEs. The EU's active surveillance once mandated testing all cattle >30 months of age (fallen/healthy) and raised the risk age limit from 24 months to 48 months in low-prevalence areas (EFSA, 2020). Similar programs in North America test tens of thousands of elderly or infirm cattle annually (USDA, 2025a, 2025b). Such targeted schemes aim to catch the sporadic cases (on the order of 1–2 per million) that passive clinical reporting would miss (FAO, 2005).

The zoonotic potential of atypical BSEs remains unknown, but recent experiments have raised concerns. One study revealed that an L-type BSE isolate caused disease in a primate more rapidly than C-BSE and yielded a prion signature indistinguishable from that in several human sporadic CJD cases (Comoy *et al*., 2008). The authors cautioned that this "possibly higher degree of pathogenicity" and its resemblance to certain human CJDs suggest ongoing caution (Comoy *et al*., 2008). Atypical BSE requires vigilant surveillance, despite its extreme rarity and the unknown human risk it poses. Efforts continue to refine tests and monitoring (for example, distinguishing atypical strains by RT-QuIC) to ensure that these cases do not go undetected.

12.9.3 Role of Novel Diagnostics in Antemortem Detection

Current BSE diagnosis relies on postmortem brain testing, so new methods for live animal detection are highly desirable. PMCA and RT-QuIC are ultrasensitive techniques for prion amplification. In PMCA, tiny amounts of abnormal PrP^{Sc} are amplified in vitro; in one study, PMCA detected PrP^{Sc} in the cerebrospinal fluid of a BSE-positive cow (albeit with only one of three samples) (Wang, Pritzkow and Soto, 2023). More strikingly, RT-QuIC (with a magnetic bead capture step) identified PrP^{Sc} in the blood of BSE-infected sheep two years before symptoms (Thomas *et al*., 2023). These assays have demonstrated near-100% sensitivity in experimental vCJD blood tests, suggesting that they can flag infected cattle long before clinical signs appear (Wang, Pritzkow and Soto, 2023).

In addition to prion amplification, novel biosensors are being explored. DNA aptamers, short nucleic acids selected to bind PrP^{Sc}, have been created to distinguish the disease form of PrP in blood (Devi *et al*., 2021). One aptamer assay even detected BSE prion protein in the brain tissue of infected cows (Devi *et al*., 2021). Other approaches (immuno-PCR, nanoparticles with PrP-capturing ligands) are in early stages. The PMCA/RT-QuIC and aptamer/biosensor methods show great promise for antemortem BSE screening but remain largely experimental.

12.9.4 Ethical, Economic, and Public Perception Concerns

BSE's impact extends far beyond science. The 1996 discovery of human vCJD from infected beef shattered public confidence (Washer, 2006). Consumer panic ("mad cow hysteria") and media coverage led to massive market disruptions and political fallout (Ratzan, 2005). As one analysis noted, "ethical concerns, unclear scientific evidence and public health issues" can "easily mobilize domestic publics and put pressure on governments" to act aggressively. In practice, this meant emergency bans, recalls, and restructuring of the beef industry. For example, after the first North American cases in 2003, 58 countries closed their markets immediately to US beef, costing roughly $3 billion in lost exports (Health and Threats, 2006). Japan alone maintained an import age restriction on US beef for 16 years (Clemens, 2007).

Governments and industries have also incurred significant compliance costs. National BSE surveillance programs require funding for testing, veterinary staff, and compensation for farmers. Producers have had to remove SRMs and, at times, cull entire herds, creating a profound ethical dilemma for

farmers and regulators. The UK slaughtered approximately 4 million cattle at taxpayer expense by 2001 (Cunningham, 2023). Even routine operations, such as rendering and the use of animal proteins for fertilizer, carry a stigma. The loss of domestic and export markets forces some producers out of business, raising questions of justice and international fairness.

Public perception remains a challenge. Despite strong scientific evidence showing that the current risk is negligible, segments of the public and certain trading partners remain fearful. Some policies reflect that caution: China only recently resumed imports of Canadian beef and bone meal decades after its first case. Ethical debates continue over how much precaution is "enough"—balancing zero risk (often unattainable) with economic costs and animal welfare. Ultimately, BSE has highlighted a fundamental tension: society demands absolute food safety but must contend with scientific uncertainty. As one commentator noted, confusion over prion science led to "regrettable decisions of great economic and political importance" (Health and Threats, 2006). Addressing these challenges requires transparent communication and rational trade rules, even as we refine the science of BSE detection and prevention.

12.10 Conclusion

In conclusion, BSE remains a critical challenge at the interface of animal health, food safety, and global trade. Although C-BSE has been primarily controlled through feed bans, the removal of SRMs, and robust surveillance, sporadic atypical cases continue to emerge, underscoring the need for ongoing vigilance. The exceptional resistance of prions to heat and disinfectants demands strict adherence to hygienic slaughter, rendering, and processing standards. Advancements in diagnostic tools such as ELISA, WB, PMCA, and RT-QuIC have improved postmortem detection, but developing reliable, affordable antemortem tests remains an essential research priority. Policy frameworks should emphasize the sustained enforcement of ruminant feed bans, the harmonization of international regulations under WOAH guidelines, and mandatory traceability and SRM disposal systems. Strengthening diagnostic capacities, training personnel, and promoting data sharing across nations will enhance global preparedness. Future research should explore genetic resistance, prion inactivation technologies, and "One Health" surveillance systems that integrate animal, human, and environmental health. Continuous scientific innovation, policy coherence, and international collaboration remain vital to achieving long-term BSE eradication and safeguarding public health.

Abbreviations

BARB	born after the reinforced banana
BASE	bovine amyloidotic spongiform encephalopathy
BSE	bovine spongiform encephalopathy
C-BSE	classical bovine spongiform encephalopathy
CJD	Creutzfeldt–Jakob disease
CNS	central nervous system
CNT	central nervous tissue
CSF	Center for Food Safety
CVL	Central Veterinary Laboratory
CWD	chronic wasting disease
EFSA	European Food Safety Authority
ENS	enteric nervous system
ER	endoplasmic reticulum
EU	European Union
FDCs	follicular dendritic cells
GFAP	glial fibrillary acidic protein
GPI	glycosylphosphatidylinositol
HD	hydrophobic domain

MAFF	Ministry of Agriculture, Fisheries and Food
MBM	meat and bone meal
mpi	months post-infection
NSE-WB	neuron-specific enolase Western blot
OASERD	Obihiro Asia and the Pacific Seminar on Education for Rural Development
OIE	Office International des Epizooties
PMCA	protein misfolding cyclic amplification
PRNP	prion protein-encoding gene
PrP^{C}	normal cellular prion protein
PrP^{Sc}	Scrapie-associated prion protein (pathogenic isoform)
PrP^{res}	protease-resistant prion protein fragment
RT-PCR	reverse transcription polymerase chain reaction
RT-QuIC	real-time quaking-induced conversion
SEAC	spongiform encephalopathy advisory committee
SRMs	specified risk materials
SRPs	signal recognition particles
TBMs	tingible body macrophages
TSEs	transmissible spongiform encephalopathies
UK	United Kingdom
US	United States
USDA	United States Department of Agriculture
vCJD	variant Creutzfeldt–Jakob disease
WOAH	World Organization for Animal Health

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13

Meat Microbiology, Safety, and Public Health Perspectives

Ben Braïek Olfa and Slim Smaoui

13.1 Introduction

Meat represents a nutrient-rich substrate with high water activity favorable to the growth of diverse spoilage and pathogenic microorganisms. The microbial ecology of meat depends on not only the mentioned intrinsic factors but also on extrinsic ones—temperature, processing and storage conditions, and packaging atmosphere. For spoilers, many facets of alterations of meat could be observed such as off-odors, color, and texture changes (Zagorec and Champomier-Vergès, 2017). These microbial communities exhibit complex interactions between them and meat and play a critical role in determining both shelf life and safety of meat products, and their study is crucial to understand how to control and prevent meat deterioration (Zhou *et al.*, 2022). From a public health perspective, the presence of foodborne pathogens in raw and/or processed meats such as *Escherichia coli* (*E. coli*) O157:H7, *Listeria monocytogenes*, *Salmonella* spp., and *Campylobacter* spp. poses significant challenges since they are responsible for several foodborne illnesses worldwide (Zenu and Bekele, 2024). These pathogenic microorganisms can be introduced at different steps of the meat value chain—during slaughtering, processing, handling, and distribution. For this reason, scientists point out that studying foodborne pathogen pathways is an urgent need and a fundamental way to strongly reduce the global pressure on health systems as well as the environment by controlling the ongoing and future outbreaks.

In addition, despite the efforts of meat industries in eliminating spoiler and pathogenic microorganisms through many methods, their survival is omnipresent since the sources of contamination become multiple, thus becoming important issues for meat industry as well as quality authorities (Lianou, Panagou and Nychas, 2017; Zenu and Bekele, 2024). Hence, foodborne outbreak investigation, regular inspection of animal breeding practices, advanced food safety management plans (including risk analysis strategies, good hygiene and good manufacturing practices' implementation), effective control systems such as Hazard Analysis and Critical Control Points (HACCP)–based risk management and innovative detection technologies, are mandatory approaches to ensure meat safety from farm to fork and guarantee public health.

Therefore, the objective of this chapter is to expose recent information from current scientific works on meat microbiology in view of spotting light on the role of spoilage and pathogenic foodborne microorganisms in both meat safety and quality and public health. It also highlights the several challenges globally encountered in meat safety and provides perspective strategies to control and prevent microbial risks, foodborne illnesses in order to obtain safer meats, and ensure public health worldwide.

13.2 Spoilage Microorganisms in Meat

Meat spoilage is a significant concern due to its impact on both food safety and economic losses. Spoilage microorganisms in meat include bacteria and fungi (yeasts and molds) leading to various quality changes (physicochemical, sensory, commercial, etc.). Understanding these microorganisms and their mechanisms is crucial for developing effective preservation strategies in the future.

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13.2.1 Main Microorganisms Causing Meat Spoilage

13.2.1.1 Bacteria

The main spoilage bacteria in meat are Gram-positive or Gram-negative psychrotrophic and facultative anaerobic species (Zagorec and Champomier-Vergès, 2017). They include Enterobacteriaceae such as *Acinetobacter*, *Enterobacter* (Figure 13.1), *Hafnia*, *Proteus*, *Serratia*, *Aeromonas*, *Alcaligenes*, *Providencia*, or Pseudomonadaceae (Figure 13.1). This group is the main emblematic one. In fact, the most known species encountered in meat are *Pseudomonas lundensis*, *Pseudomonas fragi*, and *Pseudomonas fluorescens* (Nychas *et al.*, 2008).

Other spoilers could also be mentioned in this line such as *Brochothrix (B. thermosphacta* and *B. campestris*), *Moraxella*, *Shewanella putrefaciens*, *Bacillus* spp., and various lactic acid bacteria (LAB) like *Carnobacterium* (Figure 13.1), *Enterococcus*, *Leuconostoc*, *Weissella* (Figure 13.1), *Lactobacillus* (*L. sakei*, *L. curvatus*, *L. algidus*, *L. oligofermentans*, and *L. fuchuensis*), *Lactococcus*, particularly *L. piscium*, and *Leuconostoc*, especially *L. gasicomitatum* and *L. gelidum* (de Alcantara *et al.*, 2012; Zhu *et al.*, 2022). Nevertheless, according to several studies, the fact of considering some of these LAB genera as spoilage bacteria is controversial since they are beneficial as natural bio-preservatives, protective cultures, acidifiers, flavor, and taste enhancers as well as shelf life extender (Ben Braïek *et al.*, 2019, 2020; Du *et al.*, 2017).

It is worth mentioning that all of these spoilage bacteria are present in the environment (air, water, soil, biofilm on surfaces) and they are strongly dominant on carcasses after slaughtering or identified in different red or white meat products (beef, lamb, poultry, turkey, or pork) stored under modified atmosphere and/or vacuum-packed ones (Gribble, Mills and Brightwell, 2014; Chaillou *et al.*, 2015; Zagorec and Champomier-Vergès, 2017).

13.2.1.2 Yeasts and Molds

These microorganisms could spoil meat products and the major known genera are *Candida* (Figure 13.1), *Cryptococcus*, *Debaryomyces* (particularly *D. hansenii* in dry-cured meat products), *Yarrowia lipolytica*, and *Rhodotorula* (Fleet, 2011; Ruiz-Castilla *et al.*, 2025). New species of *Kazachstania psychrophila* and *Yarrowia porcina* have been previously isolated in beef and pork meats, respectively (Kabisch *et al.*, 2013; Nagy *et al.*, 2014).

Molds and yeasts are significant spoilage microorganisms in meat at its several types (raw, processed, preserved, refrigerated, dried) contaminating it during diverse processing stages. These fungi are unfortunately underestimated contaminants in slaughterhouses and meat industries, whose presence could

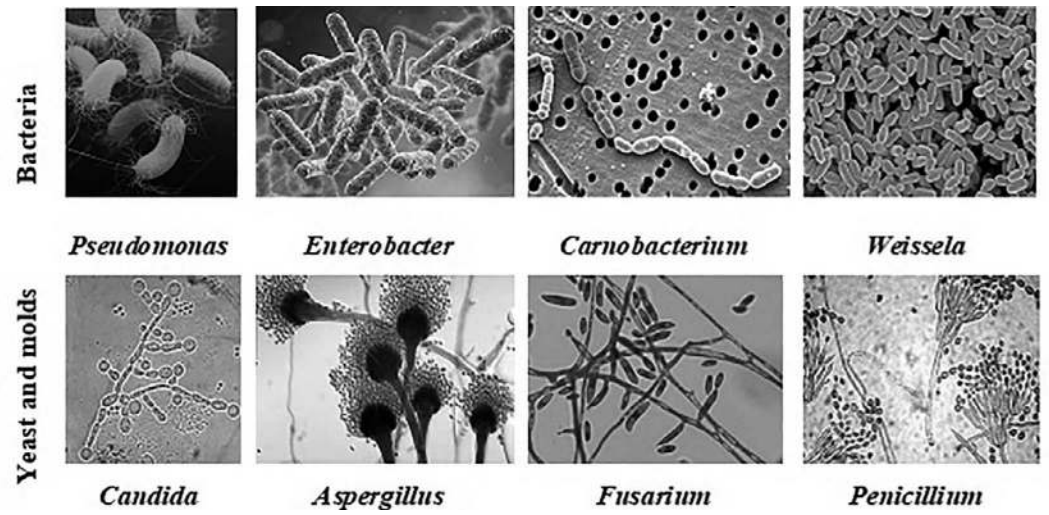

FIGURE 13.1 Some meat spoilage microorganisms.

pose concerns in terms of food safety and health issues through their synthesized mycotoxins. Indeed, mycotoxigenic species like *Aspergillus*, *Fusarium*, and *Penicillium* (Figure 13.1) could originate from the environment and bioaerosol contaminations, thus highlighting the need for better fungal control in meat plants in general.

Bacteria and fungi (Figure 13.1) are considered as significant spoiler microorganisms in meat contributing to economic losses as well as food safety concerns. Their origins are diverse such as air, water, equipment surfaces, and animal (skin, hide, digestive and urinary tracts during evisceration or skinning). They can be also transferred through cross-contamination to meat matrices (via manipulator, utensils, cut surfaces) (Zagorec and Champomier-Vergès, 2017). They are responsible for undesirable changes in meat quality. Understanding their mechanisms of spoilage is essential for developing effective control policies (Rodrigues, Teiga-Teixeira and Esteves, 2025).

13.2.2 Mechanisms of Spoilage

The spoilage of meat is primarily driven by microbial growth and then by enzymatic autolysis and oxidative processes, which collectively alter the meat's quality and safety. Understanding these mechanisms is important for developing future effective preservation approaches. This section details the key aspects of spoilage microorganisms in meat.

Regarding microbial growth, as mentioned above, there are many kinds of microorganisms (bacteria, yeasts, and molds) that are associated with meat spoilage originating from processing environment leading to contamination during handling. Their proliferation is conducted by several factors such as temperature, pH, water activity, light exposure, hygiene, and storage conditions. Besides, it is important to denote that meat is considered as a good substrate that is favorable for the growth of microorganisms that thrive in meat's nutrient-rich environment. As a consequence, they cause spoilage through enzymatic autolysis and oxidative processes involving their intracellular metabolic pathways (Soladoye, Aalhus and Dugan, 2024; Shao *et al.*, 2021). Effectively, enzymes and coenzymes produced by spoilage microorganisms can catalyze the breakdown of fats and proteins in meat contributing to its degradation (Zhou *et al.*, 2022). On the other hand, lipid oxidation in meat can negatively alter the meat quality in terms of odor, color, and texture. These mechanisms provoke the production of relatively complex spoilage compounds such as acids, aldehydes, alcohols, ketones, esters, sulfur compounds, volatile organic compounds, volatile fatty acids, and biogenic amines (such as putrescine, cadaverine), thus leading to visible defects and alterations and impacting both the meat quality and its safety for consumption (Pellissery *et al.*, 2020; Shao *et al.*, 2021; Zhou *et al.*, 2022).

For more details in this context, several studies described that some spoilage bacteria possess specific genes that encode enzymes implicated in the synthesis of such spoilage substances (Johansson *et al.*, 2011; Jääskeläinen *et al.*, 2013, 2015). Examples of these genes include those encoding acetate kinases like *ackA1* and *ackA2*, or citrate lyase like *citCDEF*, or acetolactate synthase like *alsS* involving in acidic or buttery off-odors. Furthermore, it has been reported that dextrane sucrose gene (*dsrA*) was responsible for the slime formation and the green color on the meat (Zagorec and Champomier-Vergès, 2017). However, even knowing different microbial metabolic pathways helpful for spoiling substances identification in meat, the exact mechanisms leading to meat spoilage still unknown and many deep researches are recommended to explore more and more new facets in this line.

Otherwise, several studies highlighted the fact that microbial communities in spoiled meats are complex and interactions between them are essential for the development of the spoilage. These represent the future directions for further researches to associate microbial diversity with their real activities in meat products and production of metabolites causing meat spoilage. The future will certainly see the elucidation of many of the complex bacterial metabolisms.

13.2.3 Meat Quality Changes

Spoilage microorganisms in meat, including bacteria and fungi, cause sensory changes like off-flavors, off-odors (such as putrefying odors, spoilage aroma wheel), discoloration (in terms of blue, green, gray, or yellow color appearance) (Figure 13.2), and texture alterations such as softening due to several microbial

FIGURE 13.2 Some visual spoilage aspects of meats (discoloration, green-pigmenting and slimy surface).

mechanisms as previously mentioned (Odeyemi *et al.*, 2020; Zhang *et al.*, 2024). Furthermore, physicochemical alterations such as pH changes, moisture loss, and slime formation were observed, which ultimately deteriorate the meat quality and affect its commercial acceptance by consumers (Pellissery *et al.*, 2020; Wang, Zhang and Fu, 2017). In this context, Liu *et al.* (2015) reported that *Pseudomonas* spp. was the bacterial genera most implicated in meat spoilage through its proteolytic potential, its green-pigmenting ability (Figure 13.2), and its aptitude to form biofilms, which were strongly recognized as scared traits explaining the attention paid in its risk management in meat.

In addition, Clavero (2010) described that spoilage in meat was detected by souring and gas production compromising food safety.

Hence, as can be seen, spoilage microorganisms significantly change meat quality in different ways (Table 13.1), which affects consumer acceptability and shelf life of meat products. Likewise, it is important to note that these changes not only render the meat unacceptable for human consumption, but can also harbor pathogenic bacteria posing health risks (Sánchez-Aldana, Galicia-García and Leal-Ramos, 2020; Zagorec and Champomier-Vergès, 2024).

TABLE 13.1

Several Spoilage Aspects of Some Bacterial Genus Observed in Meat

Meat	Spoilage Bacteria Genus	Spoilage Aspect
Livestock meat	Lactic acid bacteria (*Leuconostoc*, *Lactobacillus*, *Enterococcus*)	Discoloration, production of slime and gas
	Weissella	Discoloration and production of slime
	Pseudomonas	Green pigmentation and formation of biofilm
	Serratia	Discoloration
Poultry meat	*Enterococcus*	Discoloration
	Brochothrix	Discoloration
	Shewanella	Discoloration
	Aeromonas	Formation of biofilm
	Acinetobacter	Formation of biofilm
	Pseudomonas	Formation of slime and softening of meat

13.3 The Main Foodborne Pathogenic Microorganisms in Meat: Sources of Contamination, Toxins, and Effects

Pathogenic microorganisms in meat pose significant risks to food safety and public health, leading to various foodborne illnesses. The primary pathogens include Gram-negative and Gram-positive bacteria such as *E. coli*, *Salmonella*, *Campylobacter*, *L. monocytogenes*, *Staphylococcus aureus*, and *Clostridium* (Figure 13.3) which can produce harmful toxins and cause gastrointestinal diseases (Dimitrakopoulou, Kotsiri and Vantarakis, 2024; Lianou, Panagou and Nychas, 2017; Zenu and Bekele, 2024). Understanding these pathogens, their sources, and effects is crucial for effective food safety management.

13.3.1 *Escherichia coli*

E. coli is a rod Gram-negative and nonspore-forming bacterial species belonging to Enterobacteriaceae family (Figure 13.3). As it is a mesophilic bacterium, *E. coli* grows optimally at 35–42 °C and represents one of the facultative microflora of the major vertebrates' gastrointestinal tract (Lianou, Panagou and Nychas, 2017).

The primary source of the presence of *E. coli* is the environment—soil, water source, livestock harvesting conditions, sewage treatment effluent (Assefa and Bihon, 2018). Hence, with its omnipresence in different environment sites and its indigenous presence in animal gastrointestinal (poultry or livestock), this bacterium could easily contaminate their carcasses and then meat products through feces during evisceration steps, or cross-contamination, or during transforming process (e.g., cutting, slicing, grounding, packaging) added to the non-respect of appropriate food handling or food hygiene practices.

Several studies reported the presence of *E. coli* in diverse red or white meat products (e.g., raw meat, sausages, ground beef meat) (Koutsoumanis, Lianou and Sofos, 2014; Mathusa *et al.*, 2010).

E. coli group includes four pathotypes implicated in the main foodborne diseases: STEC (Shiga toxin-producing *E. coli*), EHEC (EnteroHemorrhagic *E. coli*), EIEC (EnteroInvasive *E. coli*), and ETEC (EnteroToxinogenic *E. coli*) (Lianou, Panagou and Nychas, 2017). Among all of these groups, the strain *E. coli* O157:H7 of EHEC is well known for its serious foodborne illness and its mortality outbreaks in the world (Geresu and Regassa, 2021). Effectively, the serogroup O157 represented the one most associated with severe foodborne outbreaks worldwide (EFSA–ECDC, 2015; Lianou, Panagou and Nychas, 2017).

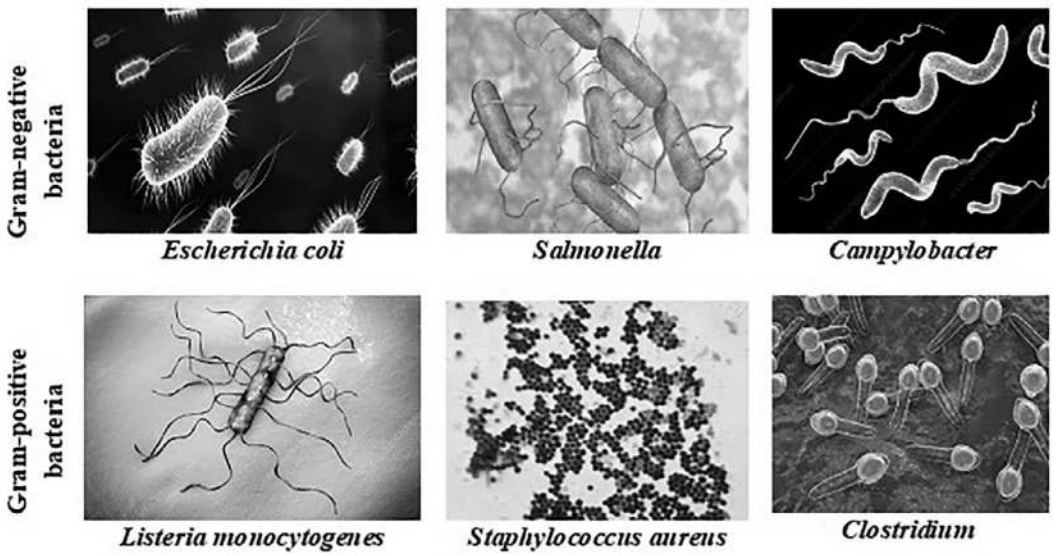

FIGURE 13.3 Main foodborne pathogenic microorganisms in meats.

However, it is important to note that even the non-O157 STEC strains, isolated from some meat products (such as ground beef and fermented sausages), were attributed to significant worldwide foodborne outbreaks and human diseases (Mathusa *et al.*, 2010; USDA-FSISI, 2011; Koutsoumanis, Lianou and Sofos, 2014; CDC, 2015). In general, the illness manifestations due to *E. coli* after consumption of contaminated meat product include diarrhea (that could be severe; from watery causing severe dehydration to bloody), vomiting, nausea, abdominal pain, headache, and sometimes fever (Abreham *et al.*, 2019). All of these health effects depend on the strain, its pathogenicity as well as the infected person (in terms of age or immunity system statute), with high population risks are kids, old persons, pregnant women, and ill people (manifesting chronic diseases or with transplantation, or cancer etc.).

13.3.2 *Salmonella* spp.

Salmonella genus includes Gram-negative motile rod bacteria belonging to the Enterobacteriaceae family (Figure 13.3). Their optimal growth temperature range from 35 °C to 40 °C (Kemal, 2014). Their natural habitat is the gastrointestinal tract of warm-blooded animals as it can be present in the environment (water, air, soil, etc.). The most species linked to meat contamination is *S. enterica* (Gal-Mor, Boyle and Grassl, 2014). According to EFSA–ECDC (2015), this pathogenic species is commonly associated with raw meat from farm animals (bovine, ovine, poultry, swine, cattle, etc.). Contaminated carcasses and edible organs of infected animals consumed by humans represent the main sources of human sickness. The most contaminated meat by *Salmonella* in Europe is chicken meat followed by turkey and pork meats (Gal-Mor, Boyle and Grassl, 2014).

The provoked foodborne disease is called salmonellosis, whose manifestations depend on the serotype (*Enteritidis* or *Typhimurium*), the pathogenicity, and the infected person, but it could be resumed as gastrointestinal malaise, abdominal cramps, and vomiting (Lianou, Panagou and Nychas, 2017).

13.3.3 *Campylobacter* spp.

The genus of *Campylobacter* regroups 14 species, of which the well-known pathogenic ones for human are *C. jejuni*, *C. coli*, *C. lari*, and *C. upsaliensis* (Lianou, Panagou and Nychas, 2017). These bacterial species are spiral or curved-shaped, Gram-negative, nonspore-forming, and microaerophilic (Figure 13.3). Its optimal growth temperature ranges between 30 °C and 37 °C (Kaakoush *et al.*, 2015). These species are naturally present in the gastrointestinal tract of warm-blooded animals, thus in animal feces, that is why the contamination of meat could occur during slaughter (Ivanova *et al.*, 2014). The most contaminated meat by this germ is fresh broiler meat (Kaakoush *et al.*, 2015). Based on EFSA–ECDC (2015), *Campylobacter* was recognized as the most commonly gastrointestinal pathogen infecting humans in Europe, known as campylobacteriosis. This infection could be detected through common symptoms—fever, headache, enterocolitis, abdominal pain, and diarrhea (Lianou, Panagou and Nychas, 2017). This infection could be more severe depending on the infectious dose, the strain, and the enterotoxin or cytotoxin synthesis.

13.3.4 *L. monocytogenes*

L. monocytogenes is the major pathogenic species among the *Listeria* genus. It is a rod nonspore forming Gram-positive bacterium (Figure 13.3). It is a psychrotrophic microorganism that is able to grow at low temperatures (Al-mashhadany *et al.*, 2016). It is known to be ubiquitous germ, which allows it to be present in many food matrices, especially meat as a very rich substrate. The particular trait of *L. monocytogenes* is its contamination of chilled food without suspected odor, or color or texture (Ben Braïek *et al.*, 2020).

This pathogen is deemed as a serious concern in both red and white meat industries. Indeed, it has been previously isolated in diverse meat products (e.g., ready-to-eat (RTE) meat products like frankfurters, fermented sausages, ground beef, etc.) (Barroso *et al.*, 2019; Skandamis and Nychas, 2015). *L. monocytogenes* is implicated in listeriosis outbreaks due to the consumption of contaminated meat. This illness is characterized by different symptoms from the simple ones like febrile gastroenteritis to severe ones like sepsis, meningitis, meningoencephalitis, central nervous system infection, or invasive

diseases (Lianou, Panagou and Nychas, 2017). This bacterium is very pathogenic for sensitive individuals leading to abortion of pregnant women (Mateus *et al.*, 2013).

Despite the international legislation fixing the absence of *L. monocytogenes* in 25 g of food (e.g., meat), its presence is still unavoidable unless the implementation of the good hygiene or/and good manufacturing practices (NF EN ISO 11290-1, 2005; NF EN ISO 11290-2, 2005). Therefore, it is very much recommended to establish operational food control strategies to limit the risk of contamination by this occupational bacterial hazard.

13.3.5 *S. aureus*

This coccus Gram-positive microorganism is deemed as the second most frequent foodborne pathogen after *Salmonella* (Figure 13.3). Although it is a commensal germ of mucous membranes, nose, and skin of healthy hosts (human and animal), it is an opportunistic foodborne pathogen able to provoke infectious diseases. Its optimal growth temperature ranges between 30 °C and 37 °C (Wang *et al.*, 2017). It could contaminate many meat products from pork, mutton, beef, goat, and poultry (Zenu and Bekele, 2024). These facts are considered as favorable for its growth, particularly the drug-resistant *S. aureus* (Zenu and Bekele, 2024). This germ is deemed as a suspicious food hazard because of its ability to produce toxins responsible for food poisoning. Otherwise, methicillin-resistant *S. aureus* (MRSA) represent the *S. aureus* as exhibiting the most significant concern worldwide detected in several retail meats (Smith *et al.*, 2009; Zenu and Bekele, 2024).

13.3.6 *Clostridium* spp.

The *Clostridium* genus includes rod-shaped Gram-positive spore-forming anaerobic bacteria (Figure 13.3). The most known species as foodborne pathogens are *C. perfringens* and *C. botulinum* (Lianou, Panagou and Nychas, 2017). These bacteria are mesophilic with an optimum growth temperature ranging between 37 °C and 45 °C (Zenu and Bekele, 2024). They are able to produce many types of toxins (exotoxins or neurotoxins) responsible for food intoxication after their ingestion with food, which also are pathogenic to human (Table 13.2). Indeed, *C. perfringens*, *C. botulinum*, and *C. difficile* are frequent species in several types of meat (pork, beef, lamb, and chicken) through different ways: post-processing contamination, fecal contamination, and cross-contamination (Bouttier *et al.*, 2010; EFSA–ECDC, 2015; Candle-Pérez *et al.*, 2021; Taha, 2021). In addition, they have often been implicated in diverse outbreaks through the consumption of meat dishes (EFSA–ECDC, 2015). Effectively, the factor that contributes to food poisoning by these germs is cooling and rewarming the food, which favor the germination of its heat-resistant spores (Grass, Gould and Mahon, 2013).

Regarding their foodborne illness, they are able to cause headache, nausea, vomiting, fatigue, critical abdominal pains, and diarrheas (Table 13.2). In this line, it is worth mentioning that *C. botulinum,* causing botulism, has a mortality rate ranging between 30% and 65% (Lianou, Panagou and Nychas, 2017). This disease could occur after 12–72 hours post food ingestion and could be very severe depending on the host (particularly the immunocompromised and the elderly persons). Its acute symptoms include double vision, mouth dryness, muscle paralysis, and respiratory failure, which can finally lead to death (Zenu and Bekele, 2024).

TABLE 13.2

Characteristics of the Most Common Foodborne *Clostridium* Species

***Clostridium* Species**	**Toxins**	**Diseases**
C. perfringens	Heat-labile enterotoxin	Toxico-infection (abdominal pain, diarrhea, infant death)
C. botulimun	Neurotoxins (A, B, C, D, E, F, G)	Intoxication and toxico-infection (nausea, vomiting, headache, fatigue, double vision, mouth dryness, muscle paralysis, respiratory failure, death)
C. difficile	Enterotoxin A, toxin B (cytotoxin)	Toxico-infection (diarrhea, colitis)

Source: Zenu and Bekele, 2024.

13.4 Meat Safety and Public Health

As seen above, spoilage microorganisms as well as foodborne pathogens cause a wide range of spoilage phenotypes in meats and provoke several symptoms of foodborne illnesses, thus constituting crucial issues to meat safety management in terms of economy loss (deterioration of meat, recall of contaminated/altered meat products for particular treatments, etc.) and public health. However, pathogens are still the major public health concern since they are responsible for diseases that vary from diarrhea to cancer and/or death. Hence, as foodborne outbreaks remain a significant problem for public health, scientific researchers put their efforts on creating innovative, rapid, and efficient methods for the detection of these pathogens, thus helping food industries to apply new techniques for obtaining accurate results with regard to food safety as well as the application of innovative approaches for food control and prevention taking into account some challenges encountered in this context.

13.4.1 Meat Safety Challenges

The most important challenge facing meat safety is the control of the multidrug resistant (MDR) foodborne pathogens. The pathogens originate from the prolonged overuse of antimicrobials in animal breeding. These MDR pathogens that could be present in meat will then be transmitted to humans through consumption of contaminated meat products. This fact is occupational since the MDR pathogens are significantly resistant to the most clinically important antimicrobial agents used conventionally to treat the bacterial infections making antimicrobial resistance one of the most serious global public health threats. Examples of MDR pathogens that are known to considerably challenge global health in the future are *Campylobacter jejuni* and *Salmonella enterica* (Zhong *et al.*, 2016).

In addition, the detection of newly emerging foodborne pathogens (introduced to meat at different steps: pre-and postslaughter, during preparation or processing, post-processing, storage, etc.) are still challenging the meat safety since these germs could demonstrate different pathogenicity and virulence aspects, or exhibit new genetic determinants of antimicrobial resistance, or display low infectious doses. In this framework, the lack of available information concerning all of these facts render the control and prevention very limited and burdensome.

Other meat safety challenge could also be mentioned regarding the veterinary inspection of animal breeding establishments in order to monitor farmers' practices, particularly in terms of the overuse of antimicrobials. Indeed, although considerable efforts have been made from veterinary authorities, some farmers demonstrate a lack of responsibility regarding the excessive and prolonged antibiotic use for prophylactic purposes, despite clear advice and recommendations from veterinarians. This limited awareness, or the ignorance of veterinary guidance, not only undermine animal health but also significantly contribute to the development and spread of antimicrobial resistance. Such practices pose a serious risk to public health and additional measures are needed in this line.

Finally, additional challenges have been proposed previously and remain relevant today. In fact, they concern national and international regulations and inspections, traceability issue, the development of new and rapid techniques to detect pathogens and perform accurate laboratory tests (e.g., molecular techniques), the elucidation of responsibilities for the control of zoonotic diseases between animal health services and public health regulatory authorities, along with the development of food safety objectives based on systematic risk assessment.

13.4.2 Prevention and Control

As meat safety is of important interest in both society and economy, its associated challenges should be successfully managed to control and prevent foodborne diseases. Indeed, public health authorities and food industry should work harmonically together in order to establish robust surveillance tools and measures in this context. A first preventive strategy to reduce foodborne illnesses is the application of HACCP system in the food production chain. This system provides prerequisite programs able to efficiently control any foodborne pathogen at any process step along with the application of good manufacturing and hygiene practices.

In addition, reducing meat contamination by both pathogenic or spoiler microorganisms could be achieved by following personal, material, and environmental hygiene, the application of sanitary standards for slaughterhouses and hygienic handling of meat during processing, and the public health education programs for both food handlers and consumers (like informing vulnerable persons about proper cooking meats or avoiding raw RTE meat products, proper storing of food, and adequately washing hands).

Otherwise, continuous veterinary surveillance of animal husbandry establishments is essential to ensure best-quality farm breeding with responsible antibiotic use and to protect public health. Regular inspections by veterinary authorities and relevant regulatory bodies, combined with close monitoring of farmers' practices, allow early detection of misuse or overuse of antimicrobials in food-producing animals. Veterinarians play a central role in guiding evidence-based treatments, implementing biosecurity measures, and promoting preventive strategies such as animal vaccination and improved hygiene, which reduce the need for antibiotics. Effective control systems also ensure compliance with national and international regulations and encourage traceability and accountability within the production chain. Proper management of antibiotic use in animal breeding is critical to limit the emergence and spread of antimicrobial-resistant bacteria, which are serious public health concern nowadays.

On the other hand, meat industries should focus on the implementation of biosecurity practices and improve meat-processing methods, including preparation and storage conditions that have been identified as important approaches to control and prevent meat contamination and limit foodborne diseases' occurrence. For instance, packaging methods could be one of these common approaches. Indeed, modified atmospheric packaging (MAP) has been previously considered as efficient method to extend the shelf life of meat. In this line, Zhang *et al.* (2015) showed that frozen chicken stored at MAP with 30% CO_2 and 70% N_2 extended its shelf life. Moreover, Luong *et al.* (2020) demonstrated that treated turkey sausage with MAP at 50% CO_2 and 50% N_2 combined with 2% lactic acid and treated pork sausage with MAP at 70% O_2 and 30% CO_2 strongly prevented discoloration of meat sausages and decreased their off-flavors and acidification. Furthermore, Dohlen *et al.* (2017) revealed that the application of a novel antimicrobial packaging material containing poly-[2-(tertbutylamino)methylstyrene] inhibited the growth of both spoilage and pathogenic bacteria in meats (chicken breast fillets and veal cutlets).

Furthermore, irradiation of meat and meat products at low doses (1–3 kGy) serves as an effective control method for enhancing meat safety and extending its shelf life (Sebranek, 2024). This technology efficiently reduces pathogenic microorganisms while maintaining the sensory qualities of meat with respect to appropriate doses (Indiarto and Subroto, 2023). Indeed, the Food and Drug Administration (FDA) has approved this technique for both red and white meats (Arvanitoyannis and Stratakos, 2010). Many studies showed that low-dose irradiation of meats successfully inhibits the growth of several microorganisms such as *Salmonella* and *E. coli* without altering sensory properties of treated meat products (Kundu and Holley, 2013; Je, Chung and Shim, 2015; Jayathilakan and Sultana, 2018; Indiarto and Subroto, 2023). While irradiation presents a promising method for ensuring meat safety and quality, concerns regarding consumer acceptance and potential nutritional changes necessitate ongoing research and education efforts.

In addition, Kim *et al.* (2013) showed that dielectric barrier discharge (DBD) treatment significantly reduced the *L. monocytogenes* levels in meat since it generates reactive oxygen species (ROS) from plasma, which penetrate bacterial cell membranes and cause its death via the cell wall and/or the DNA damages.

Finally, advances in molecular biology and high-throughput sequencing are helpful too in meat microbiology to enable more detailed characterization of microbial populations and to deeply understand their functional roles in both spoilage and disease. Integration of these tools with traditional microbiological methods enhances the ability to monitor, predict, and mitigate microbiological hazards in meat, ultimately safeguarding consumer health and supporting public health initiatives globally (Johler and Guldimann, 2024). Effectively, in this context several examples of these applications can be mentioned, such as omics (metagenomics and metabolomics), predictive modeling, microbiome engineering, etc. (Zagorec and Champomier-Vergès, 2017; Zenu and Bekele, 2024).

13.4.3 Future Trends

Preservation of meat from spoilage and foodborne pathogens represents a persistent issue that remains relevant today despite the application of diverse storage methods, packaging solutions, and preservation

approaches. Recently, more attention has been paid to eradicate or minimize the levels of these microorganisms in meat through natural and bio-preservation methods. These offer many advantages for maintaining meat quality and safety compared to synthetic chemical preservatives and certain physical techniques. These tools, which include the use of plant-derived compounds, beneficial microorganisms (LAB), and bioactive metabolites (bacteriocins, polyphenols, etc.), are often perceived as safer and more sustainable, as they reduce chemical residues in meats and better align with consumer demand for clean-label product (Ben Braïek *et al.*, 2019, 2020; Smaoui *et al.*, 2016). In addition to extending shelf life, natural preservation strategies can enhance the nutritional and sensory qualities of meat while exerting antimicrobial and antioxidant effects. By relying on renewable resources and biologically based mechanisms, these methods also minimize environmental impact and help in limiting the selective pressure that contributes to antimicrobial resistance, making them a promising alternative for modern and responsible meat preservation systems.

Examples of antimicrobial substances used in such strategies are polyphenols, oxygenated monoterpens, and essential oils (EOs) from different parts of aromatic and medicinal plants (leaves, flowers, fruits, roots, stems, seeds) (Akermi *et al.*, 2024; Hać-Szymańczuk *et al.*, 2017; Lastra-Vargas *et al.*, 2023; Nikmaram *et al.*, 2018; Ricardo-Rodrigues *et al.*, 2024). In this framework, Table 13.3 emphasizes the effect of several EOs used in meat preservation.

Furthermore, the use of plant extracts (such as pomegranate seeds extracts, guarana seeds extracts, green tea extracts, cranberry extracts, etc.) or organic acids and their derivatives salts (such as acetic acid, benzoic acid, sodium benzoate, citric acid, formic acid, lactic acid, sodium lactate, potassium lactate, etc.) have also been identified as future trend areas in meat preservation that research should deeply focus on (Ben Braïek and Smaoui, 2021; Mantzourani, 2022; Munekata *et al.*, 2020; Rodionova, 2022; Smaoui *et al.*, 2020).

TABLE 13.3

Common EOs Extracted from Plants Used in Meat Preservation

EO	Meat	Effects	References
Satureja montana L. EO	Fresh pork sausages	Growth inhibition of thermophilic aerobic bacteria and Enterobacteriaceae	Sojić *et al.*, 2019
Sage (*Salvia officinalis* L.) EO	Fresh pork sausages	Growth inhibition of thermophilic aerobic bacteria	Hyldgaard, Mygind and Meyer, 2012
Black pepper EO	Fresh pork	Growth inhibition of Enterobacteriaceae, *E. coli*, and *Pseudomonas*	Zhang *et al.*, 2016, 2017
Cinnamon (*Cinnamomum cassia*) EO	Fresh Italian sausages	Growth inhibition of Enterobacteriaceae	Zhang *et al.*, 2019
Ziziphora clinopodioides EO	Raw beef patties	Growth inhibition of *S. aureus*, *E. coli* O157:H7, Enterobacteriaceae, thermophilic and psychrotrophic bacteria	Shahbazi, Shavisi and Mohebi, 2016
Thyme (*Thymus vulgaris*) EO	Minced beef meat, cooked ham, dry-cured sausages	Growth inhibition of *E. amnigenus*, *E. gergoviae*, *P. fluorescens*, *P. fragi*, *P. putrefaciens*, *L. innocua*, *A. faecalis*, etc.	Ballester-Costa *et al.*, 2017
Oregano (*Origanum vulgare*) EO	Raw ground chicken meat, refrigerated turkey mortadella	Reduction of lipid and protein oxidation Improvement of the color of both raw and cooked meats Growth inhibition of psychrotrophic bacteria, *E. coli* O157:H7, *L. monocytogenes*, and *S. enterica* Extension of shelf life	Al-Hijazeen *et al.*, 2016, 2022; Lastra-Vargas *et al.*, 2023
Garlic (*Allium sativum* L.) EO	Fresh sausages	Growth inhibition of spoilage lactic acid bacteria and *E. coli* O157:H7 Maintain pH and red color of treated sausages	Araújo *et al.*, 2018

(Continued)

TABLE 13.3 *(Continued)*

Common EOs Extracted from Plants Used in Meat Preservation

EO	Meat	Effects	References
Clove (*Syzygium aromaticum*) EO	Ground beef meat	Growth inhibition of native coliforms, *Salmonella* Typhimurium and *L. monocytogenes*	Zengin and Baysal, 2014; Khaleque *et al.*, 2016
Rosemary (*Rosmarinus officinalis*) EO	Mechanically deboned poultry meat (MDPM) from chicken	Growth inhibition of total bacterial counts, psychrotrophic and coliform bacteria. Decrease in lipid oxidation (TBARS)	Hać-Szymańczuk *et al.* (2017)
Peppermint (*Mentha piperita*) EO	Minced beef meat	Growth inhibition of aerobic plate counts, psychrotrophic counts, Enterobacteriaceae, and *Pseudomonas* spp. Inhibition of lipid oxidation by reduction of thiobarbituric acid reactive substances (TBARS) and delaying the metmyoglobin (MetMb) formation. Extension of meat shelf life with stability of its sensory quality	Smaoui *et al.* (2016)

13.5 Conclusion and Perspectives

Meat safety constitutes one of the most significant current and future societal concerns. Here, it is important to denote that meat microbiology comes in the intersection between meat safety and quality, as well as public health. As microbial interactions associated with deterioration of meats are complex and dynamic, they can also determine their potential to vehicle foodborne pathogens, including emerging or MDR ones, leading to the occurrence of several diseases. Hence, understanding the sources, behavior, and control of microorganisms along the meat production chain is therefore crucial for reducing contamination risks and ensuring consumer protection. In this line, several challenges need to be successfully managed by the meat industry and public health authorities in order to reduce the foodborne illnesses worldwide. Nonetheless, for such a goal to be attainable, it is important that integrated innovative approaches extending throughout the food supply chain, from farm to fork, are developed and efficiently applied. In fact, as highlighted throughout this chapter, effective management of meat microbiological hazards relies on integrated approaches combining good hygienic and manufacturing practices, HACCP systems, and scientifically vigorous preservation and processing strategies. Moreover, recent advances in molecular tools are strongly recommended to detect and well characterize microbial communities, as well as to improve risk assessment systems and surveillance programs. Finally, in a global context marked by increasing meat consumption and meat production added to the attention paid to public health concerns, meat microbiology remains a fundamental scientific and research field crucial for innovation by driving new and efficient technologies to support safer meat supply chains and to align meat production with public health and sustainability objectives.

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14

Classification and Varieties of Meat: Exploring Different Types and Their Characteristics

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14.1 Introduction

14.2 Importance of Meat in Human Diets

Meat has traditionally provided a core part of human nutrition, providing a source of high-quality and dense protein and micronutrients essential for growth, maintenance, and good health. Proteins from meat are considered complete since they have all essential amino acids in proportions quite close to human physiological needs, thus supporting proper muscle development, enzymatic activity, and metabolic regulation (Jairath *et al.*, 2024; Stadnik, 2024). In addition to providing protein, meat is a significant source of micronutrients such as heme iron, zinc, selenium, vitamin B12, B6, and niacin, contributing to oxygen transport, antioxidant defense, immune function, and neurological health (FAO, 2023). Notably, the heme iron within meat demonstrates better bioavailability compared to the non-heme type of iron from plants, making it especially important to populations at risk of anemia from iron deficiency, such as women of reproductive age, adolescents, and young children (Giromini and Givens, 2023).

In addition to its nutritional contributions, due to its high density of protein and nutrient composition, meat is central to satiety and energy balance. Meat consumption has been associated with better lean body mass retention, especially in older adults, and also better cognitive and physical development in children. Furthermore, intake of meat supports metabolic events involved in muscle synthesis, hormone production, and energy regulation with the provision of essential amino acids such as leucine, isoleucine, and valine (Dhakal *et al.*, 2025).

Cultural, regional, and socioeconomic determinants strongly influence meat consumption. Meat consumption in many cultures is linked to tradition and religion and thus reflects their culinary heritage and social cohesiveness, contributing to collective identity. For example, lamb and goat meat are staple meats of celebration and sacred meals in the Mediterranean, while beef is common in the Americas and Australia. These cultural determinants influence not only the species consumed but also preparation, preservation, and presentation, which affects perceived quality and nutritional intake (FAO, 2023; Giromini and Givens, 2023).

14.3 Nutritional Composition and Bioactive Components

Meat is not just a source of protein and micronutrients but also contains several functional bioactive compounds that play a significant role in health. The compounds that show antioxidant capacity, neural function, and muscle metabolism include creatine, carnosine, taurine, and conjugated linoleic acid (CLA). For example, carnosine serves as a pH buffer in muscle tissue to help improve performance during high-intensity activities, whereas taurine is an important factor in cardiovascular and neurological health. CLA is naturally found in ruminant meat and has been reported to possess anti-inflammatory

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and metabolic regulatory functions; this emphasizes the important physiological relevance of meat in regulation of human diets (Jairath *et al*., 2024; Stadnik, 2024).

Nutritional composition depends on a set of intrinsic and extrinsic factors, including species, breed, age, sex, diet, and rearing practices of the animal (Cedeno, Olubiyo and Ferreira, 2025). For example, grass-fed beef has higher levels of omega-3 fatty acids and antioxidants than grain-fed beef; the latter tends to have higher intramuscular fat (IMF) but lower polyunsaturated fatty acids. Similarly, nutrient density can vary according to muscle type: For example, oxidative muscles like the shoulder or leg have high myoglobin and mineral content, whereas glycolytic muscles such as the breast in poultry have low fat content but contain high-quality protein. Nutrient availability, flavor, and digestibility may also change due to postmortem handling, which includes chilling, aging, and storage conditions (Mo *et al*., 2023).

Besides macro- and micronutrients, meat also contains peptides with biological activity, such as antihypertensive, antioxidative, and immunomodulatory activity. These bioactive compounds are typically liberated during digestion or enzymatic hydrolysis; thus, consumption of meat may provide functional health benefits beyond nutrition. Compositional diversities in meats are important factors in the development of dietary guidelines, specialized functional foods, and targeted nutrition strategies (Stadnik, 2024).

In addition, blockchain, sensors, and artificial intelligence are some of the digital technologies that improve traceability, data-driven classification of meat, by linking intrinsic quality to production and environmental parameters (Liu *et al*., 2025b). These technologies facilitate informed decision-making regarding nutritional, ethical, and sustainability concerns on the part of the consumer and producer. As meat has become a highly globalized industry, integrating biological, functional, and sustainability criteria meat classification more relevant for industrial stakeholders and consumers (Khan *et al*., 2025).

14.4 Principles of Meat Classification

Usually, meat classification is a systematic approach used to categorize meat based on its physicochemical and sociocultural factors. Mainly, these principles of classification involve anatomical, physiological, biochemical, functional, and cultural considerations. This approach further assists in quality evaluation, processing suitability, nutritional assessment, consumer acceptability, and regulatory compliance in meat technology.

14.4.1 Anatomical, Physiological, and Biochemical Criteria

In general, meat classification based on its anatomical and physiological criteria considers the nature of the muscle within the carcass, its functional role in the live animal, and the resultant structural features. For instance, skeletal muscles and breast muscles are anatomically different, hence classified individually. This is because muscles involved in locomotion and similar physiological functions contain higher proportions of connective tissue and slow-twitch fibers, influencing tenderness compared with muscles subjected to limited or sustained use.

Moreover, animal physiology, productivity, and meat quality mostly negatively impacted by heat stress (HS), particularly in cattle and poultry. This is due to rapid growth, high output, and characteristics such as inadequate sweating and distinctive rumen fermentation that make certain species physiologically vulnerable. While extended HS lowers muscle glycogen levels, resulting in dark, firm, and dry (DFD) meat with high pH and water retention, short-term HS can result in pale, soft, and exudative (PSE) muscle. Additionally, HS causes oxidative stress and reduces shelf life. According to recent studies, HS may change the physiology of postmortem muscle glycolysis and the muscle pH, thereby resulting in poor biochemical composition of the meat. This might have an impact on meat properties and animal health (Mia, Rahman and Hashem, 2023).

Moreover, biochemical classification assesses postmortem metabolic changes, such as glycolysis and pH decline, which are the major factors of meat quality such as tenderness, water-holding capacity (WHC), and color stability. Although a complete mechanistic relationship between muscle fiber types, myofibrillar protein composition, and meat quality has not yet been fully elucidated this biochemical framework remains central to meat processing and technology (Li *et al*., 2024).

Similarly, Ayaz *et al*. (2024) found that the transformation of muscle tissue into meat involves a complex series of biochemical and physical modification, Following slaughter, muscle transitions a flexible state to a rigid form, which is known as postmortem metabolism. Mostly, meat can be classified based

on its biochemical principle such as mechanism of postmortem muscle, focusing on muscle cell organization, myofibrils, sarcomeres, and metabolic pathways, including oxidative and glycolytic pathways, particularly regarding lactate accumulation and its effects on muscle pH and quality.

14.4.2 Myoglobin Content, Muscle Fiber Type, and Meat Color

Meat color significantly influences consumer purchasing decisions and is a key indicator of meat quality and is principally determined by the concentration and chemical state of myoglobin, the heme protein responsible for the red pigmentation of skeletal muscles. The increased myoglobin content generally correlates with a darker red color, as seen in muscles with a predominance of oxidative (Type I and IIA) fibers; such traits are common among red meat species. These oxidative fibers are rich in mitochondria and exhibit higher myoglobin levels, which enhance both meat color and oxidative metabolism. Conversely, glycolytic fibers (Type IIX/IIb) have lower myoglobin content and produce paler meat.

However, recent research highlight not only myoglobin concentration but also the distribution of myofibrillar and sarcoplasmic protein distribution, muscle microstructure and pH, which significantly contribute to meat color perception and stability during storage and display (Fu *et al*., 2025).

Among consumers, meat color serves as a crucial marker for favorable physical attribute for most of the meat. Among leading meat-consuming countries, including Japan, the United States, Korea, and Australia, muscle color is an important criterion for beef quality evaluation. However, this parameter is less applied in the European Union and Ukraine. This study performed by Kruk and Ugnivenko (2024) assessed the relationship between muscle tissue color and consumer properties of beef from 21-month-old Ukrainian black-and-white dairy bulls, utilizing the Japan Meat Grading Association method. Results revealed that darker muscle tissue is linked to less boiling down of beef and better traits like cross-sectional area and water-binding capacity.

Moreover, factors affecting meat product color throughout processing and storage are critical for enhancing both quality and consumer appeal. Nitrosomyoglobin is identified as the primary compound responsible for color in meat products. Studies also examine the interplay of pH, temperature, and water retention with color in cured meat products, aiming to provide insights for further color research in this area (Han *et al*., 2024).

Furthermore, structural colors, a result of light scattering from the muscle's microstructure, contribute to meat color. While biochemical and physical mechanisms are extensively studied, understanding the underlying mechanisms and interactions of light with meat microstructures can improve our understanding of meat color. Such investigations facilitate development of innovative approaches to modulate color in the meat industry (Ruedt, Gibis and Weiss, 2023).

Another important criterion in improving meat quality highlights the understanding of muscle fibers. Slow-twitch (Type I) and fast-twitch (Type II), which are further subdivided into Type IIa, Type IIx, and Type IIb, are the two types of muscle fibers. While Type IIb fibers have a negative impact on meat quality, a larger ratio of Type I to Type IIa fibers is associated with better meat quality. Meat quality depends on the genetic factors and signaling pathways that affect the makeup of muscle fibers (Mo *et al*., 2023).

Similar to muscle fiber composition, understanding myoglobin content is essential for meat categorization. Myoglobin predominantly exists in three interconvertible states: deoxymyoglobin, oxymyoglobin, and metmyoglobin. The concentration of myoglobin and its redox state affect the color of meat. Moreover, sodium nitrite is used in cured meat products to create nitrosomyoglobin, which gives them a pink color. Recent advancements provide mathematical model, considering the chemical states of myoglobin have been developed to explain meat color differences and to understand structural changes in myoglobin during cured meat processing (Pujol *et al*., 2023).

14.4.3 Functional Characteristics of Muscle Tissues

The functional properties of meat muscle tissues, including WHC, texture, emulsification potential, and gel formation, are directly influenced by the biochemical and structural framework of muscle fibers. Muscles vary in their protein composition, connective tissue content, and fiber-type distribution, which collectively influence meat processing behavior. For instance, muscles with higher proportions of oxidative fibers often show improved water retention and tenderness. Engineering muscle fiber characteristics through breeding, nutrition, and management offers a promising strategy for improving meat quality attributes (Liu *et al*., 2025a).

One important source of premium animal protein is chicken meat. According to recent research comparing muscles of the Xueshan (Partridge Shank broilers, China) and Ross 308 (Arbor Acres broilers, Britain), the leg muscle of both breeds has a combination of oxidative and glycolytic fibers, whereas the breast muscle of both breeds has glycolytic fibers. Interestingly, the soleus muscle of the slow-growing broilers contains the greatest amount of oxidative fiber (26.51%). In comparison to breast muscles, slow-growing broilers have thicker muscle fibers, higher percentages of oxidative fibers, ultimate pH, redness, and IMF in their leg muscles. These findings suggest that thicker fibers are associated with greater firmness, while higher oxidative fibers are associated with increased redness and fat content (Weng *et al*., 2022).

Since muscle fiber composition plays a key role in meat quality, recent cultured meat technologies aim to recreate these features under laboratory conditions. These investigations describe the production of biomimetic bovine muscle tissue utilizing a culture technique that includes laminin coating, pronase enzymatic treatment, and sequential digestion. Myogenic cells are effectively extracted and purified by this method, enabling their proliferation in vitro. Furthermore, the cultivated cells maintained structural maturation within a fibrin-based gel on a thermoresponsive substrate, producing muscular tissues that resembled real bovine flesh. This study offers a fundamental method for producing techno-functional enhanced tissue-engineered meat in the future (Takahashi *et al*., 2022).

In parallel, the functional properties of meat quality are influenced by storage conditions. A study on 17-week-old female White *Kołuda* geese assessed the effects of frozen storage at −20°C on the sensory and functional properties of leg and breast muscles, The study found that WHC, water-binding capacity, cooking losses, and defrosting losses, all decreased with time. Sensory evaluation, based on PN-ISO 8586-2:2008 criteria, revealed adverse effects in appearance, taste, and smell, with breast muscle scoring worse than leg muscles. Because color measurements showed little fluctuation, the research suggests that frozen storage be kept to a maximum of 180 days to maintain meat quality (Wereńska and Okruszek, 2023).

14.4.4 Cultural, Regional, and Regulatory Influences

Beyond physico-functional and biological criteria, cultural and regional practices exert a strong influence on meat classification systems. Religious norms, dietary preferences, and sociocultural perceptions determine whether certain meats (e.g., beef, pork, and goat) are categorized and consumed in specific markets. In addition, regulatory frameworks implemented by food safety and standards authorities require classification based on species, carcass grading, and hygiene standards for consumer protection and trade. These regulatory systems influence labeling, grading, and quality assurance practices, integrating scientific and sociolegal criteria into meat classification.

Therefore, the regulatory and production process of cultured meat is examined by Zandonadi *et al.* (2025), which addresses rules, possible risks, and important details. It highlights established procedures and safety issues, such as genetic stability and microbiological safety. Toxicity, postharvest pollution, and chemical residues are important health risks. The lack of standardized testing highlights the necessity for efficient hazard and safety techniques, like HACCP, across the manufacturing process.

Furthermore, meat consumption is high in both developed countries like Switzerland and developing countries like Vietnam, with impacts on the environment, health, and society. Social and cultural habits strongly influence consumers' meat consumption. In Switzerland, environmental concerns play a major role, whereas in Vietnam, health and food safety are the main drivers. Meat is also linked to social life being commonly consumed during social gatherings in Switzerland and for special occasions in Vietnam and family influence is stronger. Overall, reducing meat intake requires understanding these cultural and social factors, not only individual choices (Markoni *et al*., 2023).

With an emphasis on sustainable meat systems, another recent study shows the consumer attitudes, cultural aspects, and sustainability issues affect the uptake of cultured beef. Although consumer intentions and cultural impacts have been studied previously, social acceptance, economic viability, and technological uptake are still poorly understood. The study concludes that meat consumption is strongly influenced by social, cultural, and familial factors, which vary between countries. It emphasizes the need for policymakers to implement regulations and frameworks that promote sustainable meat systems (Guo and Wiwattanadate, 2023).

Table 14.1 summarizes the recent advancements in meat classification using anatomical, physiological, biochemical, and functional criteria, as well as myoglobin content, muscle fiber type, and color,

TABLE 14.1

Principles of Meat Classification: Recent Technological Approaches for Evaluating Meat Quality

Classification Principle	Meat Type	Objective of the Study	Technique Used	Basis of Classification	Key Determining Factors	Resulting Meat Characteristics	Reference
Anatomical	Meat from various species	Integrating 3D scanning and virtual reality for instruct meat categorization	Computer-based instruction with 3D models and immersive virtual reality (VR)	Variables such as species, age, quality, and processing techniques	Muscle structures	VR can foster stronger medium-term retention of complex material during visualization	Hadžiomerović *et al.*, 2025
Physiological	Chicken skeletal muscles	To investigate the presence, types, deposition, and effects of microplastics (MPs) in chicken skeletal muscle	Pyrolysis–gas chromatography–mass spectrometry, laser direct infrared imaging spectrometry, oral exposure feeding experiment (>21 days)	Breast muscle and leg muscle	Polystyrene microplastics (PS-MPs) exposure reduced meat quality but increased the muscle weight of chickens	PS-MPs feeding can affect the expression of genes related to neural function of chicken	Chen *et al.*, 2023
Biochemical	Duck meat derived from Pekin duck and Liancheng duck crosses	To elucidate the genetic and biochemical bases of meat nutrition and flavor in duck skeletal muscle	Metabolome-Based Genome-Wide Association Studies	Skeletal muscle meat	Genetic variations, metabolite profiles	The nutritional status can be improved through selective breeding	Liu *et al.*, 2023
Myoglobin content	Mutton (6-month-old Tan sheep)	To determine the content of oxymyoglobin (OxyMb) and metmyoglobin (MetMb) in mutton	Spectral image fusion, modeling approaches—LSSVM (least squares support vector machine) and PLSR (partial least squares regression) models	Based on meat color	Myoglobin content and chemical state	Bright red (high OxyMb) indicates freshness; brownish (high MetMb) indicates oxidation	Wan *et al.*, 2023

Muscle fiber type	Porcine meat (pork)	To compare the similarities, physicochemical properties, and muscle fiber characteristics of different porcine skeletal muscles	Muscle fiber characterization and hierarchical cluster analysis	Differentiated muscles fan-shaped, fusiform, and strap for the parallel group, and unipennate, bipennate, and multipennate for the pennate group	Muscle architecture, muscle fiber composition	The porcine skeletal muscles show variation in color, moisture, and fiber composition,with oxidative fiber-rich and larger-fiber muscles being redder, while intrinsic properties of each muscle strongly influence meat quality	Park *et al.*, 2022
Meat color	Poultry meat	To assess the effects of pulsed light PL on meat quality, including color changes and volatile compound profiles	Pulsed light (PL) treatment	Breast muscle	Changes observed in lightness, redness, and yellowness after PL treatment	PL treatment of poultry meat reduces general bacterial load, slightly modifies color, and alters volatile compounds, with potential implications for safety and flavor	Baptista *et al.*, 2022
Techno-functional properties	Pork meat batters	To investigate the effects of chickpea protein isolate (CPI, 0.5–2%, w/w) on the techno-functional properties of 50% reduced-phosphate pork meat batters	Rheological analysis, Raman spectroscopy, gel network observation	Functional property-based classification	CPI concentration, phosphate reduction	CPI supplementation in reduced-phosphate pork batters enhances water retention, texture, color, and molecular gel structure, producing meat products with quality similar to traditional high-phosphate formulations	Wan *et al.*, 2023

to evaluate quality, processing suitability, consumer acceptance, and nutritional traits across different varieties of meat. Advanced techniques such as 3D scanning, spectroscopy, modeling, and functional protein analysis help link these factors to specific meat characteristics, including tenderness, color, water retention, and techno-functional properties.

Overall, the principles of meat classification integrate anatomical, biological, functional, cultural, and regulatory factors to evaluate quality, safety, and processing performance. Emerging technologies like cultured meat highlight the basic necessity to combine scientific understanding with sociocultural and regulatory considerations for sustainable meat systems.

14.5 Major Categories of Meat

14.5.1 Red Meat

Red meat is a term predominantly associated with meat obtained from mammals and includes beef, mutton (lamb), goat meat, and pork and has emerged as one of the most popular types of meat in both developed and developing nations because of its distinctive taste and flavor and high nutritional value (McAfee *et al.*, 2010). Red meat has been a component of the typical diet of humans throughout evolution and has also allowed our body to adapt to the consumption of red meat over a period of thousands of years because red meat contains high biological value proteins and a large concentration of essential bioavailable nutrients (Giromini and Givens, 2022). Figure 14.1 illustrates the classification of red meat.

Beef is one of the most popular red meat species worldwide; its production is impacted by the availability of feed; additionally, the sociocultural aspects in various countries contribute to its production FAO, STAT (2020). Beef is also considered a nutrient-rich protein; its nutritional components include

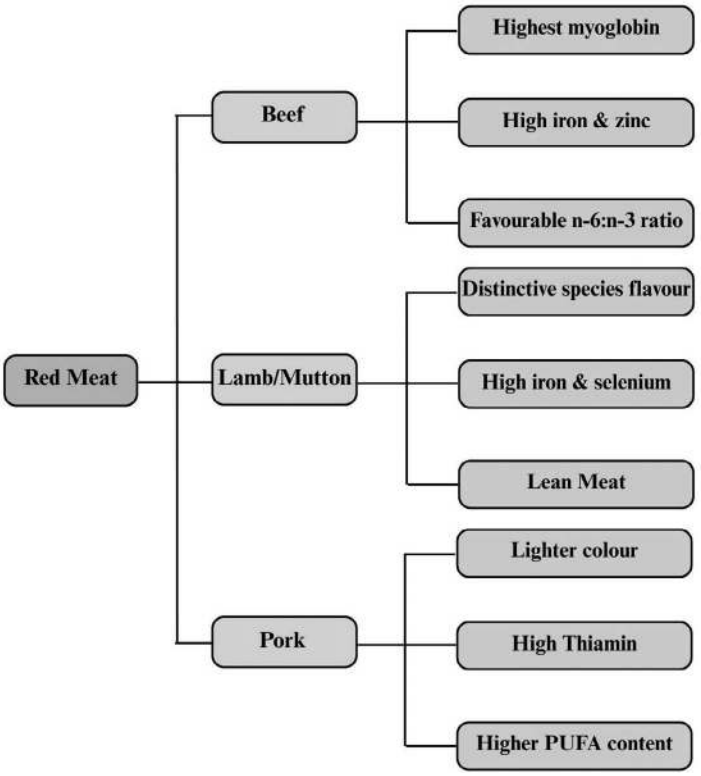

FIGURE 14.1 Classification of red meat.

essential amino acids, vitamins, and various nutrients (Ribas-Agustí *et al*., 2019). It is also related to the sensory aspect of the product; its texture involves attributes of tenderness, toughness, cohesiveness, and mouthfeel (Hall, Schonfeldt and Pretorius, 2016). Lambs and mutton are preferred because of their unique flavor and nutritional value. Lamb meat contains a variety of high-quality proteins and vitamins like iron, zinc, and selenium, which make up essential fatty acids required by the body for immunity support, oxygen transport, and protection of the body from oxidative stress (Fowler, Morris and Hopkins, 2019).

However, it is important to appreciate the fact that lamb meat contributes up to 50% of the daily iron requirement for men and older women (Williamson *et al*., 2005). Pork is also classified as red meat because of the amount of myoglobin it comprises and the nutrient it holds (Keeton and Dikeman, 2017). In comparison to beef, certain types of pork may have less total fat, particularly pork loin, while offering more linoleic acid. In fact, pork loin/leg meats may even have less fat than chicken with skin (Damigou, Kosti and Panagiotakos, 2022). Pork stands out for being a rich source of B vitamins, including thiamin, niacin, riboflavin, and Vitamin B, as well as phosphorus, potassium, and zinc (Vicente and Pereira, 2024).

Physiochemical characteristics of red meats, namely, their colors, WHC, tenderness, and lipid profile, are of prime importance for their acceptability as well as nutritional value. Beef muscle tissues are categorized into proteins and fats; they also have zero carbohydrates with no dietary fiber. Beef proteins are deficient in no essential amino acids like leucine, lysine, methionine, or valine necessary for the metabolic processes in the human body (Olaoye, 2011). The process by which the body digests proteins from beef may have biological activities and possible benefits to the body (Cabrera and Saadoun, 2014). IMF (marbling) is the most important attribute influencing palatability, juiciness, and flavor development during cooking. In mature beef, the IMF usually consists of about 45–48% SFAs, 35–45% MUFAs, and up to 5% PUFAs (Scollan *et al*., 2014).

The P:S ratio in beef is generally low (~0.1), although higher values have been reported for leaner animals. Significantly, beef has a good n-6:n-3 fatty acid balance—usually <3—due to the presence of favorable n-3 fatty acids like α-linolenic acid, EPA, DPA, and DHA. About 80% of the total fatty acids in beef are SFAs, with the predominant components being myristic (14:0), palmitic (16:0), and stearic (18:0), while oleic (18:1) is the major MUFA, accounting for almost one-third of the total fatty acids (Abbas, Mohamed and Jamilah, 2009). Though the adequate marbling of meat makes the meat more palatable, higher lipid oxidation may impair storage stability as well as nutritional quality (Wood *et al*., 2008). Red meat is well acknowledged for its superior protein nutritional value. It is complete in all essential amino acids and has better digestibility. Further, red meat is the most valuable nutritional source of heme iron. Moreover, the Fe content of red meat has very good bioavailability as compared to plant-based Fe. Additionally, red meat is the valuable source of some essential nutrients like zinc, selenium, phosphorus, and B vitamins. Here again, only vitamin B is not available in plant-based foods (Biesalski, 2005). Table 14.2 demonstrates the nutritional and physiochemical aspects of red meat.

Therefore, current research studies concentrate on more nutritional approaches based on better feeding practices for more innovative processing of red meats with a better nutritional value (McNeill and Van Elswyk, 2012).

14.5.2 White Meat

White meat, primarily poultry meat and rabbit meat, is viewed as a significant alternative to red meat. When compared to red meat, white meat has been found to have lower total fat, saturated fat, heme iron content, and a generally lower contribution to greenhouse gas emissions. Therefore, white meat is more acceptable and appealing from a health and sustainable perspective (Ramel *et al*., 2023). Poultry meat, namely, chicken and turkey meat, is a significant source of high-quality protein. Poultry meat is a good source of all essential amino acids with high digestibility and high biological value. Lean poultry meat like skinless chicken or turkey has a significantly high amount of protein (about 20–30% in 100g of meat) with a low amount of fat (~2–4% in 100g of meat), thus making it more acceptable in terms of a high protein and low-fat ratio and ideal according to healthcare suggestions for weight control and cardiovascular health (Connolly and Campbell, 2023; Zhang *et al*., 2025).

TABLE 14.2

Nutritional and Physiochemical Aspects of Different Red Meat

Nutritional and Physiochemical Aspect	Beef	Lamb/Mutton	Pork	References
Protein quality	Higher biological value and complete essential amino acid profile	Higher quality of protein	Higher quality of protein	Olaoye, 2011; Giromini and Givens, 2022
Micronutrients	Presence of iron, selenium, phosphorus, and B-complex vitamins	Presence of zinc, iron, and selenium	Rich in B-complex vitamins such as thiamine, niacin, riboflavin, and vitamin B_{12}	Biesalski, 2005; Fowler, Morris and Hopkins, 2019; Vicente and Pereira, 2024
Intramuscular fat composition	*SFA*: 45–48%, *MUFA*: 35–45% *PUFA*: less than 5%	Fat profile like ruminant	Presence of higher linoleic acid	Scollan *et al.*, 2014
Sensory attributes and physiochemical characteristics	Juiciness and tenderness Flavor influenced by marbling	Species-specific variation in traits	Mild in flavor and acceptable texture pH sensitive	Hall, Schonfeldt and Pretorius, 2016;

Data from epidemiological studies indicate that moderate consumption of white meat is not significantly associated with adverse cardio-metabolic outcomes but is even more beneficial than consumption of red meat; there are no significant risks of developing type 2 diabetes mellitus and cardiovascular diseases (Damigou, Kosti and Panagiotakos, 2022). Rabbit meat, although not as widely consumed as poultry meat, is of high nutritional standpoint as low-fat and calorie-dense meat that is highly digestible. Rabbit meat has high moisture and moderate-to-high protein content (around 20–22%), low total and saturated fat, and lower cholesterol than most common red meats, in addition to a balanced amino acid composition which supports good human nutrition (Combes, 2004). Its nutritional quality can be further enhanced through dietary strategies, including n-3 fatty acid enrichment of this meat with high value as a functional lipid composition (Petracci, Bianchi and Cavani, 2009). Rabbit meat has been compared and found to have advantages over beef and pork meats with low fat and cholesterol content but with a comparable and indeed better content of various macronutrients and micronutrients that qualify it as a health-promoting white meat (Nistor *et al.*, 2013).

Sensory-wise, white meat is considered tender and has a mild taste. Nevertheless, muscle pathology may have some effects on texture. Investigations using broiler breast fillets affected with Woody Breast (WB) myopathy have resulted in greater hardness, cohesiveness, and chewiness in extreme cases but may have no effect on juiciness and breakdown time (Brambila, Bowker and Zhuang, 2016). Detailed analyses based on white striping, woody breast, and spaghetti meat myopathies have shown that despite technological properties such as cooking loss values and shear force values being significantly affected, consumer-defined values in relation to acceptance and preference, specifically in terms of acceptability and taste, have been less affected in mild and moderate cases (Bošković Cabrol *et al.*, 2024). Cooking techniques, such as sous-vide processing, can also help to reduce texture variations caused by muscle microstructure differences (Lee *et al.*, 2021).

About consumer preferences and market dynamics, white meat, and particularly chicken, represents a considerable share of the global meat market and is also increasing rapidly due to perceived health benefits, affordability, and ease of availability and processing compared with red meat (Henchion *et al.*, 2014). Market surveys have identified a mainstream choice of chicken meat, mainly in South Asia, due to its for taste, accessibility, and overall economic viability (Magdelaine, Spiess and Valceschini, 2008). The critical specifications concerning visual appearance, such as color uniformity and the absence of defects, exhibit substantial importance in actual consumer purchasing decisions (Grzybowska-Brzezińska, Banach

and Grzywińska-Rąpca, 2023). Additionally, demographic factors have also been evidenced among women who constitute a considerable market segment where most women have evidenced a substantial preference for chicken meat based primarily upon tenderness and texture (Mohan, Maheswarappa and Banerjee, 2022). Though chicken leads in the global white meat market, rabbit meat has emerged with considerable niche preferences mainly based on nutritional and sustainability advantages than chicken.

14.5.3 Game and Wild Meat

Game and wild meats include meats harvested from non-domesticated or semi-domesticated free-ranging animals like venison (types of deer), wild boar (*Sus scrofa*), wild rabbits (*Oryctolagus cuniculus*), hares, and other harvested game varieties. Contrary to meats harvested from conventionally raised farm animals, game meats' quality and characteristics tend to depend largely on their natural dietary patterns and sources, as well as their intense exercise behaviors (Hoffman and Wiklund, 2006). Due to higher concentration levels of myoglobin associated with their intense physical activities, game meats tend to be red meats and are generally tougher and darker compared to meats derived from more normally raised livestock sources (Hoffman *et al.*, 2007).

One of the characteristics defining game and wild meat is its low IMF and high protein density. Deer meat, which is one of the most researched game meats and is highly regarded in Europe, New Zealand, and North America, is particularly valued for its high biological value protein, low total fat, and low saturated fatty acid content (Hoffman and Wiklund, 2006). The fat component in deer meat is particularly remarkable in because of its high polyunsaturated to saturated fatty acid (PUFA/SFA) ratio and its high concentration of n-3 fatty acids; this tends to denote its natural grazing diet (Wiklund, Farouk and Finstad, 2014). In contrast, the IMF in wild boar meat tends to be generally lower and its protein higher than pig meat from domesticated pigs; moreover, its fat tends to be richer in PUFA (Sales and Kotrba, 2013). The greater darkness and stronger flavor of boar wild meat tend to be linked to its greater physical activity, which results in higher myoglobin values; thus, it is very different from typical pig meats.

The meat of wild rabbits has a special role because it combines the characteristics of both white meat and red meat. It is rich in protein, contains low amounts of fat and cholesterol, and a balanced amino acid and mineral composition (Dalle Zotte & Szendrő, 2011). Compared to the meat of domesticated rabbits, the meat of the wild variant tends to have a higher protein content and a higher concentration of PUFA because of a greater consumption of natural flora and a higher level of locomotor activity (Hernandez and Gondret, 2006). Game meat can also be differentiated based on its distinctive characteristics. The taste might be termed strong, earthy, and "gamey", which can be attributed to foraging, age, habitat, and certain levels of myoglobin and volatile compounds (Daszkiewicz *et al.*, 2012). Wild rabbit meat has a stronger but finer flavor than farmed rabbit meat, which can be attributed to a varied diet and a highly active lifestyle.

In addition to nutritional and organoleptic properties, ethics, safety, and sustainability represent other dimensions in the assessment of game and wild meat. Under a sustainability analysis, regulated hunting may contribute to a ecological balance, protect crops from damage, and help in managing biodiversities, in addition to being a low-subsidy source of protein (Wiklund, Farouk and Finstad, 2014). Deer meat and wild rabbit meat have been regarded in several reports as ecologically sustainable sources in local food chains, (Daszkiewicz *et al.*, 2012). However, food safety is still a major concern because of the lack of standardized slaughterhouses and controlled veterinary inspections, as seen in other commercial meat sources. Microbiological hazards such as *Salmonella* spp., *Campylobacter* spp., *Listeria monocytogenes*, and *Yersinia enterocolitica* have been identified, especially in wild boar and deer (Avagnina *et al.*, 2012). Chemical hazards, especially those derived from the use of lead ammunition, are also a potential concern for public health, especially when consumed regularly by sensitive populations such as pregnant females and those within the age bracket considered to be children (Pain *et al.*, 2010). Therefore, appropriate postharvest food hygiene, proper ammunition selection, and proper cold chain management are critical for maintaining game and wild meat quality (Gill, 2007).

14.6 Specialty and Nonconventional Meat Sources

14.6.1 Organ Meats (Offal): Nutrient Density and Functional Properties

Because of their remarkable micronutrient profiles, organ meats, often known as offal, which include liver, kidney, heart, tongue, and tripe from a variety of animal sources, are underappreciated yet extremely nutrient-dense protein sources. B complex vitamins such as B, B, B, and folic acid, minerals, important polyunsaturated fatty acids, and amino acids with amounts similar to those found in muscle tissue are among the essential nutrients that have long been known to be abundant in offal. Organ meats are more nutritious than traditional muscle meat cuts the chemical makeup of these meats varies greatly based on the particular organ type and animal species. Sheep offal had the highest lipid content at 7.74%, indicating species-dependent compositional variations, while beef and goat liver had the highest protein content at 27.81% and 27.50%, respectively (Biel, Czerniawska-Piątkowska and Kowalczyk, 2019).

The increased mineral and trace element bioavailability of organ meats is one of their most important nutritional benefits. The naturally occurring phospholipid and protein fractions in cow offal, especially the kidneys, lungs, and heart, can increase the absorption of less bioavailable nonheme form of iron from plant sources, fortified foods, and supplements by about 200%. Furthermore, the liver is remarkably rich in phospholipids, especially phosphatidylcholine, which makes up more than half of hepatic phospholipids second only to bovine brain and egg yolk. The trace elements zinc, iron, copper, manganese, and selenium are abundant in almost all animal by-products, especially organ meats, and their nutrient levels and quantities are usually higher than those of muscle tissue. For instance, organs often have much higher iron concentration than muscle tissue, such as musculus semitendinosus, while the liver and kidneys of cows are rich sources of zinc and can help compensate for zinc deficiencies.

14.6.2 Seafood as Meat: Fish, Shellfish, and Crustaceans

Compared to terrestrial meat sources, seafood such as fish, mollusks, and crustaceans offers better nutritional advantages. Based on IMF content and composition, fish are often divided into two basic categories, namely, oily fish and white fish. At least 10% of the edible portion by weight of oily fish, such as salmon, sardines, mackerel, and tuna, contains fat. This fat is primarily composed of omega-3 fatty acids—eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), which are found throughout muscle tissue (Zhang *et al.*, 2017). The recommended daily consumption of 250–500 mg of omega-3 fatty acids is significantly exceeded by the 1,200–2,400 mg found in a normal 4-ounce portion of salmon. Mackerel can give up to 2,600 mg per serving, compared with about 1,100 mg per serving from sardines. Fish species and feed composition have a significant impact on their omega-3 concentration. Generally speaking, farmed fish have higher amounts of EPA and DHA than wild-caught fish, although this is largely dependent on feed formulations. According to recent assessments, the replacement of conventional marine ingredients with alternative feed components resulted in a considerable drop in the EPA and DHA content of farmed Atlantic salmon between 2006 and 2015 (Van Horn *et al.*, 2016).

Moreover, cod, snapper, and flathead are examples of white fish species that have significantly lower IMF content (1–3% by weight), with fat stores mostly found in hepatic tissues rather than muscle tissue. Because of this compositional difference, cod has a lower caloric density (90–120 calories per 4-ounce portion compared to 200–250 calories for salmon), but it still has high-quality protein with all essential amino acids and vital minerals, including phosphorus, selenium, and B vitamins. While both types of fish offer important nutritional components, white fish has a significantly lower omega-3 content than oily fish. Krill oil, which mostly contains omega-3 as phospholipids, shows greater bioavailability than triglyceride-bound omega-3 present in fish oil formulations, especially at lower dosages, according to recent bioavailability studies comparing omega-3 PUFA sources (Pham *et al.*, 2024).

Highly specialized seafood groups with unique micronutrient profiles are shellfish and crabs. When compared to crustaceans or finfish, mollusks which include clams, mussels, oysters, and cephalopods

show noticeably greater quantities of zinc, magnesium, and selenium. In particular, a 100-g portion of oysters provides more zinc than the recommended dietary reference intake due to their very high zinc content. For every 100 g, mollusks supply more than 20% of the daily value of iron, zinc, vitamin B12, and omega-3 fatty acids. Among shellfish species, clams are known to have the greatest vitamin B12 content (Jayasekara *et al.*, 2020).

14.7 Emerging and Alternative Meat Categories

14.7.1 Plant-Based Meat Analogues: Formulation, Composition, and Nutritional Profile

Plant-based meat analogs (PBMAs), are quickly becoming more popular substitutes for traditional meat products due to ethical, health, and environmental concerns about sustainable food production. Proteins (20–50%), polysaccharides (2–30%), and lipids (0–5%) are the primary ingredients in PBMA formulation, which utilizes metabolic similarities between plants and animals. Second- and third-generation PBMAs now use a variety of protein sources, such as pea, wheat, lentils, potatoes, rice, and algae, in addition to microorganism-based proteins, going beyond the early soy-based formulations. Achieving the intended texturization, binding, and nutritional results requires effective ingredient synergy. While other components improve flavor, color, and nutritional value, the functionality of proteins is especially crucial in determining structural properties (Jang and Lee, 2024).

Comparative nutritional studies indicate that plant-based meat substitutes differ considerably from traditional meat products in terms of proximate composition and physicochemical characteristics. Compared with similar meat products, meat alternatives have significantly reduced fat content, higher protein concentrations, and varied water levels, which reflect differing production techniques and desired textural qualities. Although they often have a lower total protein level, plant-based meat substitutes frequently have higher dietary fiber content than traditional meat products. Many plant-based meat substitutes have a lower salt content than processed meat products, although they may still be higher in salt than raw meat products. The ingredient lists of all plant-based products are generally longer than those of comparable animal meat products, and they are mostly made up of highly refined materials. This has led to industry criticism regarding the characteristics of processed products (Daszkiewicz *et al.*, 2023).

Comparing commercially available plant-based meat and dairy substitutes to their animal-based counterparts, essential amino acid (EAA) profile reveals systematic shortages in particular amino acids. When compared to their animal-based counterparts, the majority of plant-based analogues have substantially reduced total protein levels (80% of meat analogues, 100% of lunch meat and cheese analogues, and 90% of milk and yogurt analogues). Methionine deficiency is present in all examined meat analogues (varying from 2% to 73% lower than reference patterns), with 55% of meat analogues having lower levels of each individual EAA than minced beef. Three plant-based burger types were shown to have a lysine shortage (47–62% lower than reference patterns). Despite individual amino acid imbalances, the average total essential amino acid concentration of meat analogues is 430 mg/g protein (standard deviation 48), which is comparable to beef (422 mg/g protein, standard deviation 54) (Domić *et al.*, 2025).

14.7.2 Cultivated (Lab-Grown) Meat: Cellular Agriculture and Production Challenges

Cultivated meat, also known as cell-based meat or lab-grown meat, is made by cultivating animal cells *in vitro* under conditions free from illness and bacterial contamination. Using muscle cells, fat cells, and other tissue types that are grown in specialized bioreactors with the right growth media and nutrients for cellular replication and development, this new category marks a significant break from traditional animal agriculture (Anang and Fuseini, 2023). The production process begins with stem cells derived from animal tissue or umbilical cord sources. These cells are then cultivated under carefully regulated

temperature, oxygen, and nutrient conditions. In 2020, Singapore became the first nation to provide regulatory approval for the commercialization of cultivated meat. Founded in 2005 and beginning commercial production in 2015, Memphis Meats produced the first cell-based meatball in history in 2016 and chicken products in 2017 (Chandrababu and Puthumana, 2024).

The main benefits of farmed beef go beyond nutritional factors to include significant ethical and environmental advantages. Compared to traditional animal husbandry, the production of farmed meat has the potential to reduce land use by 99%, water consumption by 90%, and energy consumption by 40%. Additionally, significant greenhouse gas emissions, such as carbon dioxide, methane, and nitrogen oxide gases, are eliminated by cultivation. Conventional livestock production raises ethical and welfare issues because it does not subject animals to stress or cruel treatment (Greenwood, 2021).

14.7.3 Insect-Based Proteins: Nutritional Quality and Sustainability

Black soldier fly larvae (*Hermetia illucis*), mealworms (*Tenebrio molitor*), crickets (*Acheta domesticus*), and silkworm pupae (*Bombyx mori*) are examples of edible insects that have emerged as promising sustainable protein sources with nutritional profiles that are comparable with or better than conventional animal and plant-based proteins. High-quality complete proteins with balanced compositions that are rich in essential amino acids are found in insects. These proteins beat many conventional plant proteins in terms of nutrition and compare favorably with animal proteins. Black soldier fly larvae have a dry matter protein content of 37–63% and a polyunsaturated fatty acid content of 7–39%. Black soldier fly larvae are a great alternative source of protein since their amino acid makeup satisfies World Health Organization standards (Bußler *et al*., 2016). Over 50% of insect protein showed digestion under simulated human gastrointestinal circumstances, showing good bioavailability. Digestion of insect proteins varies from 54% for *T. molitor* to 98% for some species examined in Mexico. There are no appreciable variations in the rates of postprandial muscle protein synthesis in humans between proteins of insects, such as those from mealworms, and milk-derived proteins in terms of digestion and amino acid absorption. Depending on method of food processing and food preparation techniques, mealworm larvae and crickets can offer an ideal protein quality comparable to chicken breast, according to in vitro Digestible Indispensable Amino Acid Scores (DIAAS) (Kim *et al*., 2019).

In the context of global food security, the sustainability benefits of insect-based proteins are strong. In circular economy models, edible insects encourage waste reduction and nutrient recycling through efficient feed-to-protein conversion and low land and water requirements. Black soldier fly larvae can efficiently reduce the load of organic waste by converting home and agricultural waste materials into nutrient-dense biomass. *T. molitor* has shown exceptional value in a variety of applications, such as the bioconversion of domestic and agricultural waste and the degradation of plastic, thanks to advancements in breeding technology (Iannielli *et al*., 2025). It has emerged as especially promising during times of interruption to international trade. Despite these benefits, there are still significant obstacles still limit the widespread use of insect proteins in food systems, such as the possibility of allergies, the instability of their functional characteristics, and the lack of thorough regulatory frameworks. For safe use, improved processing technologies and regulatory frameworks are necessary because allergenicity is still a major concern. Another significant obstacle is consumer acceptance, which calls for design interventions and knowledge sharing to boost inclination to include insects in eating habits (Sharma *et al*., 2024).

14.8 Factors Influencing Meat Quality

14.8.1 Animal Genetics, Breed, and Nutrition

Animal genetics, breeds, and nutritional background represent the primary determinants of meat quality, affecting parameters like meat tenderness, color, pH value, deposition of IMF, and meat palatability. Beef also reveals marked variations in the nanostructures of muscles fibers, and pH, color, tenderness, and hardness based upon cattle breeds and categories. Bonsmara, Nguni, and non-descript cows and

heifers show marked variations in the diameters and lengths of muscles based upon breeds and types, with smaller and longer fibers contributing to enhanced tenderness. Nguni steers also demonstrate highest meat quality potential based upon final pH value, color parameters (L^*, a^*, b^* values), and Warner–Bratzler shear force values, revealing the prime utility of cattle selection based upon breeds to increase meat tenderness (Chulayo and Muchenje, 2016).

Genetic background has a significant impact on the processes of postmortem proteolysis and muscle structure that can ultimately have a significant effect on meat tenderness. Breeding programs are becoming increasingly focused on selecting animals with desirable tenderness traits for improved meat quality consistency (Petričević *et al*., 2017; Santos *et al*., 2021).

Muscle and fat proportions are known to differ among breeds. Angus breeds are known to possess good marbling and tenderness, while heritage breeds of pig and chicken are valued for their distinctive flavor (Huo *et al*., 2021). Muscle fiber types differ among breeds. Slow-twitch oxidative muscle fibers contain more myoglobin and possess better color properties than fast-twitch glycolytic muscle fibers (Haunshi *et al*., 2022). Pure breeds are known to possess better redness and color properties than crossbreed animals, thereby reiterating the significance of breeds and their effects on meat quality (Salim *et al*., 2018).

Feeding systems, in combination with genetic factors, influence meat quality. Pasture-fed systems improve the omega-3 fatty acid content, stability against oxidation, natural antioxidants, red color, shelf life of meat (Horcada *et al*., 2020; Nogoy *et al*., 2022). There exists a synergetic effect of genetic factors, breed, and nutrient content on the influence of factors such as tenderness, color stability, lipid oxidation, and fat quality of meat.

The intrinsic, extrinsic, management-related, and post slaughter factors influencing meat quality, together with their key components, effects, and representative outcomes, are summarized in Table 14.3.

TABLE 14.3

Factors Influencing Meat Quality

Category	Factor	Key Components	Effect on Meat Quality	Representative Outcomes	References
Intrinsic Factors	Genetic selection	Genomics, selective breeding, marbling-associated markers	Improves tenderness, marbling, flavor, muscle-to-fat ratio	Breeding for superior carcass traits and lean meat production	Mohammadabadi *et al.,* 2021; Talebi *et al*., 2022; Poveda-Arteaga *et al*., 2023,
	Breed characteristics	Breed-specific muscle and fat composition	Determines texture, juiciness, and sensory quality	Angus cattle show superior marbling Heritage breeds yield distinctive flavor	Huo et al.,, 2021,
	Muscle type	Fast-twitch and slow-twitch fiber composition	Impacts tenderness, connective tissue content, and fat deposition	Fast-twitch muscles are more tender; slow-twitch muscles are leaner	Haunshi et al., 2022
	Environmental adaptation	Climate-driven physiological adaptation	Alters fat thickness, marbling, and juiciness	Cold-climate animals have higher fat deposition Hot-climate animals produce leaner meat	Marmion *et al*., 2022
Extrinsic Factors	Animal diet	Forage, grains, nutrient profile	Modifies fatty acid composition, flavor, and nutritional value	Diet influences omega-6/omega-3 ratio and sensory quality	Bostami *et al*., 2023

(Continued)

TABLE 14.3 ***(Continued)***

Factors Influencing Meat Quality

Category	Factor	Key Components	Effect on Meat Quality	Representative Outcomes	References
	Grass-fed vs. grain-fed systems	Finishing method	Influences marbling, CLA, antioxidants, tenderness, and flavor	Grass-fed beef is leaner with higher omega-3 While grain-fed beef has greater marbling	Logan *et al.* (2021); Davis *et al.*, 2022
	Dietary supplementation	Fish oil, flaxseed, herbs, vitamin E	Improves omega-3 content, oxidative stability, and shelf life	Antioxidant-rich diets improve color and storage stability	Saini *et al.*, 2021
Animal Management Practices	Stress and handling	Housing, transport, overcrowding	Affects muscle metabolism, water-holding capacity, and appearance	Stress causes PSE in poultry and DFD in beef	Hussein 2021; Ismail & Huda 2024
	Low-stress management	Proper housing, gentle handling	Reduces cortisol, improving texture and shelf life	Prevention of pale and dark meat defects	González-Blanco *et al.*, 2023
Post-slaughter Handling & Processing	Carcass chilling & cold chain	Cooling rate, cryogenic freezing	Maintains microbial growth and texture deterioration	Rapid chilling prevents spoilage and off-flavors	Pogorzelski *et al.* (2022); Álvarez *et al.*, 2022; Verma *et al.*, 2022; Kannan *et al.*, 2021
	Slaughter methods	Electrical & controlled-atmosphere stunning	Reduces stress, enhances tenderness and safety	Improved meat color and texture	Pogorzelski *et al.*, 2022
	Meat aging	Wet aging, dry aging, enzymatic tenderization	Enhances tenderness and flavor	Dry aging improves flavor intensity Wet aging retains moisture	Pogorzelski *et al.*, 2022
	Packaging and preservation	MAP, vacuum sealing, antioxidants	Maintains color, texture, and shelf life	Reduced oxidation and microbial growth	Jaspal *et al.*, 2022

14.8.2 Age, Sex, and Physiological Condition

IMF accumulation is an important factor in meat quality, starting from fetal life. In the bovine, the initial IMF cells are established around day 180 of gestation, with hyperplasia persisting until about day 250, followed by fat accumulation largely because of hypertrophy of already-existing adipocytes, especially during the finishing stage (Ladeira *et al.*, 2018; Nguyen, Nguyen and Malau-Aduli, 2021). Adipogenesis is the cellular process of differentiating mesenchymal stem cells into preadipocytes and mature adipocytes, while lipogenesis is concerned with regulating the processing of fatty acids. In ruminants, intramuscular adipocytes are known to use glucose selectively for the production of fatty acids, while subcutaneous adipocytes metabolize acetate primarily for fat accumulation (Du, Ford and Zhu, 2017; Nguyen, Nguyen and Malau-Aduli, 2021).

Sex and physiological status play important roles in IMF deposition and meat quality. Heifers tend to have higher marbling than bulls of similar production, which can be attributed to the role of sex hormones on adipocyte metabolism (Picard *et al.*, 2019). The meat of females tends to have lower shear force values than that of males in cattle and buffalo, suggesting it is more tender (Andrade *et al.*, 2021). However, castration affects fat deposition, which tends to be higher in castrated males than in intact males, suggesting an interaction between sex, hormones, and marbling (Zhdanov *et al.*, 2025).

Furthermore, age is an important consideration that affects meat quality. As age increases, progressive collagen cross-linking contributes significantly to meat toughness. However, baseline meat toughness can be moderated by physiological conditions, resulting in an effect on fat deposition, marbling, or muscle growth, ultimately affecting meat tenderness as well as acceptability (Kopuzlu *et al.*, 2018). Although toughness is higher, juiciness may increase because of higher IMF deposition due to hypertrophy as well as hyperplasia. More mastication work also acts as a major trigger to stimulate saliva production, ultimately influencing juiciness (Baik *et al.*, 2023; Soulat *et al.*, 2018; Soulat, Picard and Monteils, 2023).

Overall, age, sex, and physiological status interact with nutrition and muscle characteristics to shape marbling, tenderness, and juiciness, making these factors essential considerations for improving meat quality and consumer satisfaction.

14.8.3 Slaughter Practices and Antemortem Stress

Although marbling is largely determined during growth, management practices such as slaughter age, slaughter weight, and castration can indirectly influence IMF deposition by modifying growth rate and fat distribution (Nguyen, Nguyen and Malau-Aduli, 2021).

Antemortem factors or preslaughter handling and antemortem stress play important roles in meat quality. The consequences of suboptimal slaughter practices, transportation stress, congestion, and antemortem stress include elevated stress hormones in the bloodstream, which lead to glycogen depletion and modification of postmortem pH reduction (Della Rosa, Pouzo and Pavan, 2018; Gonzalez-Blanco *et al.*, 2023; Hussein, 2021). The effects of these postmortem pH reductions include unfavorable meat characteristics, such as those of broiler meat referred to as not desirable, which include PSE, and DFD meat in beef (Birhanu, 2020; Warriss, 2020; Warner, 2023).

Acute stress yields PSE meat with low pH and poor water-holding ability, whereas chronic stress yields DFD meat with high pH and abnormal water-holding properties (Gibson and Newsham, 2018). Although DFD meat has high water-retention ability, this does not necessarily relate to their juiciness or palatability (Reesman *et al.*, 2023). Genetic predisposition to stress, such as halothane sensitivity in pigs, also affects meat quality and juiciness.

In general, preslaughter stress increases the rate of glycogen depletion and L-lactic acid production, thereby increasing ultimate pH and making carcasses susceptible to DFD traits. As such, tenderness, color, pH, WHC, juiciness, and flavor are affected by antemortem practices (Baldi, 2020; Gagaoua *et al.*, 2020). Effective application of slaughter procedures with minimal stress during transportation and lairage is important for ensuring meat quality and consumer satisfaction.

14.8.4 Postmortem Handling: Chilling, Aging, and Tenderization

Postmortem, ATP from anaerobic glycolysis becomes the main ATP-producing pathway, leading to lactic acid production and the subsequent drop in muscle pH. The rate and magnitude of this glycolysis are affected by muscle fiber type, temperature, residual concentrations of glycogen, and myosin ATPase activity, which regulate the rate of rigor mortis development and subsequent tenderization. During rigor mortis, muscles become rigid and stiff as ATP gets depleted and actin–myosin bridges form irreversibly, leading to sarcomere shortening and tougher meat (Gagaoua, Monteils and Picard, 2019; Warner *et al.*, 2021).

The process of proteolysis during aging is mainly mediated through the calpain–calpastatin system and proteasome, although mitochondrial and apoptotic pathways also take part in the tenderization process (Díaz *et al.*, 2020; Gagaoua, Troy and Mullen, 2020). The postmortem pH decline controls the color, WHC, and tenderness of meat; a rapid acidification produces PSE meat, while an inadequate decline produces DFD meat. An ultimate pH within a range of 5.5–5.8 is generally considered to be optimal for eating quality (Sristi *et al.*, 2025).

Carcass chilling rate is another important factor. Rapid chilling prevents microbial growth and the occurrence of quality defect, but when high ultimate pH is combined with it, cold shortening and darker meat color occur (Álvarez *et al.*, 2022; Della Rosa, Pouzo and Pavan, 2018; Pogorzelski *et al.*, 2022). Meat aging, either wet or dry, increases tenderness because of enzymatic proteolysis. Dry aging promotes flavor, while wet aging preserves moisture content. High-marbled beef is greatly responsive to

postmortem aging since the combination of IMF and activity of proteolytic enzyme enhances tenderness perception and overall eating quality of the meat (Baik *et al.*, 2023).

Electrical stimulation and optimized chilling are other postmortem interventions that increase the process of proteolysis, WHC, and palatability (Kaur *et al.*, 2021). Aging increases the juiciness of meat, especially in the initial period after death (14–21 days), by reducing the cross-links of the myofibrillar structure and increasing the WHC (Beldarrain *et al.*, 2020; López-Pedrouso *et al.*, 2020; Sgarro *et al.*, 2022). Excessive aging can decrease juiciness due to the degradation of the structure and the loss of meat fluids (Garmyn *et al.*, 2020; Hastie *et al.*, 2022).

The major biological and postmortem determinants of meat tenderness, including rigor mortis, sarcomere shortening, muscle pH, breed, sex, muscle fiber characteristics, connective tissue content, and IMF, together with their mechanisms and effects on tenderness, are summarized in Table 14.4.

TABLE 14.4

Association of Meat Tenderness with Biological and Postmortem Factors

Factor	Key Mechanism / Indicator	Effect on Meat Tenderness	Important Findings	References
Rigor mortis	ATP depletion → permanent actin–myosin cross-bridges → sarcomere shortening	Increased toughness and rigidity Difficult salting and processing	Rigor onset causes muscle stiffening Complete rigidity at 4 °C in small ruminants occurs within 12–16 h	Greaser and Guo,2012; Chang 2012
Sarcomere length	Shortening during rigor mortis	Short sarcomeres increase shear force (tough meat)	Sarcomere shortening is the main structural cause of toughness	Chang, 2012
Muscle pH	Glycogen → lactic acid → pH decline from ~7.2 to 5.4–5.5	Lower pH generally linked with lower shear force and better tenderness	Acceptable tenderness at pH <5.8 or >6.2 Tenderization is pH-dependent	Li *et al.* 2014; Hamoen, Vollebregt and Van Der Sman, 2013
Breed	Genetic differences in fiber number, CSA, and type	Major variation in beef tenderness among breeds	Angus, Limousin, Jersey, Piedmontese produce more tender meat Blonde d'Aquitaine and Brown Swiss differ in tenderization rate	Marino *et al.*, 2013
Sex	Hormonal and muscle metabolic differences	Meat from females is more tender than males	Confirmed in cattle, buffalo, goats, and lambs	Andrade *et al.*, 2021
Muscle fiber type	Proportion of oxidative versus glycolytic fibers	Fibers type I and IIA are more tender than IIX and IIB	Fiber diameter: I = IIA < IIX < IIB Thin fibers improve tenderness	Joo *et al.*,2013; Lian, Wang and Liu, 2013
Muscle type/ location	Variation in collagen traits and proteolysis	Shear force varies by muscle and anatomical position	Longissimus lumborum tenderness differs from anterior to posterior sections	Hammond, 2017; Xu *et al.*,2018
Connective tissue content	Collagen and elastin concentration and solubility	Higher collagen content increases toughness	Collagen content ranges 1–15% Collagen solubility decreases with age	Astruc, 2014; Nishimura, 2015
Intramuscular fat (marbling)	Fat deposition between fibers	Higher fat generally improves tenderness	Minimum fat: 3–4% for beef, 5% for mutton Fat increase from 5% to 35% reduces shear force by 1.5 kg/cm²	Xu *et al.*, 2020

14.8.5 Chemical, Sensory, and Microbiological Quality Indicators

IMF, or marbling, is a major determinant of flavor, juiciness, tenderness, and color, and thus it is one of the strongest influencers of beef quality. The existence of IMF improves sensory acceptability due to visible white flecks of fat between muscle fibers (Ladeira *et al.*, 2018; Nguyen, Nguyen and Malau-Aduli, 2021; Chen *et al.*, 2023). Marbling is also nutritionally valued due to its higher content of polyunsaturated fatty acid. Marbling develops through hyperplasia and hypertrophy of IMF cells during fetal and neonatal stages, and continues to develop throughout postnatal life by means of adipogenesis and lipogenesis, under the influence of genetics, breed, diet composition, and management practices (Nguyen, Nguyen and Malau-Aduli, 2021).

Juiciness varies significantly among species and breeds. Poultry species such as capon and broiler chicken are generally juicier than goose, turkey, and duck, while lamb and pork typically exhibit higher juiciness than beef and chicken (Damaziak *et al.*, 2019). Within species, Wagyu beef consistently outperforms Angus, Brahman, and Holstein in juiciness (Shahrai *et al.*, 2021). Similar breed-dependent differences have been reported for pork, chicken, lamb, foal, and goose meat attributed in part to variations in IMF content, muscle fiber characteristics, and metabolite composition (Cittadini *et al.*, 2022; Mercan *et al.*, 2022). Even after adjusting for IMF and tenderness, breed differences in juiciness persist, indicating the involvement of additional genetic traits. In processed meat products, formulation standardization often masks breed effects, as controlled levels of moisture, fat, and salt content results in similar juiciness across species or breeds (Mazhangara *et al.*, 2022).

In addition, color stability is mainly determined by myoglobin chemistry and postmortem metabolism (Van Wyk *et al.*, 2021). Connective tissue, especially collagen content and solubility, is one of the main contributors to meat toughness (Terlouw *et al.*, 2021). IMF is negatively correlated with shear force and thus contributes positively to tenderness and overall eating quality (Bonny *et al.*, 2018; Gagaoua, Monteils and Picard, 2019; Xu *et al.*, 2020). Juiciness is mainly determined by releasable meat fluid and WHC, but correlations between WHC and sensory juiciness are sometimes not consistent (Warner, 2023). Muscle fiber characteristics further determine postmortem metabolism, color development, and eating quality.

Marbling can be divided into lean, moderate, or high depending on their IMF content and color distribution on the surface of the meat: pale pink for lean and light meat, bright red for moderate, and darker red with evenly distributed white specks for highly marbled meats, which denote quality beef (Baik *et al.*, 2023; Nguyen, Nguyen and Malau-Aduli, 2021).

Overall, the composite effect of chemical, sensory, as well as microbiological properties defines the nature of meat quality (de Araújo *et al.*, 2022). The antemortem and postmortem factors affecting meat juiciness across different species, muscle types, and processing conditions, together with their definitions and major findings, are summarized in Table 14.5.

TABLE 14.5

An Overview of Factors Influencing Meat Juiciness

Factor Category	Type of Factor	Type of Meat / Species	Juiciness Definition	Key Findings	References
Antemortem factors	Species and breed	Poultry (broiler, turkey, barbarie duck, capon, guinea fowl, goose, ostrich) Beef, pork, lamb, goat, chicken, turkey, ostrich, reindeer, moose, rabbit, hare, roe-deer, beaver, horse, minke whale Cattle striploins LD from cattle and pigs Foal steaks Lamb LTL Goose breast and thigh	Water perceived during mastication Moisture released after three to ten chews	Species significantly differ in juiciness Wagyu beef juicier than Angus Iberian pigs juicier than crossbreds Genotype and rearing system affect juiciness Kartuska goose juiciest Breed differences consistently influence juiciness	Almeida *et al.*, 2018; Cittadini *et al.*, 2022; Damaziak *et al.*, 2019; Khan *et al.*, 2019; Mercan *et al.*, 2022; Michalczuk *et al.*, 2018; Shahrai *et al.*, 2021;

(Continued)

TABLE 14.5 ***(Continued)***

An Overview of Factors Influencing Meat Juiciness

Factor Category	Type of Factor	Type of Meat / Species	Juiciness Definition	Key Findings	References
	Intramuscular fat (IMF)	Beef striploins, pork loins, sausages, dry-cured hams, frankfurters, foal steaks, goose meat, bull and heifer beef	Moisture released during first chews; initial and sustained juiciness	Positive genetic correlation between IMF and juiciness Higher marbling increases juiciness IMF acts as flavor carrier Juiciness plateaus at ~20% IMF Replacement of pork fat reduces juiciness Iberian hams juicier than crossbred	Antonelo *et al.*, 2020; Klehm *et al.*, 2018; Lopez *et al.*, 2020; Mazhangara *et al.*, 2022; Kang *et al.*, 2020; Andrade *et al.*, 2022; Hoa *et al.*, 2019
Postmortem factors	Animal age	Heifer RA muscle, Charolais LD, Parma-style hams, beef, camel LD	Initial and sustained juiciness perception	Older cattle and pigs had higher juiciness due to higher marbling Young bulls less juicy Camel meat showed inverse trend Sustained juiciness increased with age	Soulat *et al.*, 2018, 2023; Suliman *et al.*, 2020
	Cut type	Beef tenderloin, oyster blade, ribeye, striploin, poultry breast and thigh	Fluid on surface and during chewing	Tenderloin and oyster blade highest juiciness Thigh juicier than breast Trained panels detect cut differences more than consumers	Guzek *et al.*, 2016; Liu *et al.*, 2020;
	Preslaughter handling	Beef LTL with different residual glycogen	Initial and sustained juiciness	High residual glycogen and improper handling reduced juiciness PSE meat less juicy DFD meat theoretically juicier but poor keeping quality	Reesman *et al.*, 2023
	Aging regime	Beef, pork, mutton, goat, foal, lamb	Moisture after first two tofive chews	Short-term aging (7–21 days) improves juiciness Prolonged aging may reduce juiciness Breed-dependent aging response	Berger *et al.*, 2018; Hastie *et al.*, 2022; López-Pedrouso *et al.*, 2020; Sgarro *et al.*, 2022; Beldarrain *et al.*, 2020; Garmyn *et al.*, 2020
	Cooking method and DOD	Beef, pork, camel, lamb	Juice perception during chewing	Higher cooking temperature and doneness reduce juiciness Pan-frying and steaming retain juiciness Sous vide often less juicy than oven Frying highest juiciness	McKillip *et al.*, 2017; Hobani *et al.*, 2023; Peñaranda *et al.*, 2017

(Continued)

TABLE 14.5 ***(Continued)***

An Overview of Factors Influencing Meat Juiciness

Factor Category	Type of Factor	Type of Meat / Species	Juiciness Definition	Key Findings	References
	Salt and HPP	Frankfurters, chicken sausages, bacon, hams, rabbit sausages	Moisture perceived during mastication	Salt increases juiciness via water binding NaCl substitution alters juiciness HPP improves juiciness in sodium-reduced sausages but may reduce juiciness at high pressure	Gök *et al.*, 2019;Xue *et al.*, 2017
	MAP and packaging	Beef, lamb, goose, pork sausages	Juice after five chews	High-oxygen MAP reduces juiciness Vacuum-packed lamb juicier than MAP Storage time decreases juiciness	Polkinghorne *et al.*, 2018; Ząbek *et al.*, 2021; Orkusz, 2018

14.9 Applications in Meat Processing and Consumer Choice

Meat quality traits, such as pH, WHC, and meat color, are considered critical in meat processing yield, shelf life, and product appearance. A lower ultimate pH can act as an important factor in enhancing microbial shelf stability, whereas over-acidification can contribute to protein denaturation, drip, and pale meats, hence limiting the efficiency of meat processing (Baldi, 2020). Breakthroughs in omics, particularly proteomics and metabolomics, are gaining momentum in the discovery of biomarkers of meat tenderness, susceptibility, and aging, hence predictive models of meat quality classification and meat processing improvement (Díaz *et al.*, 2020; Gagaoua, Troy and Mullen, 2020).

Fat content and fatty acid profile also contribute significantly to culinary quality, juiciness, and consumer perceptions regarding health benefits. Additionally, breed and rearing practices make differences in IMF accumulation and stability of unsaturated fatty acids, and hence consumer purchase choices (Gagaoua, Troy and Mullen, 2020; Van Wyk *et al.*, 2021).

14.9.1 Marbling and Consumer Preference

Among quality attributes, marbling is very important in beef production. High-marbling beef provides tenderness, flavor, and juiciness in premium markets, while leaner beef is more suitable for processing or low-fat products (Nguyen *et al.*, 2021; Baik *et al.*, 2023; Chen *et al.*, 2023).

Consumers also associate marbling patterns and color of the meats with consumption quality and are even willing to pay higher costs for more marbled beef (Nguyen, Nguyen and Malau-Aduli, 2021). Low IMF meats are usually used for comminuted or cured meats, whereas meats with high marbling are preferred for grilling or steaking purposes (Baik *et al.*, 2023).

14.9.2 Meat Classification and Processing

Meat classification allows processors to choose the appropriate raw material for a particular product. The tender cuts are marketed as fresh meat, while tougher cuts are directed toward minced, restructured, or cooked products. Classification based on tenderness increases consumer satisfaction, and consumption frequency (Felderhoff *et al.*, 2020; Santos *et al.*, 2021; Warner *et al.*, 2021).

Cuts with high connective tissue are suited to value-added products, while well-marbled cuts are reserved for steaks and premium offerings. Packaging technologies such as vacuum packaging and MAP

improve color retention and increase shelf life (Jaspal *et al.*, 2022). Feeding systems impact product characteristics; grass-fed meats are leaner, with a higher proportion of omega-3 fatty acids, while feeding on grain favors marbling and tenderness (Davis *et al.*, 2022; Logan *et al.*, 2021).

Different meat types also vary in myoglobin content, fat composition, and functional properties, affecting suitability for curing, fermentation, or ready-to-eat products (Moussaoui *et al.*, 2026; Zhang *et al.*, 2025).

14.9.3 Juiciness, Tenderness, and Consumer Satisfaction

Juiciness is considered one of the decisive factors for consumer acceptance and purchasing behavior (Andrade *et al.*, 2022; Hastie *et al.*, 2022). The absence of juiciness can reduce the sensory appeal of many products, even when tenderness and flavor meet consumer expectations (O'Quinn *et al.*, 2018). The juiciness of conventional meat can be influenced by selection of species, age, and muscle cut, pH management and process optimization, cooking methods, and preservation techniques like high-pressure processing and modified atmosphere packaging.

Market segmentation is driven by variation in carcass tenderness, in which prime cuts are reserved for steaks and tougher cuts are minced or further processed into various retail meat products (Guzek *et al.*, 2016). Oxidative stability and fat composition further influence suitability for processing and the potential for shelf-life extension (Horcada *et al.*, 2020; Terevinto, Cabrera and Saadoun, 2019).

14.10 Future Perspectives

The quality of meat depends on multifactorial elements such as genetics, nutrition, preslaughter handling, postmortem metabolism, and aging. Stress management in the immediate antemortem period and carcass handling within 24 hours postmortem are critical control points for meeting consistent tenderness, color, and WHC standards (Baldi, 2020; Gagaoua, Troy and Mullen, 2020).

Future studies should focus on the combination of proteomics, metabolomics, and precision livestock management tools to identify reliable biomarkers that can predict the quality of meat at early stages of the production chain. This will allow industry to produce homogeneous, quality products to meet evolving consumer demands.

Despite this progress, the relationships among muscle fiber characteristics, lean meat content, and overall meat quality remain only partially resolved due to limitations inherent to conventional histochemical methods and incomplete knowledge about myofibrillar protein diversity. Integration of muscle fiber typing with proteomics and postmortem proteolytic mechanisms is required, particularly those related to the degradation of proteins mediated by the proteasome, to explain the impact of muscle structure and protein turnover on meat tenderness.

Moreover, marbling and IMF are important determinants of beef quality influenced by genetic factors, maternal and postnatal nutrition, physiological status, and management. Adipogenesis throughout early life and targeted high-energy feeding regimens are important for increasing IMF deposition. The combination of genetic selection and precision nutrition is foreseen to be crucial for improving marbling while maintaining production efficiency, animal welfare, and sustainability (Baik *et al.*, 2023; Nguyen, Nguyen and Malau-Aduli, 2021).

Juiciness is a key sensory driver and is impacted by genetic background, IMF, the age of the animal, the anatomical cut, preslaughter treatments, aging techniques, cooking methods, the addition of salt, and preservation methods. Strategies for improving juiciness include short-term aging, controlled cooking, and good salt management. Furthermore, newer innovations such as phosphate synergy and structural changes have the potential for healthier products (low sodium) in the area of product development.

In plant-based meat analogues, achieving juiciness remains a critical challenge. The improvement in structural design, oil management, and innovative ingredients is essential to bridge the sensory gap with animal meat, thereby supporting sustainability and public health goals (Godschalk-Broers, Sala and Scholten, 2022; Schouteten *et al.*, 2016).

Improvements in genetics, nutrition, and process technologies will lead to even higher quality and more sustainable meat in the future (Naeem *et al.*, 2026). The rise of new protein sources such as cultured meat, plant-based alternatives, and their hybrids is likely to reshape global meat markets, driven by consumers who increasingly consider ethics, the environment, and health (Prajapati *et al.*, 2024; Safwa *et al.*, 2024).

Tenderness, flavor, and juiciness remain as the main sensory parameters determining meat palatability, while juiciness has become particularly important in predicting consumer satisfaction (Garmyn *et al.*, 2020; Liu *et al.*, 2020). Approaches that improve such attributes in both conventional meat and meat analogues are crucial for further development of a more sustainable and consumer-acceptable food system.

Future innovation should also focus on biomarker-based quality prediction, rapid instrumental grading techniques, and diet-based strategies to improve oxidative stability and shelf-life extension, ensuring consistent eating quality and enhancing consumer confidence.

14.11 Conclusion

This chapter shows that meat is a heterogeneous category of foods encompassing red meat, white meat, game, offal, seafood, and newer alternatives like plant-based and cultivated meats. Scientific classification based on anatomical, biochemical, and physiological criteria—myoglobin content, muscle fiber type, and fat composition—accounts for the wide variation in color, texture, flavor, and nutritional quality observed among types of meats. Such a classification provides the basis for predicting processing behavior, culinary performance, and quality characteristics. From an industrial perspective, understanding meat categories aids in proper raw material selection, processing efficiency, and product development. For consumers and nutritionists, this knowledge supports informed dietary choices by understanding the nutrient composition, sensory attributes, and health implications are associated with specific types of meat. Current meat consumption patterns are also influenced by cultural practices, ethics, and sustainability. In the near future, alternative proteins and emerging biotechnologies are expected to further expand meat diversity, and the importance of sound classification systems will remain paramount in securing the quality, safety, and sustainability of food in the future.

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15

Modern Meat Preservation

Chilling and Freezing for Quality Retention in Beef, Poultry, and Pork

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15.1 Introduction

Meat and meat products are major sources of high-quality proteins, essential amino acids, and micronutrients, including minerals and vitamins. Beef, poultry, and pork dominate global consumption and are important for food security and economic development. However, meat is highly perishable due to its high moisture, nutrient-rich matrix, and near-neutral pH, which promote rapid microbial growth and enzymatic and oxidative deterioration post-slaughter (Kim *et al*., 2024; Mwakosya, Alvarez and Ndoye, 2025; Zhang *et al*., 2025).

Early preservation relied on ice and sun-drying, while modern systems use controlled chilling and freezing for consistent temperature regulation and extended shelf life. Rising demand for fresh and processed meat, including ready-to-cook and ready-to-eat products, has accelerated adoption of these technologies. Conventional chilling (0–4 °C) and freezing (–18 °C) are widely used but may cause ice crystal damage, drip loss, and texture and sensory deterioration (Ahmad *et al*., 2025; Jiang *et al*., 2025; Khokhar *et al*., 2025).

Chilling slows enzymatic activity, postmortem reactions, and microbial growth, preserving texture and flavor. However, temperature fluctuations or slow chilling can impair quality. Beef is prone to drip loss and discoloration (Nunes *et al*., 2024), while poultry and pork are more susceptible to lipid oxidation and moisture loss due to finer fibers and higher polyunsaturated fat content (Wang, Zhang and Adhikari, 2024). Freezing suppresses microbial growth and biochemical reactions, but ice crystal formation and recrystallization can damage muscle, increasing drip loss, reducing water-holding capacity (WHC), softening tissue, and altering color (Khokhar *et al*., 2025; Lu *et al*., 2022). Lipid oxidation and protein degradation further compromise nutritional and sensory quality, particularly in poultry and pork (Kim *et al*., 2024).

Advanced preservation approaches, such as rapid freezing, superchilling, cryopreservation, and assisted freezing, have been developed. Superchilling (–1 °C to –2.5 °C) partially freezes tissue water, inhibits microbial growth, and better preserves muscle integrity than conventional freezing. Assisted freezing techniques-including magnetic, electric, and electromagnetic fields, ultrasound pretreatment, and cryogenic freezing-improve ice nucleation and crystal uniformity, enhancing post-thaw texture, juiciness, and sensory quality (Lu *et al*., 2022; Zhao *et al*., 2024). Combining chilling or freezing with plant antioxidants or irradiation further reduces microbial load and oxidative deterioration, although limited infrastructure and variable consumer acceptance restrict global use (Yasin, Zeb and Ullah, 2018).

Species-specific differences in muscle structure, connective tissue, and postmortem metabolism require tailored preservation. Poultry is prone to oxidative rancidity, while pork may develop pale, soft, and exudative defects. Optimized protocols are essential to maintain quality during storage and repeated freeze–thaw cycles (Kim *et al*., 2024; Wang *et al*., 2025). Beef (*Bos taurus*) is valued for high-quality protein, vitamins, minerals, color, texture, and intramuscular fat, which enhance flavor and juiciness

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(Agarwal and Fulgoni, 2024; Dhakal, Hossain and Parajuli, 2025). Poultry, mainly chicken, is globally popular due to affordability, lean composition, and efficient production (Kumar *et al*., 2022). Pork (*Sus scrofa domesticus*), lighter in color, is rich in essential amino acids and micronutrients such as thiamine, selenium, and zinc, with consumption influenced by cultural and religious factors (Chen *et al*., 2024). Differences in myoglobin and lipid content distinguish red and white meats: beef and pork have higher myoglobin and saturated fats, while poultry provides more niacin and pantothenic acid (Setiarto *et al*., 2025; Zhang *et al*., 2025).

Although freezing at −18 °C remains central, conventional methods may cause protein denaturation and oxidative damage. Current research focuses on advanced freezing and uninterrupted cold chains to minimize quality loss. Assisted freezing methods show promise, but further validation is needed for widespread industrial adoption (Kavanaugh *et al*., 2025).

15.2 Assisted Freezing Methods

Recent emerging assisted freezing methods have been developed to overcome the limitations of conventional freezing in the preservation of various types of meat. Conventional freezing often leads to the formation of large and irregular ice crystals, which damage muscle fibers, reduce WHC, and increase drip loss upon thawing. In assisted freezing methods, external physical fields such as ultrasound, electric or electromagnetic fields, pulsed electric fields, high-velocity cold air, or cryogenic media are applied alone or in combination to accelerate the freezing rate and control ice nucleation and crystal growth. These approaches promote the formation of small and uniformly distributed ice crystals, thereby minimizing structural damage to muscle tissues. Consequently, assisted freezing techniques improve meat quality attributes, preserve fresh-like quality, and extend shelf life. A brief description of these methods is summarized in Table 15.1.

15.2.1 Ultrasonic-Assisted Immersion Freezing (UIF) of Meat

UIF is a nonthermal preservation technology that integrates low-frequency ultrasound with conventional or cryogenic freezing to improve meat quality and structural integrity. UIF systems operate at controlled frequencies (typically 20–100 kHz) and power levels and are incorporated into freezing chambers containing chilled media (Cui *et al*., 2025; Fu *et al*., 2022). Since its first application in food systems, UIF has been extensively investigated for meat preservation. UIF primarily functions through ultrasound-induced cavitation, generating microbubbles whose collapse enhances ice nucleation, disrupts large ice crystal growth, and improves heat and mass transfer. Consequently, smaller and more uniform ice crystals are formed, reducing cellular damage, micropore formation, enzymatic activity, and lipid and protein oxidation (Cheng *et al*., 2015; Zhang *et al*., 2015). The phase transition zone (−1 °C to −5 °C), critical for ice formation, is shortened under UIF, resulting in improved quality retention (Firouz *et al*., 2022). Ultrasound power is a decisive factor. Moderate intensities (200–400 W) effectively control ice crystallization and preserve muscle integrity, whereas excessive power (≥600 W) may induce localized heating, prolong freezing time, and accelerate protein denaturation and oxidation (Li *et al*., 2022). UIF enhances myofibrillar protein solubility and thermal stability by limiting aggregation and preserving sulfhydryl groups, which serve as indicators of protein structural integrity (Atani *et al*., 2022; Qiu *et al*., 2025).

15.2.2 UIF of Meat

In beef, UIF markedly improves freezing efficiency, protein stability, and sensory quality. Moderate ultrasound power (≈400 W) consistently results in the highest protein solubility, optimal sulfhydryl retention, and reduced turbidity compared with air freezing (AF) or immersion freezing (IF) (Atani *et al*., 2022). Excessive ultrasound disrupts protein spatial structure, increases oxidation, and reduces solubility due to aggregation and hydrophobic interactions. UIF-treated beef exhibits improved thermal stability, reduced drip and cooking losses (CLs), preserved microstructure, and enhanced WHC. Studies on fresh, cooked, and braised beef demonstrate that UIF accelerates freezing (>80% reduction in freezing

TABLE 15.1

Comparison of Meat Modern Chilling and Freezing Technologies

Technique	Mechanism / Principle	Freezing Rate	Ice Crystal Effects	Effects on Meat Quality	Advantages	Limitations	References
Ultrasonic-assisted freezing	Ultrasound waves applied during freezing	Rapid	Small, uniform	Reduced drip loss, improved water retention	Accelerates freezing, improves quality	Equipment-intensive, specialized	Zhao *et al.*, 2024; Lu *et al.*, 2022
Electromagnetic / electric-assisted freezing (HVEF, LVEF)	Low-voltage electric or electromagnetic field applied during freezing	Rapid	Smaller, uniform	Improved WHC, protein stability, reduced drip loss	Reduces freezing time, preserves muscle structure	Emerging technology, cost-intensive	Lu *et al.*, 2022; Zhang *et al.*, 2025; Jiang et al., 2023
Pulsed electric field (PEF) assisted freezing	Short high-voltage pulses applied to meat during freezing	Rapid	Smaller, uniform	Maintains water-holding capacity, reduces thawing loss, improves tenderness	Enhance ice nucleation, better texture retention	Specialized, high cost, limited commercial adoption	Lung et al., 2022; Wu et al., 2023
Snap / blast freezing	High-velocity cold air	Rapid	Small, uniform	Good texture, reduced drip loss	Widely used, scalable	May be uneven for irregular cuts	Lu *et al.*, 2022; Zhang *et al.*, 2025
Air blast freezing (ABF)	High-speed cold air around meat	Rapid	Small	Good texture and juiciness	Flexible, industrially scalable	Energy-intensive	Ahmad *et al.*, 2025; Zhang *et al.*, 2025
Cryogenic freezing	Immersion or spraying with LN_2/CO_2	Ultrarapid	Extremely small	Excellent preservation of structure, color, flavor	Fastest method, minimal quality loss	Very high cost, specialized equipment	Lu *et al.*, 2022; Qiu *et al.*, 2025
Immersion freezing	Submersion in cryogenic liquid (LN_2 or brine)	Ultrarapid	Very small, uniform	Excellent WHC, minimal structural damage	Rapid, uniform freezing	High cost, safety concerns	Zhang *et al.*, 2025; Mwakosya *et al.*, 2025
Plate freezing	Contact with cold metal plates	Moderate–Rapid	Small, fairly uniform	Good surface freezing, retains texture	Energy-efficient	Best for flat, uniform cuts	Zhang *et al.*, 2025; Khokhar *et al.*, 2025
Chilling + irradiation	Chilling (0–4 °C) + gamma or electron beam irradiation	Moderate	N/A (targets microbes, not ice crystals)	Extends shelf life, reduces microbial load	Improve safety, pathogen control	Limited facilities, consumer perception	Kim *et al.*, 2024; Wang *et al.*, 2024

time), minimizes phase transition duration, and preserves muscle fiber integrity, while maintaining flavor-related volatile compounds and amino acid profiles (Cui *et al*., 2025; Li *et al*., 2024). Overall, UIF at moderate intensity offers superior quality retention, whereas excessive ultrasound induces structural damage and oxidative deterioration.

15.2.3 UIF of Poultry Meat

UIF effectively preserves raw chicken meat quality by reducing drip loss and maintaining moisture through exposure of hydrophilic protein groups. Low-frequency, high-amplitude ultrasound (25 kHz, 100% amplitude) improves water retention about 4%, while high-frequency or low-amplitude (130 kHz, 60% amplitude) treatments may increase drip loss about 10% and surface heating without structural benefits (Santos *et al*., 2025). Intermittent ultrasound application significantly shortens freezing time without negatively affecting WHC, CL, protein digestibility, or color stability (Astráin-Redín *et al*., 2021). Appropriate ultrasound parameters are therefore essential to avoid oxidative discoloration and quality loss.

15.2.4 UIF of Porcine Meat

In pork, UIF significantly accelerates freezing, reduces thawing and CLs, and improves tenderness and microstructure. Moderate ultrasound intensity (15, 30, and 45 W/L) produces refined ice crystals, compact muscle fibers, and enhanced water retention, whereas excessive ultrasonic density damages tissue and increases freezable water content (Li *et al*., 2022). UIF-treated pork closely resembles fresh meat in physicochemical and sensory attributes and shows improved protein solubility and thermal stability. Recent advances include ultrasound-assisted thawing using plasma-activated water, which further enhances protein solubility, reduces aggregation, and preserves myofibrillar structure, indicating UIF's suitability for both freezing and thawing applications (Kong *et al*., 2024).

15.3 Electrostatic and Magnetic Field–Assisted Freezing

15.3.1 Electrostatic Field–Assisted Freezing (EF-AF)

EF-AF employs high-voltage, low-current fields (1–30 kV, μA range) during chilling or freezing to regulate ice nucleation and crystal growth. Polarization and alignment of water molecules weaken hydrogen bonding, delay ice nucleation, and promote formation of smaller, uniformly distributed ice crystals, thereby minimizing cellular rupture, drip loss, and protein denaturation. EF-AF does not induce electroporation or thermal effects, making it suitable for raw and minimally processed meat. EF-AF systems can be integrated into existing freezing technologies and require minimal energy input, offering clean-label, industrially scalable solutions. In beef, EF-AF reduces purge and CLs, improves tenderness, preserves microstructure, and limits lipid oxidation (Wu *et al*., 2022, 2023). In poultry, electrostatic fields have been applied primarily for thawing, accelerating ice melting, and reducing thawing time without quality deterioration (Hu *et al*., 2025). In pork, both high- and low-voltage electrostatic fields (LVEFs) reduce ice crystal size, improve WHC, and maintain muscle integrity during frozen storage (Jia *et al*., 2017; Wu *et al*., 2024b). These techniques are also used to preserve the duck meat (Chang *et al*., 2023), minimizing the antimicrobial compounds to control the growth of *Campylobacter jejuni* in raw chicken (Clemente *et al*., 2020). The beef meat quality was also improved by applying the pulsed electric field prior to freezing (Faridnia *et al*., 2015). The properties of the myofibrillar protein in frozen pork was also improved by changing the pH with magnetic field–assisted freezing (Chen *et al*., 2024)

15.3.2 Pulsed Electric Field–Assisted Freezing (PEF-AF)

PEF-AF applies short, high-voltage pulses (5–50 kV/cm) before or during freezing to induce reversible or irreversible electroporation, increasing membrane permeability and water mobility. This enhances

ice nucleation uniformity, reduces freezing time, and limits cellular damage. However, excessive intensity can cause irreversible membrane rupture, moisture loss, and protein denaturation (Nowacka *et al.*, 2024; Ahmed, Ranjan, and Roy, 2025). PEF has been shown to improve tenderness, accelerate salting and curing, enhance freeze-drying efficiency, and maintain myofibrillar protein functionality in beef, pork, and poultry when optimally applied (Dong *et al.*, 2021; McDonnell *et al.*, 2014). Similarly, pork meat exposed to low-voltage (4.0 kV) and high-voltage (12.0 kV) electrostatic fields under controlled freezing-point storage (–1.0 °C) showed a significant reduction in CL and improved WHC. The microstructural changes revealed that high-voltage electrostatic field (HVEF) preserved myofibril integrity and reduced myofibril fragmentation due to changes in actomyosin behavior, The dissociation and aggregation changes also influenced myofilament structure and water distribution within the muscle (Xu *et al.*, 2024). Nevertheless, industrial adoption remains limited due to higher energy requirements, equipment complexity, and regulatory constraints.

15.3.3 Electrostatic–Magnetic Field–Coupled Freezing

Coupling LVEFs with static magnetic fields represents a novel electromagnetic-assisted freezing approach. This hybrid system significantly shortens freezing time, reduces ice crystal size, improves WHC, and preserves protein functionality in beef and pork (Yang *et al.*, 2025b). Moderate magnetic field intensities (≈6 mT) are most effective, while higher intensities do not yield proportional benefits. Magnetic field–assisted freezing has been shown to improve the quality of frozen pork. Pork samples were precooled to 4 °C and frozen at –20 ± 0.5 °C using IF combined with static magnetic fields ranging from 0 mT to 10 mT. An optimal magnetic field intensity of 6 mT produced the better preserve quality, reducing thawing loss by 44.96% compared with the 0 mT treatment. This condition also helped maintain pH, reduce cooking and centrifugal losses, limit protein oxidation, and preserve myofibrillar protein integrity. However, increasing the magnetic field intensity beyond this level did not further enhance meat quality, indicating that magnetic field–assisted freezing is most effective at an optimal field strength rather than at higher intensities (Gan, Zhang and Jiang, 2024). Similar results of meat quality were observed when applying the static electromagnetic field in immersion superchilling freezing storage (Wang, Zhang and Adhikari, 2024). The schematic diagram of electromagnetic-assisted freezing is presented in Figure 15.1.

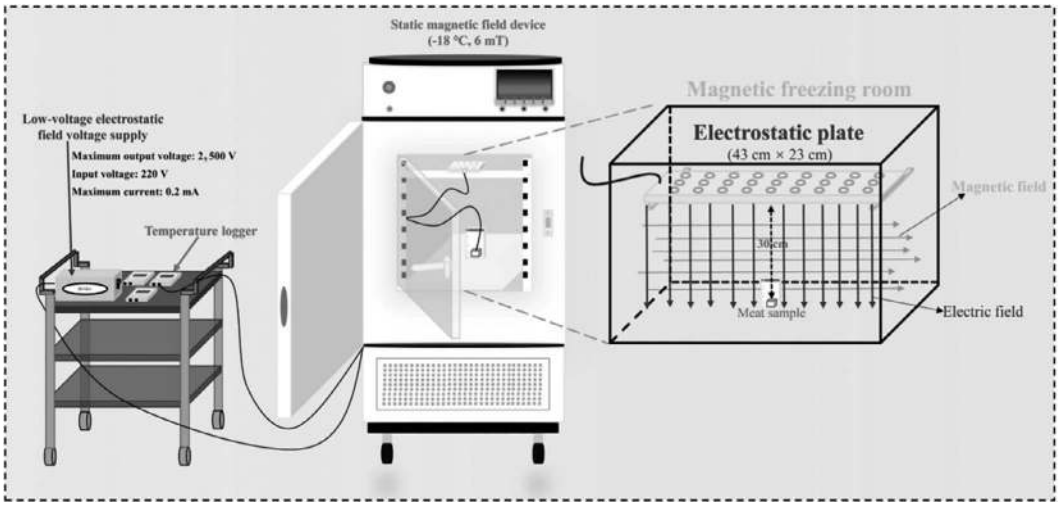

FIGURE 15.1 Schematic diagram of electromagnetic-assisted freezing. (Reproduced with permission from Yang *et al.*, 2025a. License Number: 6180220671972.)

15.3.4 Oscillating and Static Magnetic Field–Assisted Freezing

Magnetic field–assisted freezing alters hydrogen bonding in water, suppresses recrystallization, and improves frozen meat quality (Owada and Kurita, 2001). Commercial systems such as the Cell Alive System (CAS) claim to control ice crystal geometry through weak oscillating magnetic fields, although results remain inconsistent and debated (Rodríguez, James and James, 2017; Wowk, 2012). Evidence suggests that improved heat transfer, rather than magnetic effects alone, may drive observed benefits (Kobayashi and Kirschvink, 2014).

15.3.5 HVEF-Assisted Thawing

HVEF significantly affects thawing behavior in frozen meat, with responses dependent on muscle type. In chicken breast meat, total freezing time was 3.17 hours, while thawing times under HVEF intensities of 0–50 kV/m were 8.31, 7.38, 6.61, and 7.40 hours, respectively. Although differences were not statistically significant, thawing was fastest at 30 kV/m, suggesting an optimal intensity for enhancing heat transfer. In pork tenderloin, with a freezing time of 2.97 hours, HVEF application significantly reduced thawing time. Thawing durations at 0, 10, 30, and 50 kV/m were 10.31, 6.61, 5.49, and 6.92 hours, respectively, with the shortest time at 30 kV/m, corresponding to 53.07% of the control. Both lower and higher intensities were less effective, indicating that moderate HVEF optimizes ion migration and heat transfer without excessive electrostatic effects (Hu *et al.*, 2025).

Overall, physical field–assisted technologies effectively accelerate freezing and thawing processes. Moderate HVEF intensities (~30 kV/m) optimize thawing efficiency, particularly in pork, while magnetic field–assisted freezing demonstrates that controlled field strengths can enhance freezing rates without extreme operating conditions. These approaches offer promising strategies for improving efficiency and process control in meat preservation systems.

15.3.6 Cryoprotectant-Assisted Freezing

Cryoprotectants mitigate freezing-induced structural and chemical deterioration by inhibiting ice crystal formation, oxidation, and protein denaturation. Protein hydrolysates are particularly effective due to their water-binding and antioxidant properties, reducing lipid oxidation and glycated end-product formation during freeze–thaw cycles (Lin *et al.*, 2025; Lu *et al.*, 2022). Phosphates, edible coatings, and plant-based extracts further enhance WHC, color stability, and sensory quality in frozen meat products (Nora'zizi *et al.*, 2025; Yeddes *et al.*, 2025). Emerging field-assisted cryoprotection strategies integrate electrostatic and magnetic fields with cryoprotectants to stabilize myofibrillar structure and limit oxidative damage during cold-chain distribution (Wang, Zhang and Adhikari, 2024; Wang *et al.*, 2025). Collectively, cryoprotectant-assisted freezing offers a robust approach to preserving the structural, nutritional, and sensory quality of raw and processed meats during frozen storage.

15.4 Other Advanced Freezing Technologies for Meat Preservation

15.4.1 Snap Freezing

Snap freezing, typically performed using liquid nitrogen (–196 to –210°C), is an ultrarapid freezing technique that minimizes ice crystal growth and cellular damage. Rapid exposure to cryogenic temperatures produces small, uniform ice crystals, preserving muscle fiber integrity, WHC, texture, color, and sensory quality in poultry, beef, and pork. Enzymatic activity and lipid oxidation are strongly suppressed, extending shelf life (Sun *et al.*, 2025).

Comparative studies show that snap freezing results in the lowest drip, evaporation, and CLs compared with conventional (–20 °C) and deep freezing (–70 °C), due to reduced structural disruption and shorter thawing time. Faster freezing rates generate finer intra- and extracellular ice crystals, limiting damage

during thawing (Sardari *et al*., 2025). Flavor retention is also enhanced, with high-rate freezing (quick freezing and liquid nitrogen freezing) better preserving key volatile compounds, although quick freezing may offer an optimal balance between protein stability and flavor retention. Despite its effectiveness, snap freezing remains limited by high operational costs and safety requirements.

15.4.2 Superchilling

Superchilling (–1 °C to –2.5 °C) partially freezes tissue water, slowing microbial growth and biochemical reactions while maintaining fresh-like quality. Chicken breast stored under constant superchilling showed reduced drip loss, improved color stability, and stable pH during early storage, whereas fluctuating temperatures significantly increased drip loss and discoloration due to recrystallization. Ice crystals formed as band-like structures and enlarged after prolonged storage, leading to increased drip loss after day 15. Constant superchilling was superior to chilling and fluctuating conditions in preserving quality during cold-chain simulation (El-Abdi, Alvarez and Ndoye, 2025). Similar trends have been reported for poultry stored under unstable temperature regimes (Kaewthong *et al*., 2019; Rathod, Ambadkar and Naveena, 2022).

15.4.3 Air-Blast Freezing

Air-blast freezing (–18 °C) remains widely used for industrial storage. Pretreatment with plant-based antioxidants significantly improves oxidative stability during frozen storage. Beef treated with African spice extracts retained lipid stability, heme iron, and endogenous antioxidant enzyme activity comparable to synthetic antioxidants, particularly at moderate extract concentrations. Although early storage showed transient discoloration and heme destabilization, long-term storage demonstrated enhanced oxidative protection (Evuen *et al*., 2025).

15.4.4 Immersion Freezing

IF employs chilled liquid media (e.g., sucrose–salt or glycerol solutions) to enhance heat transfer and achieve temperatures between –21 °C and –47 °C. This method provides faster freezing than AF and can be applied via contact or noncontact systems (Cui *et al*., 2025; Sardari *et al*., 2025).

15.4.5 Modified Atmosphere Packaging for Frozen Meat Storage

Packaging atmosphere strongly affects protein stability during refrigerated and frozen storage. Vacuum and modified-atmosphere packaging (MAP) limit oxidative reactions, preserve sarcomere structure, and reduce protein denaturation compared with air packaging. Breast meat (*pectoralis major*) from *Korat* (Thai hybrid) chickens stored at 4 °C under air, vacuum, and MAP (30% CO_2/70% N_2) for 12 days showed distinct quality changes (Indriani *et al*., 2025). Air packaging caused greater losses of water-soluble proteins due to oxygen-driven enzymatic hydrolysis, protein denaturation, and microbial activity, whereas vacuum and MAP better preserved protein integrity.

Salt-soluble myofibrillar protein content increased by ~50% in modified packaging, reflecting progressive degradation and higher solubility. Total collagen remained relatively stable (0.36–0.43%), but insoluble collagen increased, particularly in air-packaged meat, likely due to oxidative cross-linking that contributed to stiffness. Sarcomere length declined from 1.96 μm in fresh meat to 1.52–1.65 μm after 12 days, with vacuum and MAP maintaining sarcomere integrity more effectively. Sarcomere shortening, combined with protein oxidation and carbonylation, promoted myofibrillar aggregation, reduced WHC, and increased toughness. Reductions in fiber diameter and enlarged inter-fiber spaces further indicated oxidative protein aggregation and collagen degradation, ultimately compromising tenderness and overall meat quality under conventional packaging.

15.4.6 Partial Freezing

Partial freezing stores meat at 1–2 °C or below its biological freezing point, slowing protein oxidation, pH changes, and protease activity while limiting ice crystal damage (Fu *et al*., 2021b). Surimi treated with trypsin and alkaline protease exhibited less formation of protein carbonyl content ranging from 10.26% to 17.95%, compared with the control (Zhang *et al*., 2022). In conventional freezing, ice crystal formation mechanically disrupts muscle tissue, leading to increased thawing loss, enhanced protein oxidation and aggregation, reduced tenderness, and loss of volatile flavor compounds. To overcome these limitations, partial freezing has been explored as an alternative preservation strategy. When meat is stored below its biological freezing point (1 – 2 °C), ice crystal damage is limited and quality is better preserved. Partial freezing effectively slows changes in pH, trichloroacetic acid -soluble peptides, and total volatile basic nitrogen, while delaying protein oxidation and inhibiting endogenous protease activity. However, when applied alone, partial freezing provides only a relatively short shelf life, which restricts its broader industrial application. Although effective for short-term preservation, shelf life remains limited when partial freezing is used alone, restricting large-scale application (Yi *et al*., 2025).

15.4.7 Irradiation-Assisted Freezing

Gamma and electron-beam (e-beam) irradiation combined with freezing effectively reduce microbial loads in beef, pork, and poultry. Fresh boneless beef marinated with 0.01% BHA, packaged in zip-lock bags, and irradiated at 3, 5, and 7 kGy (^{60}Co source) showed progressive increases in free fatty acids, peroxide value, and TBARS during −20 °C storage for 120 days, regardless of dose. Irradiation initially lowered total viable counts, coliforms, yeasts and molds, *Salmonella* spp., and *Staphylococcus* spp., but microbial recovery occurred over storage; *Salmonella* spp. showed a slight increase by the end of study (Sadakuzzaman *et al*., 2025).

E-beam irradiation (0.5 – 10 kGy, 10 MeV) of frozen pork cutlets contaminated with *E. coli* achieved 5-log reductions to 2.7 kGy, with no detectable growth above 7 kGy. D_{10} values for *E. coli* O157:H7, *S. typhimurium*, *L. monocytogenes*, and *S. aureus* ranged 0.40–0.54 kGy. Color changes appeared above 4.5 kGy, and lipid oxidation increased dose-dependently to 0.79 µg MDA/g at 10 kGy. Irradiation-induced hydrocarbons (e.g., 1,7-hexadecadiene, 8-heptadecene) appeared from 2 kGy onward, highlighting the need to balance microbial safety and quality (Yeom *et al*., 2025).

Iranian turkey minced meat irradiated at 1.5–3 kGy and stored at −18 °C for six months showed reduced mesophilic and psychrotrophic bacteria. Physicochemical properties, including pH and water activity, remained stable, although TBARS and peroxide values increased with irradiation (Salari and Khatami, 2025). Overall, combining irradiation with freezing extends shelf life and enhances microbial safety, but higher doses can induce lipid oxidation and color changes, requiring careful dose optimization (Sadakuzzaman *et al*., 2025; Salari and Khatami, 2025; Yeom *et al*., 2025).

15.5 Effect of Freezing on the Chemical Composition of Meat

15.5.1 Amino Acid Profile

Broiler breast meat stored at -20 °C for 90 days under repeated freeze–thaw cycles and thawed at 4 °C for 12 hours showed comparative stable amino acid composition up to 30 days. With prolonged frozen storage, amino acid losses increased, particularly in refrozen samples. Total amino acid content declined by approximately 6% in frozen meat and 23% in refrozen meat, indicating enhanced protein degradation during repeated freeze–thaw–refreeze cycles. Alanine, threonine, serine, glutamine, and isoleucine were least affected (≤5%), whereas leucine, valine, tyrosine, arginine, and methionine showed moderate reductions (7–13%). After 90 days, the greatest losses were observed for glycine (19.3%), aspartic acid (20.0%), and lysine (17.5%), while phenylalanine increased slightly (1.1%). Overall amino acid losses ranged from 8.3% to 55%, with tyrosine showing the highest reduction and isoleucine the lowest. These changes were mainly attributed to drip loss, protein denaturation, and leaching of soluble amino acids during freeze–thaw and refreezing processes (Ahmed and Mohammed, 2025).

15.5.2 Fatty Acid Profile

During frozen and refrozen storage, broiler meat exhibited a significant decline in fatty acid content. Lipid oxidation was the primary degradation mechanism, followed by lipid hydrolysis, resulting in reductions across saturated, monounsaturated, and polyunsaturated fatty acids during freeze–thaw–refreeze cycles. After three months of refrozen storage, fatty acid levels were markedly lower than in raw meat, except for linoleic acid. Among saturated fatty acids, stearic acid (C18:0) decreased significantly under both frozen and refrozen conditions, while myristic, pentadecanoic, palmitic, and heptadecanoic acids showed inconsistent variations. Within monounsaturated fatty acids, eicosenoic acid was least affected after 30 days, whereas myristoleic, palmitoleic, and oleic acid (C18:1 *cis*) declined progressively with storage duration and repeated freezing. Polyunsaturated fatty acids including linolenic acid, eicosatrienoic acid, and arachidonic acid were also decreased significantly during extended frozen and refrozen storage. These changes are primarily attributed to ongoing lipolytic enzyme activity, which persists under frozen conditions, and to enzyme release from ice crystal–induced cell membrane damage during freeze–thaw cycles (Ahmed and Mohammed, 2025; Shin *et al.*, 2024; Wu *et al.*, 2024b).

15.5.3 Mineral Profile

The contents of calcium (Ca) and magnesium (Mg) in broiler breast meat decreased slightly with extended storage periods under both freezing and refreezing conditions compared with fresh meat. In contrast, the levels of sodium (Na), potassium (K), manganese (Mn), zinc (Zn), copper (Cu), selenium (Se), and iron (Fe) showed more pronounced declines. Frozen storage resulted in a minor decrease in phosphorus content, whereas phosphorus levels decreased significantly during refrozen storage (Ahmed and Mohammed, 2025).

15.5.4 Glycogen Distribution

Fresh chicken skeletal muscle exhibited abundant glycogen deposits in both breast and leg muscles, with values ranging from 118 to 120 arbitrary image-analysis units (AU). In contrast, frozen chicken meat showed reduced glycogen distribution, likely due to prolonged storage duration. Iraqi frozen chicken exhibited slightly lower glycogen levels (114–116 AU), while moderate glycogen contents were observed in Iranian and Brazilian frozen samples, typically displaying a scattered distribution pattern. Turkish frozen chicken showed the lowest glycogen content in both breast and leg muscles. Overall, fresh meat retained higher glycogen levels than frozen samples, indicating progressive glycogen depletion associated with freezing and extended storage duration (Najman and Al-Badri, 2025).

15.5.5 Cooking Loss (CL), Weight Loss, and Water Distribution in Frozen Meat

CL, thawing or weight loss, WHC, and water distribution are critical quality attributes that reflect the structural integrity of muscle tissues and their ability to retain moisture during freezing, thawing, and subsequent cooking. These parameters are strongly influenced by storage duration, freeze–thaw conditions, and the application of physical or antioxidant-based interventions.

15.5.5.1 Cooking Loss

CL is primarily associated with protein denaturation and structural damage to muscle fibers during frozen storage and thermal processing. Although no significant differences were observed among additive treatments, CL increased significantly during the first month of frozen storage, reaching 84.4%, compared with other storage periods. On the first day of storage, significantly lower CL values were recorded in the control (72.6%) and in meat treated with 0.25% lemongrass extract (72.7%), indicating better initial moisture retention before prolonged frozen storage (Karim and Majid, 2025).

The application of HVEF during thawing effectively reduced CL in frozen meats. In chicken breast, CL decreased progressively with increasing HVEF intensity, from 31.16% at 0 kV/m to 24.68–24.65%

at 30–50 kV/m, with no additional benefit observed beyond 30 kV/m. Similarly, in pork tenderloin, CL values under HVEF intensities of 0, 10, 30, and 50 kV/m were in the range of 27–34%. The lowest CL was achieved at 30 kV/m, indicating this intensity as optimal for minimizing moisture loss during cooking (Hu *et al.*, 2025).

15.5.5.2 Weight Loss and Thawing Loss

Weight loss, particularly thawing loss, reflects the extent of drip formation resulting from ice crystal damage and membrane disruption. No significant differences were observed among additive treatments; however, thawing loss increased significantly during the second month of storage, reaching 96.9%, compared with other storage periods (Karim and Majid, 2025).

Freeze–thaw dynamics play a decisive role in weight loss and spoilage development. Post-freeze–thaw samples exhibited higher spoilage rates than pre-freeze samples due to cellular damage caused by ice crystal formation, which enhances microbial access to intracellular nutrients. Repeated freeze–thaw events exacerbate membrane rupture, while longer thawing periods provide additional time for microbial proliferation. Milder freezing conditions (−4.3 °C) resulted in lower weight loss than deeper freezing (−6.7 °C), supporting the freeze-intensity hypothesis, which links ice crystal size and distribution to moisture retention. Rapid freezing favors smaller ice crystals, limiting drip loss and microbial access upon thawing. Unexpectedly, samples stored under stable subfreezing temperatures without freeze–thaw cycles exhibited greater weight loss, likely due to sublimation and continued metabolic activity of cold-adapted microorganisms such as *Pseudomonas* (Ong and Norris, 2025).

Fresh pork and chicken breast meat were stored for 48 hours using simulating domestic conditions. The meat was thawed in electric field incubator at 4 °C by three electric currents—10, 30, and 50 kV/m conditions. There were slight variations in the freezing duration of pork and chicken meat, at 2.97 and 3.17 hours, respectively. High-voltage electric field incubation reduced the thawing time by 53.07%, from 10 hours to 5.49 hours, which is approximately a 40% reduction when treated with various intensities (10, 30, and 50 kV/m). The intensity of the electric field has a strong effect on the thawing process; when the electric field intensity is low, it is insufficient to initiate thawing, which prolongs the thawing time compared with higher-intensity fields (Hu, Zhang and Mujumdar, 2022; Wu *et al.*, 2024a). In contrast, chicken breast meat remains relatively stable under high-intensity electric field thawing. A reduction of 11–20% in thawing time was observed, with values of 7.38, 6.61, and 7.40 hours compared with the control (8.31 hours).

15.5.5.3 Water-Holding Capacity

WHC reflects the ability of meat proteins to retain water within the myofibrillar structure. Rosemary extract treatments at concentrations of 0.25% and 0.50% significantly increased WHC (39.8 and 39.0, respectively), while combinations of lemongrass and rosemary extracts (0.125% and 0.25% each) produced comparable WHC values (39.6 and 39.2) to the control (38.4). Storage time also influenced WHC, with the highest value observed during the first month (41.8), followed by a slight decline in later storage periods. No significant interaction between additive type and storage duration was detected (Karim and Majid, 2025).

15.5.5.4 Water Distribution and Mobility

Low-field nuclear magnetic resonance distinguishes bound (T21), immobilized (T22), and free water (T23) fractions in meat. Frozen–thawed samples consistently showed reduced immobilized water (A22) relative to fresh meat, reflecting structural disruption. In chicken breast, HVEF-treated samples retained higher A22 and exhibited a leftward shift in T22 relaxation times, indicating stronger water binding, whereas untreated samples showed increased free water (A23), suggesting greater thawing loss. Similar patterns were observed in pork tenderloin, with the highest A22 in samples treated at 30 kV/m. Excessive HVEF intensity (50 kV/m) increased free water, reducing water retention (Hu et al., 2025). UIF also improved water stability, with shorter T22 and T23 relaxation times compared with AF; however, excessive ultrasonic power promoted water migration (Cui *et al.*, 2025).

Overall, CL, weight loss, and water distribution depend on freezing intensity, thawing conditions, and muscle structure preservation. Moderate physical field applications—HVEF around 30 kV/m and controlled UIF—minimize ice crystal damage, optimize moisture retention, and, when combined with natural antioxidants, enhance WHC, juiciness, yield, and overall meat quality.

15.6 Protein Physicochemical Properties and Structural Changes

15.6.1 Solubility and Turbidity

Freezing significantly reduced beef myofibrillar proteins (BMPs) solubility, primarily due to protein aggregation induced by ice crystal formation. The AF group showed the lowest solubility (36%), as slow freezing promotes muscle tissue damage, protein denaturation, and aggregation. Partial protein unfolding from hydrophobic interactions further reduced protein–water interactions, lowering solubility. Ultrasound-assisted freezing at 400 W (UIF-400 W) significantly improved solubility (55%) compared to IF, UIF-200 W, and UIF-600 W, indicating that optimal ultrasound mitigates structural disruption and limits aggregation. However, excessive ultrasound power (UIF-600 W) reduced solubility due to over-denaturation.

Protein turbidity trends mirrored solubility results. Freezing increased beef myofibrillar proteins (BMP) turbidity, reflecting oxidative denaturation and enhanced hydrophobic interactions. UIF-200 W and UIF-400 W treatments effectively reduced turbidity compared to AF and IF, with UIF-400 W being superior, likely due to stronger cavitation preventing large ice crystal formation. Conversely, UIF-600 W caused higher turbidity, consistent with solubility observations (Li *et al.*, 2025).

15.6.2 Ultrastructure of Muscle Fibers

Electron microscopy (TEM and SEM) is used to assess internal and external ultrastructural changes in muscle. TEM reveals alterations in myofibrils and sarcomeres during freezing, while SEM shows surface fiber integrity and protein cross-linking, which influence texture, WHC, and overall meat quality. TEM of raw meat provides a baseline of myofibrillar arrangement, sarcomere length, and band clarity. Freezing induced structural damage, with AF causing warped myofibrils, blurred bands, and Z-line loss. IF reduced distortion, maintaining longer sarcomeres and partially clear bands. Ultrasound-assisted freezing preserved structure best at moderate power (UIF-150), with orderly sarcomeres, clear bright bands, and mostly intact Z-lines, whereas higher power (UIF-300, UIF-450) caused greater fiber deformation, internal pores, and loss of band clarity (Cui *et al.*, 2025).

15.6.3 Sulfhydryl Groups and Protein Oxidation

Sulfhydryl groups are essential for maintaining protein structure. Total sulfhydryl content decreased in all frozen samples compared to the control (73.62 ± 0.51 μmol/g), with AF showing the lowest level (55.54 ± 0.24 μmol/g). Ultrasound-assisted freezing at 400 W (UIF-400) preserved higher sulfhydryl content (66.19 ± 0.32 μmol/g), likely due to rapid freezing and smaller ice crystals minimizing structural damage. Active sulfhydryl content increased after freezing as buried groups were exposed from protein unfolding, peaking in AF (38.45 ± 0.05 μmol/g) and rising with ultrasound power up to 400 W before declining at 600 W due to disulfide bond formation. Protein oxidation during storage, indicated by carbonyl content, increased from 0.66 μmol/g in fresh meat to 2.32 μmol/g (LP) and 3.35 μmol/g (PS) after 24 days. LVEF-assisted freezing (LP) slowed oxidation by promoting small ice crystal formation and preserving muscle structure, reducing protein denaturation and cross-linking (Liu *et al.*, 2025).

15.6.4 Stability

Differential scanning calorimetry revealed that freezing reduced T_{max1} and T_{max2} values, indicating increased susceptibility to thermal denaturation due to exposure of hydrophobic side chains. AF and UIF-600 W treatments showed lower T_{max} values, reflecting less stable protein structures, while

UIF-400 W maintained the highest T_{max} and ΔH values, suggesting that optimal ultrasound preserves protein conformation by limiting ice crystal damage and oxidation during freezing. Reduced enthalpy (ΔH) in AF samples further confirms structural disruption from slow freezing (Li *et al.*, 2025). Likewise, HVEF intensity of 30 kV/m denatured the protein due to temperature effect, while 30 kV/m HVEF maintain protein thermal stability among other tested intensities (Hu *et al.*, 2025).

15.6.5 Secondary Structure

Circular dichroism spectroscopy showed the α-helix as a dominant secondary structure of myofibrillar proteins, with negative peaks at 208 and 222 nm. The greatest loss of α-helix was observed in meat treated with UIF-600 W, while the lowest loss occurred in the UIF-400 W group, which was slightly higher than the control. This was accompanied by increases in β-sheets, β-turns, and random coils, indicating enhanced protein–protein interactions and aggregation. UIF-400 W preserved the highest α-helix content (26.58 ± 0.67%) and the lowest random coil fraction (36.44 ± 0.17%), suggesting that optimal ultrasound treatment mitigates freeze-induced denaturation (Li *et al.*, 2025).

15.6.6 Tertiary Structure

Intrinsic fluorescence, primarily from tryptophan residues, reflected tertiary structural changes. Freezing induced a redshift in λ-max (from 324 nm in control to 328 nm in AF) and increased fluorescence intensity, indicating protein unfolding. UIF-400 W treatment reduced fluorescence intensity compared to other freezing treatments, suggesting that accelerated freezing and cavitation effects limited structural unfolding and preserved BMP tertiary structure, thereby mitigating quality deterioration (Li *et al.*, 2025).

15.6.7 Surface Hydrophobicity

Surface hydrophobicity reflects conformational changes in proteins caused by biochemical and physical treatments, such as freezing. AF increased meat surface hydrophobicity, whereas ultrasound treatment at 400 W maintained hydrophobicity close to that of untreated meat. Both very high and very low ultrasonic intensities reduced surface hydrophobicity, likely due to protein unfolding and extension induced by freezing, which disrupted conformational integrity and increased instability. Gradual freezing preserves protein interactions, including van der Waals forces, hydrogen bonds, and disulfide bonds, but structural changes still occur in secondary and tertiary protein structures. These changes of protein structure expose the internal hydrophobic residues, modifying the distribution of hydrophobic regions on the protein surface (Li *et al.*, 2025).

15.6.8 In Vitro Digestibility

The meat treated with ultrasound waves before freezing only induces slight changes in myofibrillar protein structure and reduces the protein aggregation and its denaturation and preserve more enzyme activity by preserving their active site. This indicates that meat treated with ultrasound did not experience significant changes in protein structure, as confirmed by in vitro digestibility tests using pepsin and trypsin. Ultrasound-treated meat exhibited a higher protein digestion rate than immersion- and air-frozen meat, demonstrating that UIF improves the digestibility of proteins. The rate of protease hydrolysis was closely related to the protein's spatial conformation (Li *et al.*, 2025).

15.6.9 Particle Size

The particle sizes of BMP digestion products were larger in the freezing-treated groups compared to the control. With increasing ultrasonic power, particle size initially decreased and then increased, with the smallest size observed in the UIF-400 W treatment. Smaller protein particles were more accessible to proteolytic enzymes, enhancing their hydrolysis and potential absorption in the human digestive system.

After trypsin digestion, particle sizes further decreased, following the same trend observed during pepsin digestion. Ultrasound-treated groups showed significantly smaller particles compared to the AF and IF groups, with particle size decreasing and then increasing as ultrasonic power rose. Pepsin and trypsin hydrolysis converted large-molecular-weight proteins into small peptides or amino acids, resulting in reduced particle sizes, consistent with SDS-PAGE findings. These results indicate that ultrasound treatment enhances BMP hydrolysis, promoting smaller digested products (Li *et al.*, 2025).

15.6.10 Digestive Microstructure

The microstructures of digested and undigested protein products were examined through confocal laser scanning microscopy, using rhodamine B as a stainer which produces the red fluorescent dots. Digestion with pepsin and trypsin led to an overall decrease in fluorescence intensity across all samples, reflecting the breakdown of myofibrillar proteins into smaller peptides. Control proteins showed higher digestibility, indicating easier enzymatic hydrolysis and potential absorption.

In the AF and IF groups, protein particles appeared strongly aggregated, dispersed, and disorganized, with particle sizes substantially larger than conventional freezing group. In contrast, proteins from UIF-treated samples were more uniformly distributed, exhibiting only slightly larger particles than controls, with no significant differences among UIF groups. Gastric digestion reduced particle size in all samples; however, large aggregates persisted in AF and IF groups and were gradually degraded during trypsin digestion. In UIF samples, red fluorescence was faint or absent after digestion, whereas it remained pronounced in the AF group, indicating reduced digestibility following conventional freezing.

Structural denaturation of proteins enhances particle aggregation, which obscures protease recognition sites and decreases enzymatic sensitivity, thereby reducing digestibility (Choi and Chin, 2020). Pepsin cleaves bonds between aromatic and hydrophobic amino acids, while trypsin targets linkages between arginine and lysine residues. Aggregation resulting from denaturation can hinder access to these cleavage sites, reducing overall protein hydrolysis (Li *et al.*, 2025).

15.6.11 Endogenous Enzyme Stability

Frozen beef treated with 10% pepper exhibited the highest endogenous antioxidant enzyme activities on day 28. Peroxidase (POD) activity reached 11.30×10^{-4} units/mg tissue, approaching the activity of BHT (12.50×10^{-4} units/mg tissue) and markedly exceeding the control (2.57×10^{-4} units/mg tissue). Similarly, superoxide dismutase (SOD) activity was maximized in the 10% *X. aethiopica* group (14.90×10^{-4} units/mg tissue), comparable to BHT (16.17×10^{-4} units/mg tissue) and substantially higher than the control (4.04×10^{-4} units/mg tissue). Catalase (CAT) activity also peaked in this group at 8.90×10^{-4} units/mg tissue, closely matching BHT CAT value as 9.32×10^{-4} units/mg tissue and exceeding the control (2.86×10^{-4} units/mg tissue). Lower concentrations of *X. aethiopica* and combined formulations of spices also enhanced enzyme activities, albeit to a lesser extent. Collectively, these findings indicate that appropriate spice extract treatments effectively stimulate endogenous antioxidant defenses in frozen beef, thereby improving oxidative stability and potentially extending shelf life (Evuen *et al.*, 2025).

15.6.12 Sarcoplasmic Proteins

The square wave voltammograms of beef *longissimus lumborum* (LL) sarcoplasm were recorded at 37 °C in an oxygenated buffer (pH 5.6) using High-purity graphite (HPG) electrodes coated with sarcoplasm extract. Polished HPG electrodes without sarcoplasm extract showed no peaks, confirming their suitability for electrochemical monitoring. Voltammograms of myoglobin- or meat extract-coated electrodes showed peaks at +0.82 V (positive) and −0.25 V (negative). LL sarcoplasm without freeze–thaw (F-T) cycles was used as a control and displayed smaller peak currents compared to F-T–cycled sarcoplasm. Repeated F-T cycles increased oxidation peaks in the positive scan and oxygen reduction in the negative scan, indicating protein oxidation, including myoglobin oxidation (Bhandari *et al.*, 2025).

15.6.13 Myoglobin Content

Myoglobin, a polypeptide containing an iron-centered heme group, is the primary pigment responsible for meat color. The red, purple, and brown hues of meat are determined by the oxidation state of myoglobin: bright red oxymyoglobin, purple deoxymyoglobin, and brown metmyoglobin (MMb). Myoglobin and its ligands undergo redox reactions that generate these color changes. In broiler breast meat, myoglobin content slightly decreased during prolonged frozen storage and repeated freeze–thaw cycles. Freezing alone exhibited a slower oxidation rate compared to refreezing. Extended storage of refrozen meat significantly reduced myoglobin levels, as ice crystal formation physically damages cells and their internal structures, exposing lipids and myoglobin to oxidation-promoting agents (Shin *et al.*, 2024). HVEF treatment affected metmyoglobin (MMb) formation during thawing. In chicken breast, MMb values decreased from 39.09% to 22.66% when HVEF at 10 kV/m was applied. However, when the HVEF intensity increased to 50 kV/m, MMb values increased again to 55.08%. This shows that moderate HVEF can reduce oxidation-related color changes, while higher intensity may promote oxidation. In pork, electrostatic treatment after freezing increased MMb at 10 kV/m, leading to noticeable color changes (Hu *et al.*, 2025).

Spectrophotometry showed peaks at 503 nm for metmyoglobin (MMb), 557 nm for deoxymyoglobin, and 582 nm for oxymyoglobin. Repeated freeze–thaw cycles increased MMb and decreased oxymyoglobin. Electrochemical measurements correlated with these changes, with positive currents reflecting overall oxidation and negative currents indicating metmyoglobin-driven oxygen reduction, confirming their reliability for monitoring protein oxidation and myoglobin redox dynamics (Bhandari *et al.*, 2025).

15.7 Lipid Oxidation

Lipid oxidation in meat is a prime destruction that leads to deterioration during frozen storage, degrading unsaturated fatty acids and producing peroxides, aldehydes, ketones, and esters that impair flavor, color, nutritional value, and shelf life (Ahmed and Mohammed, 2025; Hu *et al.*, 2025; Karim and Majid, 2025). Oxidation occurs even under freezing, as lipases and phospholipases remain partially active, generating free radicals that initiate self-propagating peroxidation. Malondialdehyde (MDA) and thiobarbituric acid reactive substances (TBARS) are standard indicators, with MDA providing a precise measure of advanced oxidation. TBARS may overestimate oxidation due to contributions from sugars, amino acids, and Maillard products, particularly in cooked meat.

Under continuous frozen storage at constant temperature for 90 days, MDA increases gradually but remains <2 nmol/mg. In contrast, freeze–thaw–refreeze cycles accelerate oxidation, with MDA exceeding 2 nmol/mg at 30 days and approaching 5 nmol/mg at 90 days, producing rancid odors (Ahmed, Ranjan, and Roy, 2025). Natural antioxidants, such as lemongrass and rosemary, suppress MDA formation: 0.25% combined extracts reduced MDA to 0.0584 mg/kg versus 0.1573 mg/kg in controls after three months at −20 °C (Karim and Majid, 2025).

HVEF treatments during thawing limit TBARS by reducing oxygen exposure and thawing time. In chicken breast, TBARS ranged 0.0318–0.0376 mg/kg (fresh meat: 0.0324 mg/kg), while pork tenderloin decreased to 0.0409–0.0431 mg/kg versus 0.1111 mg/kg in controls (Hu *et al.*, 2025). LVEF partial freezing similarly reduced TBARS in beef to 0.35 mg/kg after 24 days at 0.5 °C versus 0.50 mg/kg in static storage (Liu *et al.*, 2025). Protein hydrolysates also mitigate freeze–thaw oxidation in pork (reducing TBARS 11–31%), while reheating at 100 °C intensifies oxidation (Lin *et al.*, 2025). Sodium tripolyphosphate reduces TBARS in buffalo loin during 28 days of 4 °C storage (Nora'zizi *et al.*, 2025). Plant extracts (grape seed, green tea, rosemary, mate) at 0.02–1% maintain TBARS <0.5 mg/kg in 60 days frozen patties, with mate showing pro-oxidant behavior in pork (Paglarini *et al.*, 2025).

Lipid oxidation also drives color deterioration via metmyoglobin formation. Longer thawing without HVEF increases TBARS and b^* values, whereas HVEF at 10–30 kV/m minimizes ΔE, preserving redness (Hu et al., 2025). Free fatty acid (FFA) and peroxide value (PV) assessments confirm oxidative protection by bioactive additives. For example, 0.50% lemongrass reduced FFA to 0.262% versus 0.372% in controls and PV to 1.30 meq/kg (Karim and Majid, 2025). Spices such as 10% *Piper guineense* and

5–15% *Xylopia aethiopica* also reduce FFA and acid values, outperforming BHT and controls (Evuen *et al.*, 2025).

15.8 Flavor Compounds, Metabolites

The flavor profile and overall quality of meat are profoundly influenced by processing and storage conditions, particularly freezing and thawing methods. Volatile compounds, including aldehydes, alcohols, ketones, esters, and nitrogenous molecules, play a critical role in sensory perception, while nonvolatile metabolites such as amino acids, peptides, nucleotides, and lipids contribute to flavor development and shelf life stability. Screening volatile compounds using gas chromatography–ion mobility spectrometry provides information on how freezing methods influence water migration, protein degradation, lipid oxidation, and microbial activity. Understanding these interactions is essential for optimizing storage strategies to preserve meat quality, enhance flavor retention, and extend shelf life.

Using GC–IMS, a total of 37 volatile flavor compounds were identified in beef and 36 in potatoes. These compounds mainly belonged to aldehydes, alcohols, hydrocarbons, ketones, acids, and esters, which together form the characteristic aroma of meat and vegetables. In beef, fingerprint analysis showed that freezing changed the aroma profile noticeably. Several key aroma compounds, including terpenes, alcohols, and pyrazines, increased after freezing. Among them, 5-methyl-2-ethylpyrazine, a typical Maillard reaction product responsible for roasted notes, was significantly higher under high-power UIF (UIF-450). This finding indicates that UIF not only helps preserve natural aroma compounds but may also promote flavor development through Maillard-related reactions. Ultrasonic treatment also increased the levels of several ketones, alcohols, and esters, likely because ultrasound accelerated freezing and enhanced mass transfer, allowing more volatile compounds to be retained. However, some volatiles decreased after freezing, which was probably due to water migration in the muscle that led to the dissolution and loss of aroma compounds. Moderate ultrasonic treatment (UIF-150) was particularly effective in retaining desirable aroma compounds in beef, while increasing ultrasonic power further led to the formation of some new volatile compounds. In potatoes, the volatile profile under UIF-150 was similar to that of the control, suggesting minimal flavor damage. In contrast, high-power ultrasound (UIF-450) reduced volatile content, likely due to cell structure (Cui *et al.*, 2025).

15.8.1 Alcohol Compounds

Five alcohols differed significantly in beef samples: 1-octen-3-ol, 1-hexanol, 1-heptanol, 1-octanol, and *trans*-2-octen-1-ol. 1-Octen-3-ol, produced via lipid oxidation, gives a mushroom-like odor considered undesirable. Its concentration initially increased during storage and then decreased. In fresh meat, it was 120.14 μg/kg. After 12 days, the Partial Freezing Storage (PS), group reached a peak of 636.26 μg/kg (OAV: 636.26), significantly higher than the LVEF combined with partial freezing group (LP) (408.76 μg/kg, $P < 0.05$), indicating that LVEF treatment delayed its formation. By day 24, levels dropped to 410.22 μg/kg in LP and 109.58 μg/kg in PS. 1-Hexanol, which gives grassy or fruity notes and has a low sensory threshold, increased in LP from 24.15 μg/kg (fresh meat) to 98.31 μg/kg (OAV: 12.29) after 24 days, significantly higher than in the PS group (27.81 μg/kg, OAV: 3.28). 1-Hexanol also has antioxidant and antibacterial properties, potentially contributing to better beef preservation during storage (Liu *et al.*, 2025).

15.8.2 Aldehyde Differentiators

Nine aldehydes were detected in beef, and most of them were formed by lipid oxidation, including octanal, hexanal, and nonanal. Octanal is related to pungent odor and is an indicator of lipid oxidation. In fresh meat, its level was 39.68 μg/kg. After 18 days of storage, octanal increased sharply in the control group and reached 369.08 μg/kg, which was much higher than in the assisted freezing group (133.65 μg/kg). This suggests that LVEF storage reduces octanal formation. Hexanal is an important volatile compound that gives fruity and fatty aromas. In the assisted freezing group, hexanal reached its highest value (965.24 μg/kg) on day 18. In the control group, it peaked earlier on day 6 and then

decreased by day 24. This indicates that LVEF affects the formation and breakdown of hexanal during storage. Nonanal (volatile aldehyde compounds) levels on day 24 were lower in the LVEF group than in the control group. Benzaldehyde, a volatile compound associate with flavor deterioration and off-flavor development, was detected only in the control group during days 18–24. These results indicate that LVEF storage helps slow lipid oxidation and reduces the formation of off-flavor compounds (Liu *et al.*, 2025).

15.8.3 Esters and Ketones

Esters are formed from reactions between acids and alcohols and give fruity aromas to meat. In beef, two esters showed clear differences between treatments. Caproic acid vinyl ester increased from 29.44 μg/kg in fresh meat to 93.82 μg/kg in the electric-assisted field freezing group on day 6. Another ester, (*E*)-9-octadecenoic acid ethyl ester, was found only in the assisted freezing after 12 days of storage. Ketones are mainly produced by lipid oxidation and protein reactions and contribute buttery flavors. The levels of acetoin and 2,3-octanedione were higher in the assisted freezing than in control group. 2-Pentylfuran, which is formed from linoleic acid oxidation, increased to 46.37 μg/kg in the assisted freezing group by day 24. In the control group, it reached a peak on day 12 and then decreased. These results indicate that LVEF storage helps maintain desirable flavor compounds and reduces the development of off-flavors (Liu *et al.*, 2025).

15.8.4 Volatile Flavor Compounds during Storage

Over the storage period, 92 volatile compounds were identified, including 22 alcohols, 22 aldehydes, 13 alkanes, 15 esters, 8 ketones, 3 acids, and 9 others. LP samples contained 74 compounds, compared to 70 in PS. These compounds originate from protein degradation, lipid and carbohydrate metabolism, and microbial activity. Fresh meat contained 40 compounds totaling 854.88 μg/kg, with aldehydes and alcohols contributing 47.21% and 27.70%, respectively. During storage, total volatiles initially increased before declining. By day 24, electric-assisted freezing treatment retained 2,767.30 μg/kg of volatile compounds compared with 1,754.80 μg/kg in the control, indicating that LVEF influences transmembrane potential and electron transfer in muscle cells, thereby affecting volatile compound formation and retention (Liu *et al.*, 2025).

15.8.5 Protein Nonvolatile Metabolites

Amino acids and other nonvolatile compounds in fresh meat play key roles in flavor development. During storage, proteins gradually degrade into peptides and free amino acids, primarily due to microbial activity. By day 24, levels of argininosuccinic acid, L-serine, and L-cysteine–glutathione disulfide were lower in electric-assisted freezing compared with the control. High argininosuccinic acid levels can impart bitterness (Ramalingam et al., 2019). In contrast, L-asparagine and L-hydroxyproline increased over time, suggesting their potential as markers of beef deterioration. Notably, carnosine content in electric-assisted freezing remained consistently higher at 12.65%, compared with 3.83% in the control at day 24. Carnosine, abundant in muscle, inhibits lipid oxidation through free radical scavenging and metal chelation, thereby slowing lipid deterioration and contributing to meat quality (Liu *et al.*, 2025).

15.8.6 Total Volatile Basic Nitrogen

Total volatile basic nitrogen (TVB-N) is a by-product of microbial protein degradation into ammonia or amines, serving as an indicator of freshness and spoilage. The maximum permissible TVB-N in fresh beef is 15 mg/100 g, which gradually increases due to microbial activity and protein hydrolysis. In the LP group, TVB-N increased more slowly, reaching 10.37 mg/100 g after 24 days, significantly lower than the control. The application of an electrostatic field during freezing limited TVB-N accumulation by generating ozone, which inhibited microbial growth and enzymatic activity, thereby helping to maintain beef freshness (Liu *et al.*, 2025).

Freezing and storage conditions significantly impact the formation, retention, and transformation of both volatile and nonvolatile flavor compounds meat. UIF, particularly at optimized power levels (UIF-150), effectively preserved aroma compounds, promoted Maillard reaction products, and reduced off-flavor formation, while LVEF treatment slowed protein degradation, lipid oxidation, and microbial spoilage.

15.9 Oxidation

Protein oxidation, notably carbonyl and sulfhydryl (thiol) formation, critically influences meat quality during freezing, thawing, and reheating. Repeated freeze–thaw cycles and temperature fluctuations damage muscle proteins, increase reactive oxygen species (ROS), and promote carbonyl and disulfide cross-link formation, reducing WHC, altering texture, and generating off-flavors (Wan *et al.,* 2023). Concurrent lipid oxidation and protein degradation produce reactive α-dicarbonyls, such as glyoxal and methylglyoxal, which form advanced glycation end-products (AGEs) like N^{ϵ}-(carboxymethyl and ethyl)-lysine, further compromising flavor, color, and overall quality. This study evaluated porcine gelatin hydrolysate (PGH) for its protective effects against oxidative damage, preserving sulfhydryl groups and limiting carbonyl, α-dicarbonyl, and AGE accumulation during freeze–thaw cycles and reheating, providing insights into strategies to maintain protein integrity, sensory attributes, and freshness in frozen meat (Lu *et al.*, 2022).

15.9.1 Protein Carbonylation

Protein carbonylation, a primary marker of oxidative damage in amino acid side chains, increases during freezing, thawing, and reheating. Meat treated with PGH shows reduced protein oxidation because free amino acids and peptides stabilize proteins via radical scavenging, metal chelation, and hydrogen-bond formation with water, also limiting ice crystal damage during freezing. Heat and reheating accelerate oxidation through ROS, modifying amino acid side chains, and cleaving peptide bonds. Fresh meat carbonyl content of 17.97 nmol/mg protein doubles to 39.72 nmol/mg after 90 days of repeated freeze–thaw cycles, whereas PGH-treated meat exhibits significantly lower levels, confirming its protective effect (Lin *et al.,* 2025).

15.9.2 Sulfhydryl (Thiol) Content

Sulfhydryl (thiol) content is a key marker of protein oxidation during cooking, freezing, packaging, and storage. Oxidation of cysteine residues forms disulfide (S—S) bonds, causing protein aggregation, reduced WHC, altered texture, and sensory deterioration. Repeated freeze–thaw cycles markedly decrease thiol content in control meat, whereas hydrolysate-treated samples decline more slowly, both before and after reheating. Limiting oxygen exposure, such as via vacuum or modified atmosphere packaging, further preserves thiols and protein functionality. Oxidation of sulfur-containing amino acids also contributes to off-flavors, rancidity, and myoglobin-mediated discoloration (Indriani *et al.*, 2025).

15.9.3 α-Dicarbonyl Compounds

Glyoxal and methylglyoxal are α-dicarbonyl compounds that serve as key precursors of AGEs, which are generated during lipid oxidation and protein degradation, particularly under fluctuating freezing temperatures. Their levels increase in preheated and reheated pork with repeated freeze–thaw cycles. Protein hydrolysate treatment moderately increased glyoxal from 4.64 μg/g to 7.18 μg/g and methylglyoxal from 2.19 μg/g to 3.74 μg/g, whereas in the control group, hydrolysates slightly reduced these compounds (4.26% → 6.12%), indicating that freeze–thaw frequency strongly influences α-dicarbonyl accumulation, which can be partially mitigated by hydrolysate application (Lin *et al.*, 2025).

15.9.4 N^{ε}-(Carboxymethyl and Ethyl)-Lysine Content

Fluctuating freezing temperatures significantly increase N^{ε}-(carboxymethyl and ethyl)-lysine in pre-heated pork (47% to 65.56%), reflecting enhanced protein degradation. Protein hydrolysates, especially PGH, limit this rise to 14–17% by stabilizing reactive dicarbonyls and free amino acids formed during protein or lipid oxidation. Active peptides in hydrolysates scavenge free radicals, interact with precursor compounds such as Schiff bases, and inhibit AGE formation via the Maillard reaction. Overall, PGH mitigates oxidative damage from freeze–thaw cycles and reheating by reducing protein carbonylation, preserving sulfhydryl groups, and limiting α-dicarbonyls and AGEs. Untreated meat shows substantial oxidative deterioration, structural damage, off-flavors, and discoloration, highlighting the potential of protein hydrolysates as functional additives to maintain protein integrity, sensory quality, and overall stability in frozen and processed meat products (Lin *et al*., 2025; Niu *et al*., 2018).

15.9.5 Nucleotides and Lipids

Nucleosides and nucleotides contribute to meat flavor, particularly guanosine monophosphate (GMP), which is enhanced by electric-assisted freezing and imparts a mushroom-like flavor. In combination with disodium sarcosinate, GMP also enhances the perception of freshness. ATP in beef enzymatically degrades into ADP, inosine monophosphate (IMP), and hypoxanthine during storage. Levels of N^2-methylguanosine and xanthosine increased over time, while IMP gradually decreased, with slower degradation observed in LP. IMP is a key flavor compound that provides sweetness but is unstable, eventually degrading into hypoxanthine and xanthine, which are associated with spoilage.

Lipids also degrade during storage, producing aldehydes, ketones, short-chain fatty acids, and other derivatives. In this study, 29 differential lipid-like molecules were identified. Acetylcarnitine content increased with prolonged storage, reaching 11.39% in LP group and 29.78% in the control at day 24. 5-Hydroxyindole, generated via microbial protein breakdown, also increased during storage, with levels in LP significantly lower than in PS, indicating that LVEF effectively inhibits microbial growth and reduces spoilage-related nitrogenous compounds (Liu *et al*., 2025).

15.10 Physicochemical Properties

15.10.1 Textural Changes

Texture is one of the primary indicators of frozen food quality. In this study, freezing clearly softens both beef and potatoes compared with fresh, unfrozen samples. For beef in the air-frozen group, hardness and chewiness dropped to 14.69 N and 2.13 N, representing declines of 26.73% and 38.26%, respectively. UIF offered a solution to this problem. Beef in the UIF-150 group maintained hardness and chewiness close to those of fresh samples. This improvement was attributed to ultrasound accelerating freezing, shortening the phase transition, forming small, uniform ice crystals, and minimizing muscle fiber damage. The cavitation and mechanical effects of ultrasound also helped preserve overall dish quality (Sardari *et al*., 2025). However, more is not always better. As ultrasonic power increased, texture began to decline. In the UIF-450 group, beef chewiness and hardness decreased to 13.81 N and 2.18 N, demonstrating that excessive ultrasound can compromise texture (Cui *et al*., 2025). Tenderness, measured by Warner–Bratzler shear force (WBSF), showed a similar trend. Freezing and thawing affected muscle fibers, leading to fiber rupture, protein denaturation, and changes in WHC. Beef shear force decreased over 24 days, with LVEF-assisted freezing retaining higher shear force than static controls. LVEF produced smaller, more uniform ice crystals, reducing tissue damage and better preserving structure (Liu *et al*., 2025). Interestingly, steaks that underwent two freeze–thaw cycles were slightly more tender than those with only one, while storage temperature had little effect on shear force (Edwards *et al*., 2025).

Sous vide cooking (vacuum-sealed cooking) buffalo loins meat cuts illustrated another approach to improving tenderness. Adding sodium tripolyphosphate (STPP) softened the meat, reducing shear force from 113.4 N in the control to 93.8 N and 79.0 N with 0.15% and 0.3% STPP, respectively. Polyphosphate increases meat tenderness by preserving water and disrupting interactions among muscle fibers (Nora'zizi *et al.*, 2025). Chicken breast responded similarly to physical interventions. Freezing and thawing reduced hardness due to ice crystal damage, but HVEF thawing minimized these losses. Without HVEF, hardness was higher than fresh samples due to tissue gaps from ice expansion. Springiness decreased with varying HVEF intensities, while resilience generally declined, although greater hardness improved it. The optimal HVEF intensity was 50 kV/m, which also enhanced cohesiveness. Chicken meat is more sensitive to ice crystal effects due to its low-fat content and unique fiber alignment, which are better preserved by the application of HVEF (Hu *et al.*, 2025). Overall, these results highlight how advanced freezing and thawing methods, combined with chemical or physical interventions, can maintain the texture, tenderness, and quality of meat and vegetables, even after extended frozen storage.

15.10.2 Fourier Transform Infrared (FTIR)

FTIR spectroscopy is used to examine variations in the primary and secondary structures of meat proteins. In raw meat, FTIR provides a baseline protein conformation, showing the natural arrangement of α-helices, β-sheets, and other secondary structures. Changes in FTIR spectra can detect structural alterations caused by freezing, thawing, or different freezing methods, by analyzing variations in absorption and intensity to identify denaturation, unfolding, or aggregation using chemometric analysis. For example, ice crystal formation, water redistribution, and mechanical stress during freezing can alter hydrogen bonding and expose hydrophobic residues, resulting in structural changes. By comparing frozen and unfrozen meat, FTIR can reveal how treatments such as AF, IF, or ultrasound-assisted freezing affect protein stability and quality, which directly influences texture, WHC, and cooking performance.

The Amide I region (1,700 cm^{-1} to 1,600 cm^{-1}) of the FTIR spectrum exhibited greater changes in spectral intensity in meat without polyphosphate treatment, indicating higher levels of structural alterations and protein denaturation during cooking. In contrast, meat treated with 0.15% and 0.3% polyphosphate showed smaller variations and more consistent spectral patterns, suggesting that STPP stabilized the protein structure. Protein secondary structure was preserved through interactions between polyphosphate and protein side chains, reducing water loss and denaturation during cooking (Nora'zizi *et al.*, 2025).

15.10.3 Color

Meat color was measured using redness (a^*), yellowness (b^*), and lightness (L^*) values. High electrostatic voltages increased meat lightness, with L^* values rising from 51 to 54, while low-intensity treatments (10 and 30 kV/m) had minimal effects, producing color values like those of fresh meat. Redness (a^*) decreased due to oxidation and free radical formation, which disrupted heme pigments. Increases in b^* were attributed to pre-oxidant formation during freezing and thawing, promoting metmyoglobin formation and discoloration, consistent with elevated TBARS values (21).

Trained evaluators observed no significant differences in internal cooked color of steaks, regardless of freeze–thaw cycles or storage temperatures. Freeze–thaw cycles did not affect L^*, a^*, b^*, chroma, hue, or 630/580 values, indicating stable instrumental color under the tested conditions (Edwards *et al.*, 2025). HVEF thawing preserved meat color (L^*, a^*, b^*), with 10–30 kV/m maintaining lightness and minimizing total color changes (ΔE). HVEF reduced metmyoglobin formation and preserved total myoglobin, indicating lower protein oxidation. Thermal stability of proteins, measured by DSC, was higher in HVEF-treated samples, reflecting more stable native structures (Hu *et al.*, 2025).

For freezing treatments, L^* values of beef were lowest in ultrasound-assisted freezing (UIF) and IF compared with air-blast freezing. Both L^* and b^* values initially decreased during storage and then increased. The highest color changes were observed in air-frozen beef, which also had the lowest chroma

values. UIF treatment had minimal impact on hue angle, suggesting negligible overall color changes. For potatoes, L^* decreased significantly after freezing, resulting in a darker color with a reddish hue. Ultrasound treatment increased the yellowness of meat, as measured by b^* values, with the UIF-150 group showing the highest a^* and b^* values. ΔE^* for potatoes after freezing ranged from 4.22 to 11.58, with UIF-150 showing the lowest ΔE^*, indicating better color preservation.

The addition of sodium tripolyphosphate (STPP) significantly affected L^* and a^* values, while b^* remained unaffected. Increasing STPP lightened sous vide buffalo loins and preserved redness, with a^* increasing from 14.30 (control) to 16.28 with 0.3% STPP.

No significant effect on b^* was observed (Nora'zizi *et al.*, 2025). Color differences (ΔE) ranged from 2 to 10, which are discernible by the human eye. Under superchilling at 1.3–1.6 °C and −2.0 °C, ΔE values on day 1 were 2.5, linked to partial ice crystal formation in meat. In contrast, chilling at 4 °C showed no initial color difference ($\Delta E = 0$). ΔE increased slightly but significantly from day 1 to day 15 under 1.3 °C and 1.6 °C storage and remained stable until day 21. Freezing at −2.0 °C showed a larger increase, from 2.5 to 9.1 from day 1 to day 21. Superchilling effectively maintained meat quality (El-Abdi, Alvarez and Ndoye, 2025).

For chicken breast, freezing and thawing significantly reduced L^*. At 10 kV/m HVEF, L^* values were closer to those of fresh meat, while b^* values showed greater variation due to the yellow hue of chicken. b^* values for fresh meat were 8.47, with the highest value of 9.33 observed at 10 kV/m and the lowest at 5.64 with 50 kV/m HVEF intensity. The smallest color difference (ΔE) was observed at 30 kV/m, indicating samples closest in color to fresh meat (Hu *et al.*, 2025).

15.10.4 Heme Content

Frozen beef meat pretreated with a 10% spice formulation showed a marked increase in heme iron content, reaching 3.06 mg/kg by day 28, compared with 0.46 mg/kg in the control. Moreover, meat treated with BHT exhibited a similar heme iron content of 3.20 mg/kg. Lower (5%) and higher (15%) combined spice formulations also enhanced heme iron content, with values of 3.02 mg/kg for both (Evuen *et al.*, 2025).

During early storage (days 4–12), heme iron content in beef treated with 5–15% of Ethiopian pepper, Benin kauri, and Ashanti black pepper decreased, likely due to insufficient penetration of the extracts, resulting in limited protection against myoglobin oxidation and free iron release. Control samples exhibited progressive heme iron loss over frozen storage due to oxidative cleavage of porphyrin rings and dissolution of heme complexes.

15.10.5 pH

pH values in meat are influenced by storage temperature, duration, microbial activity, and biochemical changes. In fresh beef, pH initially decreases post-slaughter due to lactic acid from anaerobic glycogen breakdown, and then gradually rises as microbial protein degradation produces alkaline compounds. Constant superchilling has minimal effect on pH, whereas fluctuating superchilling maintains stable pH for 15 days before increasing significantly by day 21 (El-Abdi, Alvarez and Ndoye, 2025). Additives generally had no significant effect on pH, although an initial rise to 6.23 was observed, followed by a decrease to 6.02 by the third month of storage (Karim and Majid, 2025).

LVEF applied in combination with partial freezing maintained a lower pH in beef (5.63–5.73 over 24 days), indicating inhibition of pH elevation compared with the control (Liu *et al.*, 2025). In sous vide buffalo loins, the initial uncooked pH averaged 6.0 and increased to 6.2 after cooking without STPP. The addition of STPP further increased pH to 6.6 and 6.8 at 0.15% and 0.3%, respectively, while reducing CL (22.19% → 17.68% → 15.48%) and improving WHC (from 81.7% to 85.75%) (Nora'zizi *et al.*, 2025).

Advanced freezing techniques, including assisted fields such as ultrasound and magnetic fields combined with IF, maintained stable pH in pork during storage (Gan, Zhang and Jiang, 2024; Li *et al.*, 2022). Pulsed electric field combined with an oscillating magnetic field also had minimal effect on pH in chicken frozen at –7 °C (Mok *et al.*, 2017). Pulsed electric field improves salting in pork without affecting pH, CL, or texture (McDonnell *et al.*, 2014).

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16

Thermal Techniques in Meat Processing: Applications and Quality Assurance in Beef, Poultry, and Pork Meat Processing

Zahra Teymouri and Theodoros Varzakas

16.1 Introduction

Thermal treatment utilizes heated air, hot water, or steam. This method can effectively reduce the invasion of pathogenic microorganisms and eliminate enzymatic activity but also lead to an increase in shelf life of meat products.

Red meat is defined as the muscle flesh of mammals (such as cattle, sheep, pigs, camels, horses, and deer), which consists of myofibrils (muscle fibers) intertwined by connective tissues (collagen and elastin) (Tiwari and O'Donnell, 2012). The red in raw meat is attributed to myoglobin, a pigment stored in muscle cells. From a nutritional point of view, red meat is a good source of high-quality protein, essential fatty acids, iron, zinc, and B vitamins, which play an important role in human health and growth. Due to its high nutritional value, red meat is an important source of nourishment for humans, especially in developing countries, where it plays a significant role in reducing deficiencies in protein and energy (Khalid, Maggiolino and Kour, 2023). Globally, demand for meat has climbed steadily in recent years due to increases in both population size and disposable income, as well as increasing public awareness of the need for nutritionally balanced diets. However, meat is generally regarded as a highly perishable food due to its high moisture and fat content, which provides an ideal environment for microbial spoilage, lipid oxidation, and the enzymatic degradation of protein, leading to changes to flavors, colors, and textures that would be considered undesirable. Therefore, it is important to maintain meat safety and quality throughout processing and storage to ensure a food supply with optimal quality for the consumer (Wang, Chen and Zhou, 2024).

To address these issues, various preservation and processing techniques have been introduced with the goal of prolonging shelf life and maintaining safe products. Of these techniques, thermal processing is the most commonly utilized and successful approach to control spoilage microorganisms and enzymes while simultaneously enhancing flavor and overall meat-eating quality. Traditional thermal processing methods include cooking in an oven and frying, while more contemporary techniques include sous vide, microwave (MW), radio frequency (RF), and ohmic heating (OH). During thermal processing, proteins denature and muscle fibers contract, the latter affecting the tenderness and juiciness of the meat post-cooking. In recent years, novel heating techniques have become popular, as they are shown to improve quality while using less energy and producing a shorter processing time. Also, the application of modern packaging both prior to and post cooking has gained significance in supporting structure, flavor, and overall product stability (Iammarino *et al.*, 2024).

In recent years, innovative cooking technologies have been recognized for their ability to potentially decrease energy usage, increase production efficiency, and enhance overall meat product quality while changing consumer preferences toward ready-to-eat products. Packaging meat before or after cooking is also recognized as a modern technique that is increasingly used as it supports retention of structural

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quality properties of meat, flavor retention, the reduction of microbial risks, and reduced labor costs (Gong, Feng and Sun, 2025).

Heat-induced gelation of myofibrillar proteins (composed of myosin and actin, accounting for approximately 50–60% of the total muscle proteins in animals) is responsible for the production of processed meat products such as ham and sausages. Protein gelation is a complex process involving partial unfolding, intermolecular aggregation, and covalent and noncovalent cross-linking. Promotion of the solubilization and unfolding of brillar proteins comes from the addition of salts, such as sodium chloride (NaCl) and potassium chloride (KCl) during processing which modify the ionic environment of proteins (Cao *et al.*, 2024; Lee, Jeong Jeong and Han, 2026).

Hence the enhancement of the formation of various cross-links, such as disulfide bonds and hydrophobic interactions, during heating.

A general overview of both classic and novel thermal techniques, along with analytical methods to track heat-induced modifications, is illustrated in Figure 16.1. Traditionally, sensory, microbiological, and physicochemical methodologies have been employed to assess the modifications to cooked meat. While these approaches are useful, they are primarily labor-intensive and costly, resulting in processors often adding additional heat to ensure the food safety of cooked meat by eliminating pathogenic organisms, resulting in indicators of quality damage such as excessive denaturation of proteins, oxidation, and digestibility reductions (Zhang *et al.*, 2024). Therefore, a pressing need has arisen for rapid, dependable, and nondestructive methods of assessing thermal processing and, thus, overseeing against both undercooking and overcooking. Recent research has also highlighted spectroscopic methods, that is, methods that measure the manner in which light interacts with food materials, which can also signal changes in meat quality while undergoing thermal exposure. These methods, overall, infrared (IR) (Chen, Zhou and Sun, 2016), nuclear magnetic resonance (NMR) (Ampem *et al.*, 2022), Raman, and fluorescence spectroscopy (Sahar *et al.*, 2016), provide rapid, accurate, and noninvasive assessment of structural and chemical changes (Alfaifi *et al.*, 2023). Mathematical modeling has also become a key tool for modeling heat and mass transfer during cooking. These models assist in process optimization, improving food structure uniformity, and developing energy-efficient machines (Tiwari and O'Donnell, 2012). In cooking, there are ample factors affecting heat and mass transfer: processing temperature, airflow rate, meat product type, and cooking medium. Mathematical modeling of the thermal processing of meat allows for investigation of all these factors, thus analyzing the mechanisms of heat and mass transfer. Knowledge gained through modeling steers the development and optimization of processing equipment, aids in planning production, and contributes to improvements in product characteristics, texture, and flavor while minimizing process losses and better controlling essential variables of the heat treatment step (Kim *et al.*, 2025).

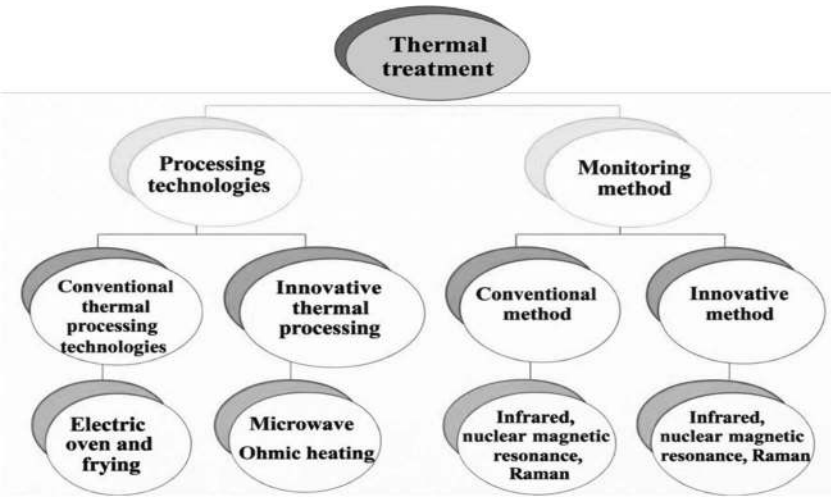

FIGURE 16.1 Schematic illustration of thermal treatments applied to meat products, including processing technologies and monitoring techniques.

We should remember that food poisoning outbreaks are caused by inadequate time/temperature exposure during cooking, hence optimal heat treatment is required not only for destruction of pathogenic microorganisms in meat and poultry but also for maintenance of the desirable food quality and product yield.

The concept of decimal reduction time (*D*-value) and thermal resistance constant (*z*-value) express the time–temperature relationship of the thermal inactivation of pathogens. The *D*-value is the time required to cause a 90% reduction of the microbial population at a specific temperature. Calculation of *D*-value at each temperature comes from the linear regression model between $\log_{10}$ of the bacteria survivors and heating time. A thermal death time (TDT) curve is prepared by plotting heating time along the linear axis and the number of survivors along the *y*-axis. The *z*-value is the temperature difference required for the thermal inactivation curve to cause one $\log_{10}$ reduction. It is correlated with the tolerance of a specific pathogen to the temperature changes in the product. Determination of the linear regression between $\log_{10}$ of *D*-values and temperature calculates the *z*-value (Griffis and Osaili, 2009).

This chapter aims to provide an overview of both conventional and innovative thermal processing technologies used in meat production, emphasizing the use of spectroscopic and modeling techniques for monitoring and improving product quality.

16.2 Thermal Processing Technologies

The utilization of heat to cook and preserve meat has been practiced by humans for over thousands of years; it is truly an ancient practice. Early humans discovered that fire improved the flavor of meat, along with making it easier to chew and safer to eat (Gazda and Glibowski, 2024). Over generations, simple fires transitioned into more sophisticated cooking methods: boiling, roasting, baking, etc. These methods form the history and context for today's advanced, technological thermal processing. Additionally, today, through modern food engineering, these heat-assisted techniques are used for more than flavor and texture, they built into the processing system for safety, efficiency value, and consistency in outcome every time (Deng, Nie and Zhou, 2024).

Currently, in meat processing, the heating technologies available include traditional methods such as grilling, frying, and oven roasting, and newer innovations like ohmic, MW, RF, and sous vide systems. Although conventional heating is still commonly practiced in households and factories, these new technologies have gained fame due to their even heat distribution, shorter cooking times, and lower loss of nutrients. Moreover, these advanced systems not only enhance safety, but preserve essential sensory attributes, including tenderness and juiciness (Alfaifi *et al.*, 2023).

Thermal processing techniques are classified mainly by heat transfer mechanisms and cooking medium. Dry-heat methods (roasting, grilling, frying) will use air, radiant energy, or oil as the cooking medium to develop unique flavor and color through Maillard browning. Additionally, dry-heat methods can provide uneven heating patterns and denature nutrients (Samad, Alam and Kumari, 2024). Moist-heat methods (boiling, steaming, and pressure cooking) use water/steam as the heating medium, which allows for somewhat more uniform heat transfer and improves tenderness, but may also leach nutrients. Lastly, electromagnetic-based methods (MW and OH) are capable of volumetric heating by translating electrical energy to heat from the interior, allowing for a more rapid and uniform heat distribution (Rebezov, Khayrullin and Assenova, 2024).

Processors in both domestic and industrial applications frequently employ multiple processes to achieve the desired trade-offs between texture, flavor, and efficiency. Success of a thermal process involves factors such as temperature, time, rate of heating, and the meat properties (e.g., composition, thickness, fat), which together determine the extent of protein denaturation, water removal, and oxidative reactions that take place upon heating (Gong, Feng and Sun, 2025; Tiwari and O'Donnell, 2012). Heating to high temperatures can lead to metabolic damage to heat-sensitive nutrients and altered flavor; on the other hand, if low temperatures are used, there may be a microbial safety hazard. Thus, robust time–temperature combinations are vital in ensuring safety while retaining the quality.

In choosing the appropriate thermal process, the nature of the raw material and the type of product expected will influence the choice of method. In the industry, parameters of heat treatment are typically

TABLE 16.1

A Summary of Previous Studies Investigating Different Types of Red Meat and Thermal Processing Methods

Meat Type	Cooking Method	Conditions	Key Findings	Reference
Camel (*Latissimus dorsi*)	Sous vide, electrical oven	70 °C, 80 °C, 90 °C, 100 °C 30–180 min	• pH, cooking loss, and yellowing color increased • Density, water activity, lightness, and redness decreased • Tenderness and flavor improved, and juiciness decreased • *Optimal*: sous vide 100 °C, 180 min	Hobani *et al.*, 2023
Pork loins (*M. longissimus*)	Sous vide	60 °C, 65 °C for 2–4 hours; 70 °C, 75 °C for 1–2 hours	Cooking loss increased with longer time and higher temperature, while pH and water activity remained stable. The most tender and flavorful samples were obtained at 60–65 °C for 4 hours	Hobani *et al.*, 2023
Beef strip loins (*Longissimus lumborum*)	Grilling, oven roasting	150 °C, 230 °C	Dry-aged beef grilled at 230 °C showed increased roasted aroma, whereas lower temperature (150 °C) intensified cheesy notes. Grilling improved flavor intensity	Lee *et al.*, 2021
Pork (*short shank*)	Sous vide, ohmic	70 °C	• Tenderness increased in all methods • No notable differences in cooking loss or water-holding capacity	Ángel-Rendón, Filomena-Ambrosio and Hernández-Carrión, 2020
Beef steaks	Electrical, gas oven	Up to 110 °C	Protein, water, and physical properties similar; Electric oven increased fat but reduced TBA and peroxide compared to gas oven	Lorenzo *et al.*, 2015
Foal steaks	Frying	150–190 °C	Microwave-cooked meat had greater cooking loss and shear force. Frying in olive oil increased color and flavor quality	Bozkurt and Icier, 2010
Ground beef	Ohmic cooking	20, 30, 40 V/cm	Heating occurred considerably quicker than in traditional cooking ($p < 0.05$). Ohmic processing offered greater thermal uniformity and product stability	Palka and Daun, 1999
Beef steaks	Atmospheric pressure, sous vide, cook-vide	60 °C, 70 °C, 80 °C 15–60 min	• Sous vide and cook-vide cooking methods retained moisture and crispness better than atmospheric cooking. • Color stability was improved under oxygen-limited conditions.	García-Segovia, Andrés-Bello and Martínez-Monzó, 2007

adjusted to obtain a standardized color, tenderness, and flavor, while reducing energy consumption and/or losses during processing. Table 16.1 outlines key studies that have examined various meat types and their associated heating conditions.

16.2.1 Traditional Thermal Processing Methods

Traditional thermal processing encompasses the traditional heating methods used over the centuries to prepare and preserve meat. These normal heat transfer techniques, through conduction, convection, or radiation, ensure microbial safety and acceptable sensory properties for meat. Although traditional techniques may appear old-fashioned in comparison to modern systems, they continue to dominate home and industrial cooking because they are simple and reliable, while providing typical flavors in the meat.

16.2.1.1 Electric Oven Heating

Oven heating is one of the most widespread traditional techniques in meat preparation. This technique applies heat to the food to raise its internal temperature to a maximum of 250 °C through a combination of convection and radiation. The electric oven used in this experiment is designed to transform electrical energy into heat energy to use to prepare meat. The electric oven contains heating elements, a fan for convection, control interface, temperature and timing sensors, and a tray that holds meat samples, as depicted in Figure 16.2. The heating elements for the electric oven are positioned at the top and bottom of the oven cavity to promote consistent heating of meat samples. The transfer of energy to the product occurs from a combination of radiation, convection, and conduction. The primary variables controlling the cooking process are the temperature of the oven, duration of heating, and the properties of the meat. The evaporation of moisture on the surface of the meat usually occurs first during heating, which further increases the cooking process of the internal protein matrix from a combination of natural and forced convection.

For instance, Danowska-Oziewicz, Karpińska-Tymoszczyk and Borowski (2007) were interested in examining the effects of cooking camel meat in an electric oven on sensory quality and texture. In their results, they established that older camels necessitated a longer cooking period. They also pointed out that young camels produced more flavorful and tender meat and that the age of the animal ultimately resulted in juiciness loss. Possibly, Dawood (1995) also studied the implications of aging muscle and the heating of muscles in an electric oven on the protein structure and texture of beef muscles cooked in the range of 70–80 °C. He indicated denaturing and degradation of protein occurred, and when the cooking temperature surpassed 80 °C, more extensive structural damage continued. Notably, these protein alterations made tremendous changes to the rigidity of muscle fibers impacted by the rigidity of tenderness of meat and therefore they recommended infusing steam in cooking in electric ovens for improved tenderness. Moisture steam impedes surface drying and shrinkage, protecting juiciness and qualities of the cooked texture.

16.2.1.2 Frying

Frying represents a historical methodology of thermally preparing food, with cooking oil as the primary transfer medium in heat transfer; cooking oil is transferring energy to the meat food at the point of oil–meat contact with conduction. Although the cooking oil will transfer more heat to the surface of

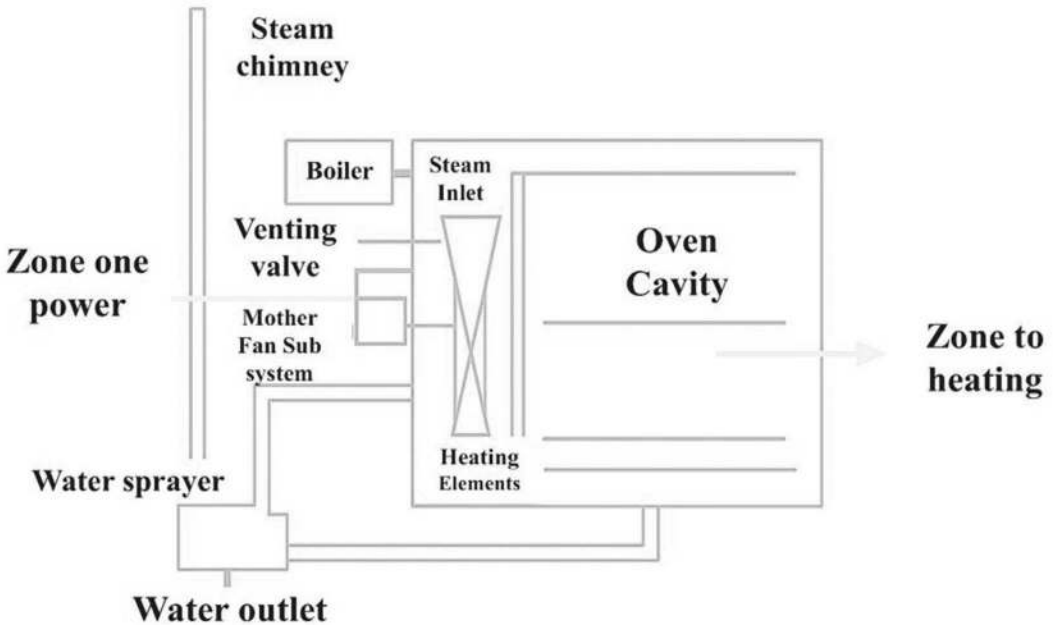

FIGURE 16.2 Schematic of the electric oven, adapted and modified.

the meat food at the point of oil–meat contact with conduction, there are many factors relating to the meat food (physical factors of the composition of the meat) that influence the efficiencies of the transfer of heat to the meat food, some of which include surface area of meat food in contact with the cooking oil and the temperature of the cooking oil at the moment in time that frying begins. Frying is generally described in a four-phase process. The first phase is the conduction of heat from oil to the outer surface of meat food (convection) (Zhang, Zhang and Adhikari, 2020). In the subsequent step, the moisture from the surface will evaporate, as convective transfer becomes more intense; that is, natural convection shifts to forced convection. During the third step, the internal heating will increase, and a crust will start to form on the external layer. In the fourth step, the temperature at the center of the meat will continue to rise until doneness is reached. Frying not only heats the meat but also accomplishes physical and chemical changes: water evaporation, protein unfolding, fat absorption, surface browning, and crust formation. Frying is recognized for its relatively fast cooking time. Sosa-Morales, Orzuna-Espíritu and Vélez-Ruiz (2006) investigated heat and mass transfer and quality changes in frying pork and stated that temperature of the oil is a major factor. Overall, the heat diffusivity of the meat remains constant during frying; however, the thermal conductivity would be expected to continue to decrease over time due to moisture loss.

16.2.1.3 Air Impingement Oven Cooking

Air impingement cooking combined with steam is extensively used in the processing of RTE meat and poultry products (Murphy *et al*., 2001). Temperature, air velocity, and conveyer belt speed greatly affect the process lethality of foodborne pathogens in meat and poultry products during thermal processing in these types of ovens.

Continuous air impingement ovens have also been used, representing an advanced convection system whereby jets of heated or chilled fluid are addressed at high velocities (approximately 10–50 m/s) onto the surfaces of a food or meat product. The product boundary layer is removed by the use of high air speeds resulting in increased rates of heat transfer (Kerry, 2011; Ovadia and Walker, 1998).

16.2.1.4 Steam or Hot-Water Pasteurization

Post-processing contamination of RTE meat and poultry products is a concern for the public as well as the government. Steam pasteurization uses superheated steam for rapid, efficient heating. It is ideal for high-volume processing and products in heat-resistant packaging, releasing significant energy upon condensation for quick pathogen kill. Immersion or sprays deal with hot water pasteurization uses, offering gentler, more controlled heating, better for delicate products or glass containers to prevent thermal shock, although generally slower.

The use of post-cook heat treatment as a prepackaging or as a post-packaging treatment has been applied to reduce the risk of contamination of RTE poultry or meat products by foodborne pathogens, particularly *L. monocytogenes*. In a prepackaging process, heat is applied to cooked products immediately before they are packaged, while heat is applied to cooked products after they are packaged in the post-packaged process (Griffis and Osaili, 2009; Karim *et al*., 2023; Murphy and Berrang, 2002; Ramesh, 2020). In-package pasteurization reduces the chances of post-processing contamination that is often the case with hot-filled products. However, during in-package processing, the packaging material is also subjected to heating conditions, unlike with a hot-fill process (Bhunia, Tang and Sablani, 2024). Murphy *et al*. (2003) used hot water as a post-cook in package pasteurization to eliminate *L. monocytogenes* from unsliced RTE turkey breast meat products.

In commercial thermal pasteurization operations, foods are heated to a temperature <100 °C to inactivate nonspore-forming pathogens of public health significance. Pasteurization can also partially inactivate enzymes and spoilage microorganisms not affecting food quality and also can lead to extension of the shelf life of food products and meats under proper storage conditions (i.e., cold storage for foods with pH > 4.6) (Peng *et al*., 2017). There are batch and continuous systems. The latter consists of a long tunnel fitted with a conveyor belt to carry the packages through preheating, heating, holding, and cooling sections of the tunnel (Ramesh, 2020). Water spray and steam at atmospheric pressure are used as

the heating media of in-packaged foods. Glass containers continuous systems are divided into several heating and cooling sections with a smaller temperature difference (20–40 °C) to avoid thermal shock to the containers.

16.2.1.5 Sterilization

Thermal sterilization involves heating of food to a temperature of 110–125 °C to ensure destruction of spore-forming bacteria (Tang, 2015).

Thermal sterilization can be classified as (i) in-package sterilization or (ii) sterilization prior to aseptic packaging. The batch retorts are manufactured in two different configurations: (i) static and (ii) agitating retorts (Jimenez *et al.*, 2023). Heating media are saturated steam, a steam and air mixture, and hot water under high pressure (Allpax, 2025). Rotary, hydrolock, and hydrostatic continuous systems are used in the food industry (Ramesh, 2020).

16.2.2 Innovative Thermal Processing Methods

Traditional food processing techniques that rely on heat utilizing external methods (via conduction, convection, or radiation) to transfer a large amount of energy relative to the mass of food. However, surface heating created uneven heating distributions, hotspots of heating, loss of nutrients and flavor, and longer cooking times. The slow nature of thermally driven systems has led to the need for newer thermal technology that are a more controllable and effective thermal process. Clearly, more recent innovations in the food processing field, such as OH, MW heating, RF heating, and IR heating, have further advanced beyond traditional methods (Iammarino *et al.*, 2024; Khalid, Maggiolino and Kour, 2023). These heating systems also introduced volumetric heat generation from both options of food. These heated generate volumes of heat, and instead of a surface flash-heating technique that traditional cooking uses, these heating systems generally heat more quickly since food and food products are exposed to more uniform heating (as opposed to surface heating). This is also accompanied by creating a substance that will degrade food materials less during the heat treatment while preserving the flavor and nutrients. Moreover, these heating systems use energy more effectively and provide uniformity in the final product. In conclusion, these faster methods of heating have facilitated innovative confirm-composting processes, mostly but not in completion, using OH, MW, RF, and utilization to control heating and speed up processing times (Samad, Alam and Kumari, 2024; Wang, Chen and Zhou, 2024; Zhang *et al.*, 2024). This leads to better heat transfer performance and preservation of desirable sensory characteristics.

16.2.2.1 Ohmic

A fundamental aspect of OH in the processing of meat is that electrical energy is transformed into heat, and that heat is generated exclusively in the product itself. When electrical current passes through the meat, charged species in the tissue get agitated from the alternating current, and heat energy is generated from the displacement of those molecules. This is unlike conductive metals, where the conducting of electrical current is due to the movement of individual electrons. In meat, the electrical current is conducted by the ions present in proteins, minerals, and charged species, as they move back and forth to complete the circuit from the anode to cathode. The literature proposes that water will raise the voltage value observed to cause a rise in temperature, thus contributing to an overall rise in temperature. This internally generated heat will lead to a greater uniform cooking temperature distribution and may affect mechanical and physical properties and eventual textural properties of the final products (Richa, Shahi and Singh, 2017).

There are many useful features of OH for meat applications. According to Özcan *et al.* (2018), an advantage of ohmic treatment is that it is not limited by heat transfer at the surface, allowing for fast and uniform energy dispersion. Using OH typically results in meat products that have better temperature uniformity, color stability, shelf life, and retention of nutrients. OH is also considered a green and less energy intensive option compared to recommendations for traditional cooking procedures. Figure 16.3 shows the schematic of a basic OH unit consisting of a rectangular processing chamber, titanium-coated

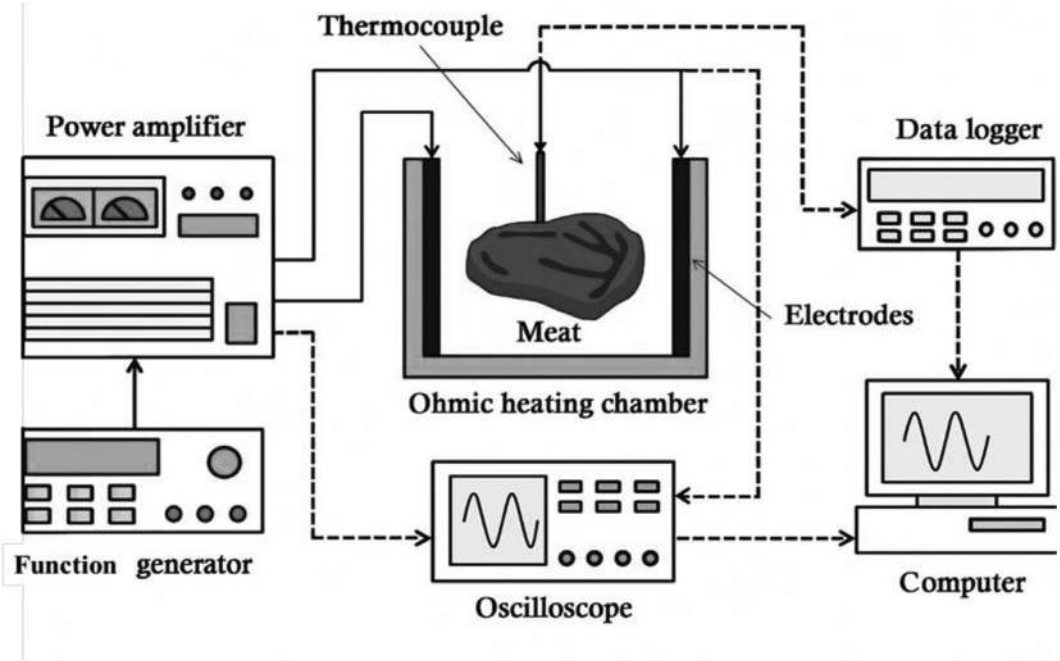

FIGURE 16.3 Schematic representation of the OH system.

stainless-steel electrodes, an adjustable wattage source, voltage and current controllers, data acquisition unit, thermocouples, and transformers. A meat sample is placed into the processing chamber, and the sample is exposed to an alternating electric field of set intensity. During the treatment, the voltage applied, controlled by the controller, induces heating in the product that is uniform and steady (Aydın, Kurt and Kaya, 2021). The heat produced in the product is controlled by the applied voltage controlled through the voltage controller and depends on the amount of current selected, producing a uniform temperature in the product meat.

Researchers have been experimenting with OH for meat products to evaluate how it actually changes the meat quality. In one of the earlier works, Bozkurt and Icier (2010) analyzed beef with different fat contents (about 2%, 9%, and 15%) and applied electric field strengths between 20 V/cm and 40 V/cm. They found that the meat cooked way faster than with traditional heating, and it lost less juice, around 10% instead of more than 30% (conventional thermal cooking). The texture also stayed tighter and lower cooking losses. Later, Aydın, Kurt and Kaya (2021) examined fish pâté treated by both OH and water bath heating methods. The findings showed that OH decreased processing time, while enhancing sensory quality attributes such as flavor, aroma, and appearance. Ghnimi *et al.* (2008) investigated the impact of ohmic treatment on the electrical conductivity of minced beef and determined that meat composition significantly speeded up the heating process in relation to conductivity and overall product quality. There is emerging research investigating the application of OH to Industry 4.0 food systems for sustainability and process optimization. The method is emerging as a new thawing technology for meat and seafood, reducing the time and drip loss while maximizing product quality such as better shrimp peelability and thawing for minced beef (Llave *et al.*, 2018; Zia, Khan and Shabbir, 2022). Experimental data and additional details on OH system applications in meat processing are presented in Table 16.2.

16.2.2.2 Microwave and Radio Frequency

MW and RF heating techniques are modern thermal processing methods and have provided efficient alternatives to traditional heat-based processes. As with OH, the electrical energy used in these processes is converted into electromagnetic waves to supply heating directly within the food matrix

TABLE 16.2

Overview of Ohmic Heating Applications in Meat and Seafood Products

Meat-Based Food	Treatment Purpose	Process Conditions	Most Results	Reference
Vacuum-packed sausage	Pasteurization	*F*: 50 Hz *T*: 75 °C *Duration*: 30 seconds *Current*: 40 A *Voltage*: 430 V	• The count of *Listeria monocytogenes* decreased by more than 5 log • There were no notable changes in pH, lipid oxidation, moisture loss, or chemical structure • Only slight modifications were observed in color and texture, and sensory quality remained unchanged	Inmanee, Kamonpatana and Pirak, 2019
Meat-based baby food	Sterilization	*F*: 25–50 kHz *T*: 90 °C *Duration*: 10 minutes	• Furan contents reduced by 70–90% • Lower lipid oxidation and fewer Maillard reaction products compared with traditional heating	Hradecky *et al.*, 2017
Australian and Japanese beef	Cooking	*F*: 50 Hz to 25 kHz *T*: 5–65 °C *Voltage*: 50 V	• Cooking was slower in high-fat Japanese beef; both beef types showed reduced drip loss at 20 kHz	Llave *et al.*, 2018
Meatball	Cooking	*Heat fluxes*: 3.7, 5.7, 8.5 kW/m² *Duration*: 4, 8, 12 minutes *Ohmic heater*: 15.26 V/cm	Significant reductions observed in total aerobic bacteria, yeasts, molds, *S. aureus*, *C. perfringens*, *Salmonella* spp., *L. monocytogenes*, and *E. coli* O157:H7	Sengun, Icier and Kor, 2017
Beef loin	Thawing	*Voltage*: 50 V	• Increased quicker thawing • Lowered total counts of *Pseudomonas* spp. and coliforms • Color parameters remained stable	Külcü and Gürbüz, 2018
Shrimp	Thawing	*Voltage*: 92, 138, 184 V *F*: 60 Hz, current: 40 A *T*: 30–60 °C	• Overheating resulted in protein denaturation, tougher skins, and loss of pigment • No increase in peelability was observed	TemThi *et al.*, 2020
Scallop muscles	Thawing	*Voltage*: 50 V (heating), 100 V (thawing) *F*: 50 Hz to 20 kHz *T*: −20 °C to 65 °C	• Higher frequency and temperature accelerated heating and reduced resistance • Minimal effect on moisture loss and texture • Reduced actin denaturation	Llave *et al.*, 2018

Abbreviations: A, amperes; *F*, frequency; Hz, Hertz; kW, kilowatt; MHz, megahertz; *T*, temperature; V, volt; W, watt.

(Zia, Khan and Shabbir, 2022). The dielectric heating allows processing time to be reduced, the penetration of energy deeper into the product, and the heating to be evenly distributed throughout the product to the center. The studies of importance on the application of MW and RF heating for meat are summarized in Table 16.3.

The main mechanism associated with RF thawing is associated with the oscillation of ions and the rotation of polar molecules in the frozen tissues which converts the electromagnetic energy into heat that

TABLE 16.3

Overview of RF and Microwave Heating Applications in Meat and Seafood Products

Thermal Processing	Meat-Based Food	Process	Operating Conditions	Main Findings / Outcomes	Reference
Radio frequency heating	Pork hams	Cooking	5,300 V, 27.120 MHz Conveyor belt 10 m/h	RF cooking reduced time of processing by approximately 50%, with a slight decrease in sensory quality	Muñoz, Serra and Guàrdia, 2020
	Chicken breast meat	Thawing	10 kW, 27.12 MHz 1,500 V	• Thawing rate increased • Drip loss reduced and texture improved due to uniform field distribution	Bedane *et al.*, 2018
	Pork tenderloin	Cooking	27.12 MHz, 1.4 kW *Electrode distance*: 100–140 mm	RF heating reduced processing time, enhanced water retention, promoted β-sheet self-assembly, and created a highly stable, ordered protein gel network	Wang, Wang and Yang, 2021
	Raw Pacific sauries	Pasteurization	27 MHz, 9 kW 19 minutes to reach 120–130 °C	Achieved 5-log reduction of *Bacillus subtilis* spores, confirming effective inactivation of heat-resistant microorganisms	Uemura *et al.*, 2017
	Lean beef meat block	Thawing	27.12 MHz, 6 kW *Conveyor belt speed*: 1–60 m/h	• Stable heating obtained during thawing • Optimal results at 0.2–0.4 °C with 3 m/h belt speed	Llave and Erdogdu, 2022
	Lean pork	Thawing	3 kW, 27.12 MHz	• Reduced tempering time with uniform temperature distribution • Maintained acceptable sensory and physicochemical quality (lower cooking loss, pH, and TVB-N • Higher *b** value)	Zhu *et al.*, 2019
Microwave	Chicken thigh and breast meats	Cooking	180 W for 10 min	• Cooking loss and color remained similar to traditional heating • Firmer texture due to protein changes	Ghnimi *et al.*, 2008
	Grass carp meat	Cooking	600 W *Final temperature*: 70 °C	• Increased saltiness perception • Reduced tertiary structure unfolding and cooking loss • Maintained the compact meat structure	Wang *et al.*, 2019
	Pork bellies	Cooking	800 W for 100 seconds 400 W for 200 seconds	Increased tenderness was accompanied by improved water retention capacity and favorable microstructural changes	Wang *et al.*, 2020
	Beef (gluteus medius)	Roasting	35 kW at 180 °C and 80 °C *Intensity levels*: 30% and 100%	• Moderate energy improved texture and limited shrinkage • Excessive energy negatively affected quality	Półtorak, Wyrwisz and Moczkowska, 2015
	Yak meat	Cooking	420, 560, and 700 W *Heating time*: 90–310 seconds	• Longer heating increased losses and shear force • Improved aroma and texture but caused a slight reduction in color and moisture	Li *et al.*, 2019

Abbreviations: A, amperes; *F*, Frequency; Hz, Hertz; kW, kilowatt; MHz, megahertz; *T*, temperature; V, Volt; W, Watt.

enhances thawing (Llave and Erdogdu, 2022). Bedane *et al.* (2017) successfully conducted RF thawing of beef blocks with a conveyor-based RF system. The study revealed that the motion/rotation of the sample during processing was responsible for a redistribution of the electromagnetic field which allowed for improved heating distribution. There were also several processing conditions which were assessed in both static and dynamic developing conditions. Overall, RF thawing at 27.12 MHz, 6 kW, and 3 m/h conveyor speed was noted to impart the best uniform heat to the products. The use of RF for the meat industry has not yet gained a great amount of traction; however, that traction should evolve and develop in the near future.

MW heating happens in frequencies that go from 300 MHz up to 300 GHz. These correspond to wavelengths around 1 m to 1 mm (Khalid, Maggiolino and Kour, 2023). This technology really changed food-based system for preparing meat in both industrial settings and home kitchens. It generates heat faster and uses less energy. The technology has been transformative for the preparation of meat in both the industrial and household cooking processes by producing heat more rapidly and with less energy all while maintaining the nutritional quality of the food due to volumetric heating. Industrial MW systems tend to operate on 915 and 2,450 MHz (32.8 cm and 12.2 cm wavelengths, respectively), whereas domestic MW ovens are typically 2,450 MHz. Commonly, a MW will include a metallic cabinet that will have an access front door to the oven cavity for placement of food, a transformer that increases the input voltage (110–220 V) to about 3,000–4,000 V, a MW-generating device called a magnetron, and a waveguide to allow waves to access the cavity (Rebezov, Khayrullin and Assenova, 2024). A fan provides cooling to the magnetron to prevent overheating, and is fitted with a rotating turntable to improve uniformity of heating, if needed. For the user, the machine provides the settings via a user interface. MW energy produces heat throughout the volume of the product, which is different than standard heating processes, which conduct heat from the surface of the product enriched with moisture and salt, from the outer surface toward the center. The MWs stimulate conversion of electromagnetic energy to thermal energy in the tissue (Chandrasekaran, Ramanathan and Basak, 2013). This stimulation occurs primarily due to dipolar rotation and ionic conduction, as the waves travel and penetrate into the meat item.

MW heating works quite differently from traditional cooking methods. Instead of slowly transferring heat from the outside in, MWs heat food from the inside out by converting electromagnetic waves directly into thermal energy (Chandrasekaran, Ramanathan and Basak, 2013). This transformation happens, thanks to two key mechanisms: dipolar rotation and ionic conduction. When MWs pass through meat, water molecules spin rapidly, generating friction that turns into heat. At the same time, charged particles like salt ions vibrate, adding even more warmth. While various factors—like the food's physical, thermal, and dielectric properties—can influence how well this process works, the amount of water and salt present plays the biggest role in heating efficiency. Compared to conventional cooking, MWs heat food faster, use less energy, and better preserve nutrients in meat (Zia, Khan and Shabbir, 2022).

Scientists have been exploring MW cooking since the mid-1900s, beginning with foundational studies by Decker, Beyer and Chao (2024). As people increasingly look for quicker and safer ways to prepare meals, interest in MW technology has grown. Researchers have examined how MWs affect meat texture, protein structure, internal composition, and flavor compounds. For instance, when yak meat was cooked using both MW and traditional methods, MWs enhanced its texture and aroma, but also led to more moisture loss and reduced color vibrancy (Mirzazadeh, Sadeghi and Beigmohammadi, 2021).

MW cooking offers a safer option for preparing beef cocktail smokies, producing fewer harmful compounds like volatile *N*-nitrosamines and polycyclic aromatic hydrocarbons compared to frying or grilling (Jouquand, Tessier and Bernard, 2015). Despite these advantages, several disadvantages persist, particularly uneven heating, limited surface browning, and textural inconsistencies. These can be improved by combining MWs with other heating techniques such as convection, IR, or induction. Although MWs are a staple in home kitchens and catering setups, their use in large-scale food production is still limited. This is mostly due to uneven heat distribution and the high cost of equipment, although newer technologies are starting to address these challenges (Chandrasekaran, Ramanathan and Basak, 2013; Mirzazadeh, Sadeghi and Beigmohammadi, 2021).

Compared to ohmic or RF heating, MWs are especially practical for home use. Recent developments, like solid-state MW generators and hybrid systems, have expanded their capabilities (Ekezie *et al.*, 2017). Replacing conventional magnetrons with solid-state sources offers improved control over frequency and power, increasing process precision and reproducibility while reducing energy waste and addressing the common problem of nonuniform heating. The integration of solid-state and hybrid MW technologies represents an important step toward developing intelligent and adaptive food processing systems aligned with Industry 4.0 standards (Atuonwu and Tassou, 2018).

16.2.2.3 Infrared

IR heating has gained attention in the meat processing industry as a modern method for applying thermal energy. Like MW and RF systems, it operates through electromagnetic waves, offering rapid surface heating and notable energy efficiency. However, its limited ability to penetrate deeper layers of meat and slower internal heat transfer make it best suited for thin cuts or surface-level pasteurization (Özcan *et al.*, 2018). Even with these limitations, IR heating is valued for its ability to minimize nutrient degradation and achieve quick, uniform browning on meat surfaces. When used in combination with other heating methods, its overall efficiency and product quality can be significantly enhanced. For instance, Creed (1998) looked into two-step process involving OH followed by IR heating in meatball production. OH ensured consistent internal cooking but lacked the surface coloration consumers. The addition of IR heating corrected this, enhancing the meatballs' appearance and overall sensory appeal. This combination illustrates how IR technology can complement other methods to improve both efficiency and product quality in contemporary meat processing.

16.2.2.4 Sous Vide

Sous vide is known as a complex low-temperature cooking technique in which meat is vacuum-sealed in heat-resistant pouches and immersed in a carefully controlled water bath for an extended period of time (Hobani *et al.*, 2023). Unlike traditional high-heat techniques, sous vide typically uses temperatures between 50 °C and 90 °C, with cooking times ranging from 2 hours to 8 hours depending on the type and thickness of the meat (Lee *et al.*, 2025). Originally developed in France, the method has gained international popularity for its consistency, energy efficiency, and fine control over cooking conditions. One of the key benefits of sous vide is its ability to preserve the natural qualities of meat. Ayub and Ahmad (2019) reported that the stable, sealed cooking environment of sous vide helps maintain the natural color gradients, juiciness, and structural integrity of meat tissues. The technique also supports better flavor retention and ensures a uniform texture and appearance across the entire product.

When cooking meat sous vide, the controlled temperature and sensory changes occur that are much different from those of high-temperature cooking, the protein unwinds, muscle fibers do not contract, and unappealing colors and textures are prevented (Ayub and Ahmad, 2019; Hobani *et al.*, 2023). For the best results, the sous vide treatment of beef and lamb is usually carried out at a relatively low temperature of 58–63 °C for anywhere from 10 hours to 48 hours (Llave *et al.*, 2018): a procedure that has turned into the go-to technique for producing consistently top-quality meat products. Well-known for its ability to produce evenly distributed flavor, color, and texture, a flowchart of the sous vide process is depicted in Figure 16.4. There has been a lot of study on the use of sous vide in red meat; in particular, Vaudagna, Sánchez and Neira (2002) looked at pork cooked at 53 °C, 58 °C, and 60 °C for 20 hours, and their results showed a marked increase in tenderness. However, extended cooking at 60 °C slightly took away from the tenderness but really amplified the juiciness, and the 53 °C option proved to have the best balance. Similarly, Tang and Chan (2007) examined the results of cooking beef at 50–65 °C for 90–360 minutes and confirmed that meat became less tough and less prone to cooking loss. Crucially, the conditions used in the study were able to kill off pathogenic bacteria, such as *Clostridium* spp., making the meat safe for consumption, and simultaneously preserved the meat's sensory appeal.

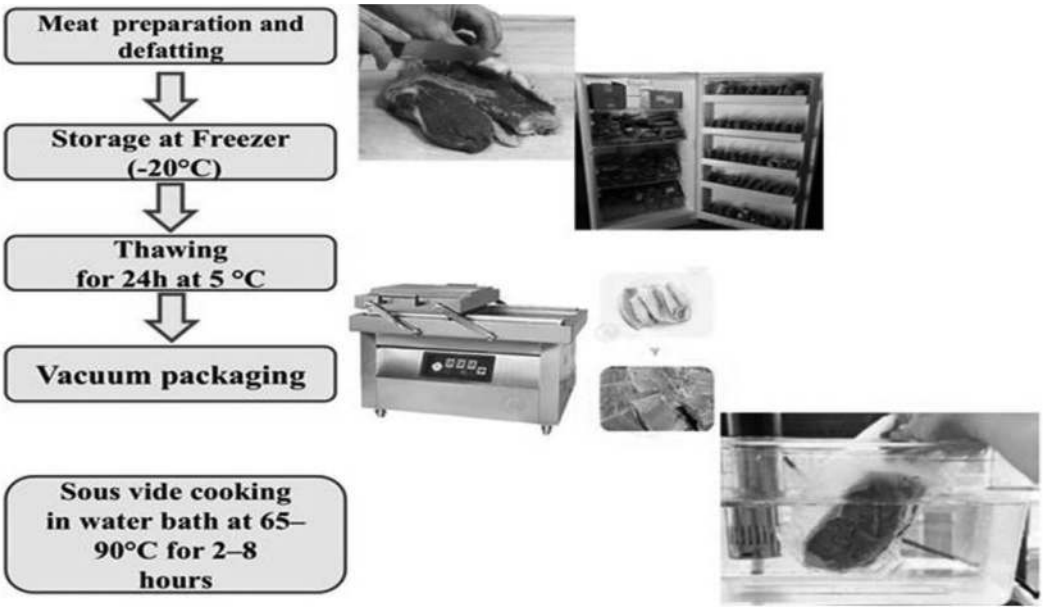

FIGURE 16.4 Schematic chart of sous vide cooking.

16.3 Conventional Approaches for Assessing Quality Changes in Meat Products

The overall quality of meat is significantly impacted by heat treatment, which alters the meat's microbial, physicochemical, and biochemical characteristics as well as its nutritional profile and sensory perception. Numerous traditional analytical techniques have been used over time to track these changes and ascertain how heat exposure impacts the characteristics of meat. The primary quality parameters that are usually changed during thermal processing are enumerated in the following section, along with the traditional approaches that are most commonly employed to assess them (Sahar *et al.*, 2016).

16.3.1 Sensory and Microbiological Analysis

Thermal heating has a big impact on how meat looks, feels, and tastes. It changes the color, makes it more or less tender, and affects the flavor. To check these changes, we can use expert tasters, ask regular people, or use machines to measure things. To look at color, we use special tools called colorimeters. These use a system called CIE L^*, a^*, b^*. L^* shows how light or dark something is, from 0 to 100. a^* shows red to green, from −60 to +60. b^* shows yellow to blue also from −60 to +60. To check how tough or soft meat is, and how it springs back when you press it, we use tests like the Warner–Bratzler shear force test and texture profile analysis (TPA) (Rebezov, Khayrullin and Assenova, 2024).

Flavor is also key to meat quality. Thermal heating causes chemical reactions between sugars amino acids, and fat contents. This happens when fat contents break down in the air and during something called the Maillard reaction to create the flavors and taste. To detect and quantify the volatile compounds responsible for flavor formation, chromatographic techniques such as gas chromatography and GC–MS remain the standard tools in meat analysis. From a microbiological aspect, thermal processing serves as a key preservation parameter, ensuring both safety and prolonged shelf life. Traditional culture-based methods, including total viable count (TVC), remain the foundation for evaluating microbial load, although modern molecular techniques have enhanced speed and precision (Sosa-Morales, Orzuna-Espíritu and Vélez-Ruiz, 2006). Appropriate heat treatment can kill a wide range of vegetative microorganisms, such as *Salmonella* spp., *Escherichia coli* O157:H7, *Listeria monocytogenes*, and *Staphylococcus aureus*, depending on the time–temperature relationship applied. However, spore-forming bacteria, including

Clostridium perfringens and *Bacillus* spp., may survive conventional cooking if post-processing cooling is delayed or storage conditions are inadequate. Therefore, strict temperature control and hygienic handling after cooking are essential to prevent germination and recontamination (Cepeda *et al.*, 2013; Zhang *et al.*, 2024).

Researchers have been studying how different heating methods affect the sensory, texture, and safety of meat. Using standard lab tools, they have compared traditional heating with novel techniques like OH and IR heating. For example, Dai, Lu, and Wu (2014) compared OH with conventional water bath cooking in pork. They found that OH gave the meat a more attractive color and required less time cooking. However, the texture turned out slightly firmer, which may have been due to protein cross-linking and carbonyl formation during the process. Tenderness is often the key factor in how consumers judge meat quality. Tang and Chan (2007) examined pork subjected to low-temperature water bath, MW, and steam cooking, reporting the most tender results came from steaming for 5 minutes or microwaving for 7 minutes. Similarly, Li *et al.* (2019) found that yak meat processed using MW heating displayed enhanced sensory properties in comparison with traditionally boiled samples. Additionally, MW processing is more time- and energy-efficient than conventional oven heating for both chicken breast and thigh meat. Although the impact of IR on cooking is relatively limited, the findings are promising. Taşkıran, Olum, and Candoğan (2020) studied that impact of IR on chicken nuggets achieved comparable consumer acceptability to deep-fried products, while presenting superior color uniformity and surface texture. Ultimately, this research demonstrates how modern and conventional heating techniques can be evaluated using sensory and microbiological analyses, providing a comprehensive understanding of how thermal processing affects meat quality and safety.

16.3.2 Changes in Nutritional Quality

The nutritional value of meat is often determined with examining its chemical component, particularly the high levels of biological value proteins, essential amino acids, and micronutrients such as vitamins and minerals. However, these chemical parameters alone do not fully determine nutritional quality. Factors like protein digestibility and digestion kinetics are equally considerable, as they govern the release, absorption, and bioavailability of amino acids and peptides during digestion. To evaluate these characteristics, in vitro digestion models are typically used, where enzymes such as pepsin and trypsin simulate gastric and intestinal phases at around 37 °C. Thermal heating exposure during processing causes multiple biochemical and structural changes in meat proteins, including denaturation, oxidation, aggregation, and the formation of cross-links between molecules, all of which can reduce protein digestibility and change enzymatic hydrolysis rates (Creed, 1998).

Among all processing variables, temperature has been detected as the most effective factor. For example, Bax, Aubry, and Ferreira (2012) showed that hams cooked at 70 °C had superior digestion rates, while higher heating at 100 °C increased digestibility, albeit marginally, and overall digestion inefficiently decreased. This was explained by moderate protein unfolding and exposure of enzymatic sites at mildly heated proteins, as opposed to oxidation and aggregation at too high of temperatures, which are known to freeze enzymatic activity. A similar study was conducted by Luo *et al.* (2018), who tested the in vitro gastrointestinal digestion of proteins from various meats (beef, pork, chicken, and kangaroo) subjected to MW and electrical oven heating was analyzed. They concluded that both the type of meat and the heating method and the respective processing conditions determine digestibility and digestion rates to a large extent. More recently, Rakotondramavo *et al.* (2019) reported that steamed ham (internal temperature 65 °C) had lower overall digestibility but faster digestion rates, demonstrating how little changes in a heat treatment can influence the digestive results. Very high temperatures while cooking meat may encourage the formation of undesirable compounds, such as heterocyclic aromatic amines (HAAs), polycyclic aromatic hydrocarbons (PAHs), and advanced glycation end-products (AGEs), all of which are linked to chronic disease risk and carcinogenesis. The level of these compounds is highly influenced by the degree and the length of thermal heating used. Compounding methods also play a significant part in the concentration of the compounds formed during thermal cooking. Methods like grilling, frying, roasting, and smoking produce greater concentration of these compounds in comparison to cooking methods like steaming and sous vide (Creed, 1998; Luo *et al.*, 2018).

16.3.3 Evaluation of Biochemical Characteristics

Thermal heating induces a cascade of chemical and structural changes in meat proteins which include denaturation, oxidation, aggregation, changes in surface hydrophobicity, and other changes which involve both nutritive and sensory value of meat quality (Yu *et al.*, 2016). The structural changes that occur during heating are particularly significant because they affect water retention, cooking loss, and sensory properties—three characteristics that define consumer acceptability. Several conventional biochemical techniques are used to quantify these heat-induced changes. Among them, sodium dodecyl sulfate–polyacrylamide gel electrophoresis (SDS–PAGE) and differential scanning calorimetry (DSC) are the most popular. SDS–PAGE tracks the loss and formation of protein degradation and aggregation patterns, while DSC logs the thermal transition peaks, which indicate folding and denaturation (Yu *et al.*, 2016). Other biochemical changes resulting from heating, such as protein oxidation, Maillard reaction, and loss of sulfhydryl groups, are also widely used to evaluate the extent of heating.

Recent studies that focus on comparing MW heating and water bath heating have shown new insights into how different processing conditions may impact the protein profiles. For instance, Yu *et al.* (2016) reported that changes in MW cooking conditions did not cause any significant changes in the yak meat protein's electrophoresis profile, which indicates insignificant structural degradation. Similarly, Han *et al.* (2019a) reported that MW cooked beef has less surface hydrophobicity and higher amounts of sulfhydryl groups when heated below 58 °C in comparison to the water bath–heated samples. All these findings lead to the conclusion that MW processing, while maintaining specific control, reduces oxidative damage and helps preserve the functional and nutritional value of meat proteins.

16.4 Spectroscopic Monitoring Techniques

In the last few decades, many types of spectroscopies have been employed for the examination of meat and meat products, such as visible, vibrational, fluorescence, Raman, and NMR spectroscopy. The analyses are rapid, nondestructive, and do not require the use of reagents, as they provide qualitative and quantitative assessments without the complicated and time-consuming sample preparations (Sahar *et al.*, 2016). Moreover, innovation in spectroscopic monitoring is related not only to the type of spectroscopy employed but also to the measurement configuration, particularly the arrangement of the illumination source and detector. Two common acquisition modes are distinguished: transmittance, where the light passes through the sample and the detector is positioned on the opposite side, and interactance, where the light source and detector are placed on the same side, capturing scattered and partially absorbed light. These configurations enable nondestructive and real-time monitoring, providing valuable insights into both external and internal quality parameters of the examined sample. Changes in optical properties, such as absorption and scattering, reflect structural and chemical modifications in the sample, including those induced by thermal treatments.

Figure 16.5 shows the combination of spectroscopic approaches along with chemometric analysis in different food matrices.

The core reason for using spectroscopy to observe meats thermally processed is that it uncovers changes to optical properties, specifically absorption and scattering, as a result of protein unfolding, denaturation, and other heat-induced transformations. The interactions of light with biological tissue is a result of absorption by chromophoric molecules and scattering from structural components (Sahar *et al.*, 2016). While scattering intensity is mainly influenced by the microstructure and physical texture of the tissue, absorption depends on the chemical composition and concentration of absorbing groups at characteristic wavelengths. As heat treatment progresses, these optical interactions undergo measurable changes, typically manifested as increased scattering and decreased absorption intensity. Such spectral changes are largely attributed to decreased absorption of key functional groups associated with water, proteins, and other organic molecules, reflecting structural rearrangements and compositional changes that occur during heating (Hassoun *et al.*, 2021).

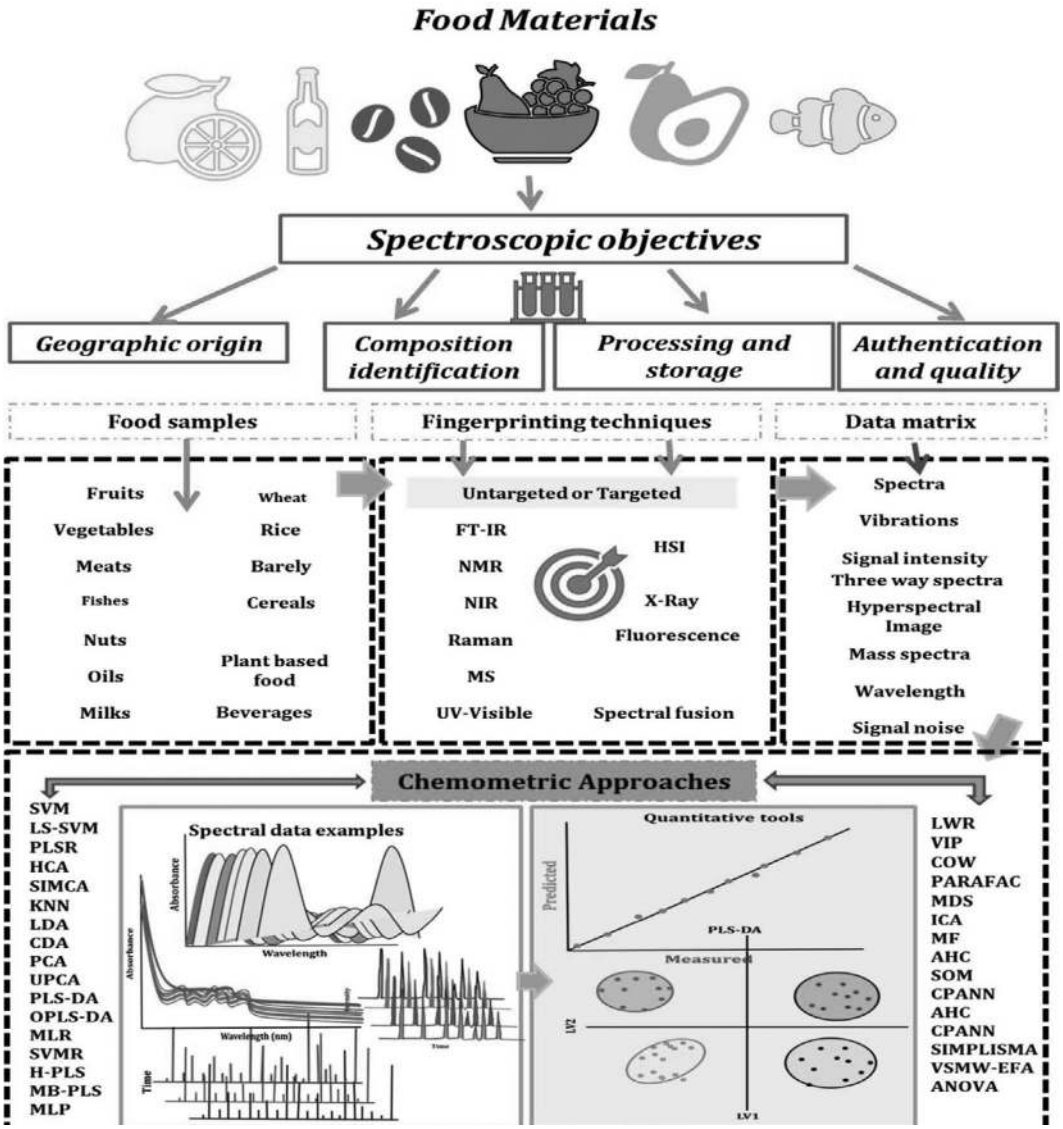

FIGURE 16.5 General flow of advanced spectroscopic techniques along with chemometric approaches in food analysis. (Kharbach *et al*., 2023.)

16.4.1 IR Spectroscopic Techniques

During the last decade, IR-based spectroscopic methods, particularly near-infrared (NIR) and mid-infrared (MIR) spectroscopy, have drawn substantial attention as versatile tools for evaluating the quality attributes of meat and meat products. This growing interest stems from their analytical reliability, minimal sample preparation, and the increasing availability of commercial instruments for both research and industrial applications. The NIR region mainly reflects molecular overtone and combination vibrations, while the MIR spectrum originates from the fundamental vibrational movements, including stretching, bending, and rotational oscillations, of molecular bonds (Wold *et al*., 2020).

There are numerous NIR spectroscopy applications where the prediction of the physicochemical and sensory quality of meats, both in the raw and the cooked form, has been documented, particularly in assessing the pH, color, lipids, drip loss, tenderness, juiciness, and the flavor. While it is extensively used

to assess the quality of fresh meats, far fewer studies have used it to assess quality changes due to cooking (Hassoun *et al.*, 2021). For example, Hassoun *et al.* (2021) used NIR spectroscopy (850–1,045 nm) to model sensory properties of pork loins subjected to different heating treatments, including oven cooking at 150–180 °C and confit processing for up to 4 hours. Using principal component analysis (PCA), they successfully differentiated meat samples based on cooking temperature and duration, with strong correlations ($R^2 > 0.8$) between NIR data and sensory outcomes, particularly in confit-processed pork. In subsequent research, the same team confirmed that NIR spectra could classify samples based on cooking conditions, with correlation coefficients exceeding 0.5 for parameters such as texture and cooking loss (Han *et al.*, 2014).

In recent years, NIR spectroscopy has been integrated for inline and real-time monitoring to simulate industrial-scale processing. O'Farrell *et al.* (2011) used the interactance mode to monitor core temperature in baked liver pâté, obtaining prediction errors of 1.5 and 4.3 °C. Likewise, Wold *et al.* (2020) showed that NIR interactance spectroscopy was able to continuously monitor the temperature of sausages within a steam-oven when heated, attaining an accuracy of about ±1.0 °C. These findings illustrate the capability of NIR spectroscopy as a nondestructive and contactless instrument for real-time control functionality within contemporary processing of meat.

Another innovative technique, hyperspectral imaging (HSI)—which integrates spectroscopy and imaging—focuses on the nondestructive analysis of meat quality (Pessoa *et al.*, 2022). By simultaneously recording spatial and spectral data, HSI enables accurate visualization of heterogeneous food matrices such as meat, which vary in chemical components (e.g., protein, fat, collagen) and physical structure. When combined with multivariate analysis and chemometric modeling, including PCA, partial least squares regression (PLSR), and artificial neural networks (ANN), HSI allows for the creation of chemical maps and the prediction of sensory, nutritional, and grading properties in different types of thermally processed meats (Firago *et al.*, 2022). An HSI instrument typically produces a three-dimensional data cube (supercube) consisting of two spatial axes (X and Y) and one spectral dimension (λ). Depending on the measurement approach, data collection may be performed in reflectance, transmittance, or interactance modes, with reflectance being the most commonly used for meat due to its operational simplicity and rich signal output.

There are four principal configurations for HSI data collection: whiskbroom (point scanning), pushbroom (line scanning), tunable filter (staring), and snapshot systems. The optimal configuration depends on the analytical aim, system cost, and the need for real-time performance. Tunable filter or staring systems record one spectral band per frame, offering high spatial resolution but slower data acquisition rate, making them suitable for multispectral imaging (MSI). In contrast, pushbroom and snapshot systems allow rapid data acquisition, aligning well with continuous industrial workflows. The HSI snapshot system represents the most advanced design, capturing spatial and spectral data simultaneously without moving parts. This technology supports video-rate imaging, enhanced portability, and miniaturization. For example, a compact Cubert HSI camera captures 50 spectral bands (450–850 nm) at a frequency of more than 15 Hz and offers a resolution of 250×250 pixels in a small footprint of $29 \times 29 \times 49$ mm (Firago *et al.*, 2022).

In addition, MIR spectroscopy techniques, such as Fourier transform infrared (FTIR) spectroscopy, have been utilized for analyzing the chemical and structural properties of meat. Despite being less frequently used for heat analysis, Calabrò and Magazù (2012) analyzed FTIR spectra of beef cooked by MWs (800 W for 95 seconds or 650 W for 160 seconds) and in a conventional oven at 165 °C over the course of 16 minutes. According to the findings, microwaving beef did little to alter the protein's secondary structure and yielded a far fewer Maillard reaction products than when beef was oven-cooked. Additionally, when Han *et al.* (2014) examined meat pastes heated from 20 °C to 74 °C, they observed a marked change in secondary protein structure from alpha helix to beta-sheet that was highly correlated with color ($L^*R = -0.82$), pH ($R = -0.91$), SH group content ($R = 0.92$), and water loss.

16.4.2 Raman Spectroscopy

In the past decade, Raman spectroscopy has emerged as the most informative instrument for studying molecular and structural changes occurring during the processing of meat. In contrast to most standard

optical methods, the method is not related to the elastic light scattering, but it relies on the inelastic scattering of light with single frequency enabling fine determination of vibrational transitions concerning molecular bond force in the ground-energy state (Damez and Clerjon, 2013). This property makes Raman spectroscopy particularly attractive for the investigation of changes in protein conformation and other physiochemical alterations induced by heat treatment.

Recently, studies have shown the utility of this technique in monitoring temperature changes in meat systems (Table 16.4). For instance, Xu *et al.* (2011) explored how heating affects pork myofibrillar proteins by coupling Raman spectral analysis with TPA. Upon increasing temperatures of cooking, they detected a decrease in the level of α-helix structure concomitant with an increase in β-sheet, β-turn, and random coil, indicating a progressive unfolding and reorganization of protein molecules. In addition, PCA on combined Raman and TPA data showed significant correlations between the microstructural changes and textural hardness of heat set gels, precluding a direct comparison between molecular rearrangement and macroscopic texture.

TABLE 16.4

Examples of Key Studies Exploring the Application of Spectroscopic Techniques for Monitoring Thermal Processing in Meat and Meat Products

Product	Thermal Method	Spectroscopic Technique	Main Findings	Reference
Pork	Conventional oven	NIR	NIR spectroscopy was able to discriminate pork samples based on the temperature and cooking time	González-Mohino *et al.*, 2018
Liver pâté	Oven	NIR	NIR was able to accurately predict internal temperature, with error values ranging from 1.5 °C to 4 °C	O'Farrell *et al.*, 2011
Pork	Water bath	NIR	NIR effectively classified pork samples subjected to various heating durations	Perez-Palacios *et al.*, 2019
Sausages	Steam oven	NIR	NIR was able to provide precise predictions of the internal temperature of sausage with great accuracy	Wold *et al.*, 2020
Chicken breast	Oven heating	VIS/NIR HSI (400–1,000 nm)	Hyperspectral imaging provided visual maps showing moisture distribution across samples heated at various temperatures	Kandpal *et al.*, 2013
Beef	Microwave	VIS/NIR HSI (400–1,000 nm)	HSI mapping revealed that beef color changes after different microwave heating times	Liu *et al.*, 2018
Bovine breast meat	Microwave + oven	FTIR	FTIR results showed increased carbonyl and methylene groups in oven-treated samples, suggesting enhanced Maillard activity	Calabrò and Magazù, 2012
Meat batters	Water bath	FTIR and NMR	FTIR and NMR techniques were advantageous in demonstrating the migration of free water, conformational modifications of proteins, and structural changes at particular phase temperatures	Han *et al.*, 2019a, 2019b
Chicken meat	Isothermal heating	Raman	The Amide I Raman peak proved to be a sensitive marker for analyzing heating intensity	Miyaoka, Ando and Harada, 2020
Pork	Water bath	Raman	Raman spectra correlated strongly with heating temperature, duration, and analyzing cooking loss	Berhe *et al.*, 2015
Pork	Water bath	Raman and fluorescence	Combined Raman–fluorescence analysis obtained accurate estimation of internal temperature	Berhe *et al.*, 2015

(Continued)

TABLE 16.4 ***(Continued)***

Examples of Key Studies Exploring the Application of Spectroscopic Techniques for Monitoring Thermal Processing in Meat and Meat Products

Product	Thermal Method	Spectroscopic Technique	Main Findings	Reference
Pork	–	NMR	NMR data showed strong correlation with traditional physicochemical measurements of meat quality	Han *et al.*, 2014
Sausage	Water bath	NMR, Raman	NMR detected oil and water proton dynamics, while Raman spectroscopy tracked secondary protein structure changes under different heating durations	Yang, Zhang and Li, 2016
Beef	Water bath	NMR, MRI	Both techniques demonstrated temperature-related protein decay and water redistribution, modeling multilevel moisture changes	Sun *et al.*, 2017
Bovine meat	Steam	Fluorescence	EEM fluorescence coupled with PARAFAC successfully discriminated samples according to both heating time and temperature	Sahar *et al.*, 2009
Bovine meat	Steam	Fluorescence	Fluorescence intensity at 360 nm excitation increased with temperature, correlating with protein and lipid oxidation	Gatellier *et al.*, 2009
Bovine meat	Steam	Fluorescence	PARAFAC-processed EEM fluorescence effectively discriminated samples by both cooking time and temperature	Sahar *et al.*, 2010
Bovine meat	Boiling	Fluorescence	Fluorescence intensity at 360 nm excitation rose with higher temperature, reflecting lipid and protein oxidation	Deb-Choudhury *et al.*, 2014
Bovine meat	Water bath and steam	Fluorescence	EEM fluorescence integrated with PARAFAC analysis discriminated samples based on different cooking temperatures and time	Sahar *et al.*, 2016
Pork	Oven + Autoclave	Fluorescence	Fluorescence of tryptophan and Schiff's bases served as reliable indicators of protein oxidation during various heat treatments	Mitra *et al.*, 2018

Abbreviations: EEM, excitation–emission matrix; FTIR, Fourier-transform infrared spectroscopy; HSI, hyperspectral imaging; MRI, magnetic resonance imaging; NMR, nuclear magnetic resonance; PARAFAC, parallel factor analysis VIS/NIR, visible–near infrared spectroscopy.

In a separate investigation, Berhe *et al.* (2015) used Raman spectroscopy to predict the cooking time and temperature for pork heated in a water bath (50–70 °C for 2–10 hours). Through multivariate statistical analysis, they successfully achieved discrimination between samples processed under and above 60 °C by multivariate statistical analysis with spectral ranges associated with amide I, amide III, and disulfide bond as the main indicators. They developed models with good R^2 values for temperature (0.96), time (0.78), and cooking loss (0.82). In a subsequent work, the same working group further developed this method to fit endpoint temperatures ranging from 50 °C to 80 °C with exceptional precision (R^2 = 0.98, error < 1.7 °C) (Berhe *et al.*, 2015). They also demonstrated that Raman spectra could differentiate between meat samples below and above 65 °C over 97% of the time, which validated the capability of this method for noncontact temperature prediction coupled with quality evaluation.

Further evidence was presented by Miyaoka, Ando, and Harada (2020). Raman analysis was used to establish thermally induced conditions for heat-exposed chicken meat, which were based on amide I band shifts as diagnostic indicators. Complementary parallel SDS–PAGE experiments confirmed denaturation of actin and myosin in the 60–80 °C temperature range, and they were fully consistent with

Raman. These results collectively indicate that Raman spectroscopy may be a rapid, noninvasive, and structural informative technique for monitoring heat-induced muscle molecular/secondary structure changes, which is becoming a cornerstone in modern meat science as well as the industrial field of quality surveillance.

16.4.3 Nuclear Magnetic Resonance

Over the years, NMR spectroscopy has become one of the most powerful analytical tools for studying the structure of biomolecules in meat systems. This nondestructive method exploits the magnetic properties of certain atomic nuclei, providing detailed insights into their surrounding molecular environments. In a typical NMR system, a strong magnetic field aligns the spins of these nuclei, and subsequent exposure to controlled RF pulses excites them selectively. The energy released when the nuclei return to equilibrium reflects their concentration and local chemical environment, allowing for precise qualitative and quantitative analysis of molecular components. Several types of NMR are used in food analysis, particularly high-resolution NMR (HR-NMR), low-field NMR (LF-NMR), and magnetic resonance imaging (MRI). Each approach contributes unique capabilities for characterizing free water and water-holding capacity (WHC) in muscle foods, making NMR a core technology in meat processing (Damez and Clerjon, 2013).

The growing of researches confirms that both NMR and MRI are highly effective for tracking structural and physicochemical transformations during heat treatment of meat, especially when identifying temperature-dependent transitions in tissue organization (Table 16.4). For instance, Sun *et al.* (2017) applied LF-NMR, focusing on transverse relaxation time (T_2), in conjunction with MRI to optimize the cooking temperature and duration of traditional Chinese braised beef. Their study revealed that while cooking time exerted only a minor effect, temperature had a major influence on water redistribution and protein denaturation, significantly reshaping the final texture and juiciness of the product.

Similarly, Xu *et al.* (2011) used T_2 relaxation analysis via LF-NMR to investigate the thermal gelation behavior of pork myofibril proteins and the corresponding changes in WHC. Gradual heating induced a measurable change in T_2 values, which was closely related to microstructural reorganization and the formation of a stable gel network. In a related investigation, Han *et al.* (2019b) investigated the relationship between protein unfolding, water of hydration, and free water in meat batters exposed to different phase transition temperatures. Their results showed a sharp decrease in WHC around 50 °C, indicating the conversion of immobilized water to freer forms with the collapse of protein structures.

To further understand these dynamics, Bouhrara *et al.* (2012) introduced an in situ MRI protocol capable of simultaneously monitoring structural deformation and internal moisture migration during the controlled heating of beef from 20 °C to 75 °C. This spatially resolved imaging method captured both temperature gradients within the sample and real-time changes in water distribution and protein matrix integrity. Using these data, the researchers successfully modeled the interplay between denaturation, free water, and texture development, demonstrating enormous potential of NMR-based approaches to elucidate complex heat-induced transformations in meat systems.

16.4.4 Fluorescence Spectroscopy

Fluorescence spectroscopy is a precise method of analysis that takes advantage of the ability of certain biomolecules to absorb ultraviolet (UV) or visible light and then emit fluorescence when their electrons are relaxed to the ground state. In this process, an electron is raised to a higher energy state by absorbing energy, and the energy is released as emitted light as it returns to the ground state. By selectively holding either excitation or emission wavelengths constant, a corresponding excitation or emission spectrum is obtained. This traditional way of measurement yields two-dimensional spectral data and is still the most widely used method of characterizing molecular interactions and conformational changes in biological systems (Sahar *et al.*, 2010).

A notable innovation in fluorescence spectroscopy is the use of excitation–emission matrices (EEMs), which allows for the simultaneous acquisition of multiple spectra over a wide wavelength range. This multidimensional approach provides more information about molecular interactions and environmental

dynamics. A further refinement, synchronous fluorescence spectroscopy (SFS), acquires excitation and emission spectra simultaneously while held at a fixed interval ($\Delta\lambda$), producing better spectral resolution along with greater ease in distinguishing between overlapping emission signal (Sahar *et al.*, 2009). The speed, nondestructive character, and sensitivity to molecular interactions of fluorescence methodologies makes it particularly appropriate for monitoring the biochemical transitions and changes that occur during heat-induced processes in meat systems (Table 16.5). For instance, fluorescence emission spectroscopy (390–600 nm, λ_ex = 360 nm) was used to assess oxidative changes during cooking. Their results indicated that there was a notable increase in fluorescence intensity when surface temperatures exceeded 141 °C, attributed to the generation of protein–aldehyde adducts due to lipid oxidation.

TABLE 16.5

Summary of Mathematical Models of Meat Applied to Various Processing Conditions

Meat Heating Study	Mathematical Model	Main Findings	Reference
CFD simulation has been employed to optimize the beef heat treatment process and model protein denaturation degree	Computational fluid dynamics (CFD) simulation	By utilizing CFD, the method was able to predict protein denaturation levels with precision, making it a useful resource for optimizing beef heat treatment to ensure consistent and superior products	Szpicer, Wierzbicka and Półtorak, 2022
Color changes in beef during pan heating: kinetics, modeling, and prediction of turnover time	Finite element method (FEM) implemented in COMSOL multiphysics	With accuracy, the model predicted the duration of a particular color change in beef during pan preparation	Moya, Lorente-Bailo and Salvador, 2021
A mathematical model for meat heating	Finite difference equations based on Flory–Rehner theory implemented in C++	The model that was factored in meat shrinkage during oven roasting, and its several results were highly consistent with experimental observations	Shehadeh *et al.*, 2019
Modeling the electrical conductivity of muscle meat during ohmic heating	Experimental equations	The validated experimental model effectively simulated the changes in electrical conductivity of muscle tissue during ohmic heating	Van der Sman, 2017
Mathematical modeling of ground beef in a heating cylinder	Finite difference equations solved via fourth-order Runge–Kutta method (C++)	The model successfully predicted the temperature gradient in cylindrical meat samples under different heating conditions, with close correlation to experimental data	Ahmad, Khan and Kamil, 2015
Ohmic heating of pork meatballs: modeling and quality evaluation	Sukprasert's model and modified finite difference model	Both models showed high precision in predicting temperature changes of pork meatballs under ohmic heating	Engchuan, Jittanit and Garnjanagoonchorn, 2014
Prediction of heating times and weight losses during roasting	Finite element method (FEM) using COMSOL multiphysics and MATLAB	The validated model accurately predicted heating time and weight loss in oven-roasted beef samples	Goñi and Salvadori, 2010
Pasteurization by ohmic heating: influence of process conditions	Finite element method (FEM) implemented in COMSOL multiphysics	The modified model effectively tested the effects of processing parameters on temperature uniformity during meat pasteurization, ensuring a consistent product	Zell *et al.*, 2011

About 80% of the fluorescence response was associated with protein carbonyls confirming that protein oxidation was primarily responsible for the spectra shift. These results are similar to results from a more recent study by Mitra *et al.* (2018), who documented changes in fluorescence intensity and emission maxima associated with tryptophan and Schiff base compounds in thermally processed pork, thereby supporting the method's potential for monitoring oxidative and structural changes. The use of SFS in conjunction with chemometric modeling was further exemplified by Sahar *et al.* (2009). They studied bovine samples cooked for different times/temperatures, collected EEM spectra between 250 and 550 nm, and constructed over 1,000 spectra using parallel factor analysis (PARAFAC). The resulting models demonstrated clear fluorescence pattern changes associated with both heating temperature and time reflective of alteration in molecular conformations. The spectra demonstrated a strong emission peak for tryptophan near 295 nm in the raw meat that decreased with heating, while a new emission band appeared near 470 nm reflective of advanced (Sahar *et al.*, 2016). Progressive peak shifts from 294 nm to 355 nm, and then to ~468 nm, followed protein unfolding and fluorescent formation of advanced glycation end-products (AGEs).

Additionally, Berhe *et al.* (2015) used EEM fluorescence to examine thermally induced effects upon the microenvironment of aromatic amino acids in pork subjected to water bath thermal heating at 50–80 °C for 2 hours. In their findings, fluorescence data demonstrated a progressive decrease in fluorescence intensity from 280 nm to 430 nm, consistent with temperature-induced quenched and denatured muscle proteins.

In a separate study, Berhe *et al.* (2015) conducted a study using excitation–emission matrix (EEM) fluorescence spectroscopy to investigate the impact of temperature on the microenvironment of aromatic amino acids in pork samples that were immersed in a water bath at temperatures ranging from 50 °C to 80 °C for 2 hours. The emission intensity, which was measured within the wavelengths of 280–430 nm while scanning the excitation wavelengths from 240 nm to 320 nm, was found to diminish with increasing temperature. The results suggest that thermal upregulation of the temperature induces structural changes to the proteins and causes fluorescence quenching in the samples. Finally, Sahar *et al.* (2010) demonstrated the application of SFS to detect heterocyclic aromatic amines (HAAs) produced during grilling of beef at high temperatures. Using PARAFAC, they identified four individual HAA compounds and quantified their concentrations using the fluorescence data. Complementary work by Deb-Choudhury *et al.* (2014), combining fluorescence spectroscopy and microscopy, verified the observation that the minced beef samples underwent a rapid increase in fluorescence intensity early in the heating process (0–30 min) suggesting rapid formation of AGEs, and subsequently, a gradual improvement or plateau in fluorescence as cooking proceeded.

16.5 Mathematical Modeling

Thermal heating of meat can be described mathematically by testing the simultaneous heat and mass transfer mechanisms that occur during the operation. Understanding mathematical models for these thermal heating is essential for explaining the physical mechanisms included in heat and moisture migration, optimizing instrument design, maintaining product quality, reducing energy and production costs, and extending the shelf life of thermally processed meat. Such models are created from mathematical relationships that define the dynamics of heat and mass transfer within meat during thermal heating. They enable prediction and simulation of temperature and moisture distribution under different process conditions and help to optimize and control operational parameters such as processing time, internal temperature, and sensory and textural properties of the final product. However, validation of the model against experimental data is still essential to ensure prediction accuracy and reliability (Nelson *et al.*, 2020).

During traditional thermal heating, like an oven, heat is transferred to the meat's surface through convection and radiation; once this happens, the energy is absorbed and then directed toward the core of meat. The surface absorbs internal moisture through diffusion and convective flow, which is then dispersed by evaporation (Singh, Akins and Erickson, 1984). The complex heat and mass phenomena

are explained by transport equations that account for the interplay between different physical processes, such as energy transfer, moisture migration, internal fluid flow, and mechanical changes such as wielding shrinkage and structural deformation (Cepeda *et al.*, 2013).

The principle of conservation of energy for heat transfer, which includes both conduction and convection, can be expressed as follows (Ahmad, Khan and Kamil, 2015):

$$\left(\frac{\partial T}{\partial t}\right)\rho cp + \nabla \cdot \left(-k\nabla T\right) + \rho_w c_{p,w} u_w \nabla \cdot T = 0 \tag{16.1}$$

where ρ, c_p, and k showed the density (kg/m³), specific heat (J/kg·K), and thermal conductivity (W/m·K) of the meat, respectively; ρ_w, $c_{p,w}$, and u_w explained the corresponding properties of the water phase; T is the temperature (°C), and t denotes time (second).

Similarly, the governing equation for mass transfer by diffusion and convection follows the mass conservation principle (Ahmad, Khan and Kamil, 2015):

$$\left(\frac{\partial C}{\partial t}\right) + \nabla \cdot \left(-\mathrm{Dw}\,\nabla C + u_w C\right) = 0 \tag{16.2}$$

where C is the local moisture concentration (mol/m³) and D_w is the effective moisture diffusion coefficient (m²/s).

The internal fluid velocity within the porous structure can be estimated using Darcy's law, expressed as follows:

$$uw = \frac{-x}{\mu w}\nabla p \tag{16.3}$$

where κ is the permeability of the meat matrix (m²), μ_w is the dynamic viscosity (Pa·s), and ∇p is the pressure gradient (Pa/m).

The accuracy of thermal processing outcomes depends on factors like heating method, meat thickness, and other variables that affect the amount of heat and mass transferred. Many attempts at modeling have been made without considering mechanical effects such as elasticity, contraction, and stickiness, in order to use the laws of mass, momentum, and conservation of energy (Nelson *et al.*, 2020).

Multiple investigations have suggested mathematical models to explain the thermal treatment of meat. A computational model for the thermal processing of minced meat was created using a C++ program by Ahmad, Khan, and Kamil (2015) and developed by Wang and Sun (2002). They used both natural and forced convection heating to heat 6.6 cm of diameter, 18 cm, 650 g of mass, respectively. It included constant thermal and moisture diffusivities to the model, but not fat migration. The resulting temperature distributions were numerically solved by means of the fourth-order Runge–Kutta method, and shown to be in good agreement with experimental data through validation using tabular methods. COMSOL multiphysics, version 5.2a, was utilized in constructing a three-dimensional computational model that accurately simulated the mechanical deformation and coupled heat/mass transfer involved in steak processing on a double-sided pan with different thickness and processing times. The experimental results were consistent with root mean square errors of 2.16 °C for very rare, 3.56 °C for rare, and 4.57 °C for well-done samples, and corresponding moisture losses of 1.48%, 2.08%, and 2.40%, respectively. The food industry considers the thermal processing parameters and consistency of meat products to be highly reliable and effective using this model, as determined by these authors (Moya *et al.*, 2021a, 2021b).

In addition, there are experimental mathematical correlations that have been developed to describe the water retention and storage coefficients in meats subjected to thermal processing. The Flory–Rehner theory, which considers meat as an elastic, solvent-saturated medium, was used by Nelson *et al.* (2020) to model beef steak during heating. The researchers discovered that heating leads to protein denaturation and moisture loss, which in turn results in significant volumetric shrinkage, up to 30%.

16.6 Microbial Effects of Thermal Processing

Thermal treatment of meat and meat-based products serves as one of the most critical interventions for controlling microbial activity and ensuring product safety. Traditionally, heating processes such as boiling, roasting, or canning have been employed to reduce spoilage organisms and destroy pathogenic microorganisms. Although the inner muscle tissue of healthy animals is sterile, microbial contamination occurs inevitably during slaughter, cutting, and handling. The efficiency of microbial inactivation depends primarily on two interrelated factors: time and temperature. Traditional heat treatments are not desired to attain absolute sterility, except in products like canned meats, where commercial sterility is the purpose (Soni and Brightwell, 2022).

However, traditional thermal heating has several drawbacks, including long heating times and the potential for overheating, which may destruct texture, flavor, and nutritional quality. In response, innovative thermal engineering has been introduced such as OH, RF heating, and MW heating, that achieve microbial destruction more efficiently while minimizing quality loss. During OH, the meat absorbs electrical current directly through its natural resistance, which uniformly heats it up internally. This technique allows for a fast and uniform spread of temperatures, which significantly minimizes the thermal gradients that are typical of traditional systems. Optimal voltage gradients can effectively inactivate *C. perfringens* and *Bacillus cereus* spore, while uniform heating reduces cold spots where bacteria could potentially survive (Silva, 2018).

The heating of radio waves (RF) uses electromagnetic fields that is more effective than just traditional heat dissipation, as oscillating electric fields can cause microbial cell membranes to electrophoretically expand, which results in the release of cytoplasmic components before thermal denaturation. RF processing can preserve better protein structure than conventional conduction heating and reduce *L. monocytogenes* and *E. coli* populations within seconds of exposure when surface temperatures exceed 70 °C, as experimental data shows.

The inactivation of spore-forming bacteria, such as *C. perfringens* and *B. cereus*, is dependent on higher thermal loads. RF treatment results in damage to sporulating microorganisms by both direct thermal damage to the spore coating and secondary oxidative stress induced by local electric field gradients. Preheating or mild pressure treatments can result in significantly reduced *D*-values (reverting time to decimal reduction) compared to traditional retorting. The lethal temperature reached by RF heating is spread throughout the product, which minimizes the risk of survival during post-processing cooling. RF heating is particularly affected by this factor (Aydın, Kurt and Kaya, 2021; Silva, 2018; Zhang *et al*., 2024).

MW heating performs at higher frequencies (commonly 915 MHz or 2.45 GHz) and relies primarily on dielectric polarization of water molecules that causes intense frictional heating at the molecular level, leading to extremely fast temperature rise rates. For vegetative pathogens such as *Salmonella* spp., *S. aureus*, and *L. monocytogenes*, such rapid heating can result in irreversible denaturation of cellular enzymes, disruption of membrane potential, and damage to nucleic acids. Additionally, nonthermal MW effects are hypothesized to involve disruption of hydrogen bonding networks and alteration of membrane permeability, contributing synergistically to microbial death (Rosnes, Skåra and Skipnes, 2011).

Overall, MW and RF heating offer promising opportunities for microbial control and safety assurance of meat products, as they can achieve logarithmic reductions comparable to or better than traditional thermal pasteurization, but with significantly reduced times and improved sensory and nutritional quality. The use of real-time dielectric modeling and microbial kinetic analysis could lead to a safer and more energy-efficient alternative to traditional thermal sterilization methods. This is an ideal situation for future optimizations.

16.6.1 Safety: Destruction of Pathogens

Foodborne illnesses may arise either as infections, when viable microorganisms are ingested and subsequently multiply in the gastrointestinal tract, or as intoxications, when preformed microbial toxins are consumed. Public health concerns regarding *E. coli* O157:H7, *Salmonella* spp., *L. monocytogenes*, *C. perfringens*, and *C. botulinum* are among the many pathogen types associated with meat and meat

products. These organisms are the primary focus of meat processing, which involves the use of thermal technologies. The destruction of microbial pathogens in meat products is dependent on the interaction between thermal energy and cellular macromolecules. The spatial temperature gradients are created by the heat that enters the product surface from its core during conventional heating methods (Rosnes, Skåra and Skipnes, 2011). Microbial lethality in these systems is primarily caused by the cumulative denaturation of essential enzymes, as well as their aggregation and breakdown of membrane integrity after critical temperature thresholds. The use of traditional heat preservation methods remains crucial for controlling pathogens, as they provide reliable inactivation of vegetative microbial cells by denaturing essential proteins, disrupting membrane structures, or inactivating metabolic enzymes. Even so, these procedures often degrade the texture and flavor while retaining nutrients due to extended exposure to high temperatures. This is particularly problematic. In response, novel thermal heating, including ohmic, RF, and MW heating, has been developed to achieve equivalent or superior microbial kill while maintaining product quality through rapid, volumetric energy transfer (Rosnes, Skåra and Skipnes, 2011).

A distinct method of destructing microbes is introduced by OH. Instead of transferring surface heat, a changing electric current moves through the meat matrix and transforms electrical energy into internal heating via direct ionic conduction. Interactions between microbial membranes and the electric field result in electroporation, which is an event that can cause temporary or permanent pore formation by disrupting ion gradient patterns and maintaining cytoplasmic homeostasis. At lower bulk temperatures, this effect in vegetative cells promotes the diffusion of protons and small molecules, which speeds up enzyme inactivation and membrane rupture. Localized electrical stress can disrupt the outer protein layers of spores or cause them to germ earlier, making them more vulnerable to heat exposure (Peng *et al*., 2017).

RF heating, operating at 13–40 MHz, produces electromagnetic oscillations that produce volumetric heating via ionic displacement and dipole rotation. Microbial cells undergo continuous polarization and depolarization cycles that result in molecular vibration and internal friction, increasing local temperatures rapidly. Apart from thermal denaturation, RF fields can weaken electron transport chains and cause oxidative stress by increasing the number of intracellular radicals. The mechanisms involved in this phenomenon cause cellular instability and metabolic function to break down even before reaching equilibrium temperature, as shown by conventional thermal lethality curves (Wu *et al*., 2025).

MW heating, which oscillating electromagnetic field creates, localized "hot spots" where dipole rotation and molecular friction increase the temperature at a rate of more than 20 °C per second. These pheromones generate a combination of thermal and nonthermal effects: rapid unfolding of cytoplasmic and membrane proteins, disruption of lipid bilayers due to localized vapor pressure, and possible alteration of DNA conformation through MW-induced ROS production. Although uneven heating remains a challenge, hybrid systems that combine MW and convective or ohmic preheating can achieve more uniform thermal fields and improve both safety and product quality.

In all systems, the microbial response was caused in a sequence of sublethal injury, inhibition of repair, and cell death. Initially, a mild heat wave disrupts membrane permeability and ATP synthesis; with continued exposure, essential proteins coagulate and genetic material is degraded, rendering the cells unusable. In contrast, spores require a two-phase mechanism, first activation and then destruction, which is often accomplished more efficiently under uniform volumetric heating from ohmic or RF systems (Sengun, Icier and Kor, 2017).

The practical application of these emerging and innovative technologies enables them to provide a progressive level of microbial control by reducing processing time, improving uniformity, and minimizing nutrient loss. A key limitation of traditional methods is thermal inhomogeneity, which innovative systems overcome by combining rapid volumetric heating with precise control of field intensity and frequency to provide more electromechanical and oxidative modes of microbial inactivation. Mechanical robustness is key to achieving microbiological safety in meat products while maintaining their flavor and nutritional value.

16.6.2 Destruction of Parasites

Trichinellosis is an infection caused by nematodes belonging to the *Trichinella* genus, which primarily affect meat products. Once the cysts are ingested, the larvae are released in the stomach under the

action of gastric acid and digestive enzymes, particularly pepsin. Then, they penetrate the mucosal layer of the small intestine, where maturation into adult worms occurs. Roughly a week after this stage, the adult females begin producing larvae that enter the bloodstream and striated muscle tissues. In fact, they become enclosed within cysts, a process that generally finishes within four to five weeks. These encysted larvae can remain dormant yet infectious for several years inside the muscle fibers. Traditionally, control of *Trichinella* (such as *Trichinella pseudospiralis*) infection in meat has relied on postharvest treatments capable of reaching thermal or physicochemical thresholds that compromise larval viability. When exposed to internal temperatures of 57–60 °C, the larval cuticle undergoes structural and biochemical degradation, leading to collagen denaturation, intracellular proteins coagulation (dead cells), and key metabolic enzymes involved in anaerobic glycolysis becoming irreversibly inactivated. At temperatures above 57–60 °C, structural and biochemical degradations occur, leading to the loss of elasticity in the larval cuticle, the coagulation of intracellular proteins, or the irreversible inhibition of key metabolic enzymes involved in anaerobic glycolysis. Mitochondrial inflammation and vacuolation hinder the synthesis of energy, leading to cell collapse within minutes, which is necessary for this process. During the process of freezing, membranes and nucleic acids are disrupted, particularly in *T. spiralis* (which is commonly found in subzero temperatures), but other cryoresistant species like *T. nativa* can survive without refrigeration (Erickson and Ortega, 2006). In addition to traditional thermal and freezing methods, radiation methods are also used. Ionizing radiation at sublethal doses (~0.3 kGy) produces hydroxyl radicals and reactive oxygen intermediates that oxidize membrane lipids and induce fragmentation of larval DNA, eliminating infectivity even at low temperatures (Barber, Berkhout and Ismail, 2016).

By contrast, novel technologies such as OH, RF heating, and MW heating achieve the balance between lethality via combined thermal and electromechanical effects (Godínez-González *et al.*, 2019). Larvae tissues experience both internal heat generation and localized electrical field gradients that cause disturbance of membrane potential and ion transport through OH. RF heating prevents the formation of micro cold spots that may be the site of viable cysts accumulation and creates deep, volumetric heating that ensures uniform energy distribution in the dense tissues of the meat (Erickson and Ortega, 2006). The dipolar rotation of water molecules is amplified by MW treatment, leading to intracellular friction and explosive denaturation of larval proteins within seconds. Combined, these mechanisms (heat-induced protein denaturation) act through electroporation and oxidative stress along with rapid dehydration to complete inactivation of *Trichinella* larvae but maintain intact meat.

16.7 Conclusion and Future Perspectives

Red meat, composed primarily of skeletal muscle tissues from mammals like cattle, sheep, pigs, camels and deer, providing them with high-quality proteins along with heme iron, zinc and B-complex vitamins. Its high-water activity (aw > 0.95), endogenous enzymatic activity, and susceptibility to lipid and pigment oxidation make it highly perishable, even though it has some nutritional value. Its inherent traits make it difficult to maintain its safety, sensory characteristics, and shelf life throughout the production and distribution process. The use of traditional thermal heating, such as boiling, steaming, roasting and stirring, as well as autoclave sterilization, has been in place for a long time to guarantee microbial safety that governs the destruction of pathogenic and spoilage microorganisms through protein denaturation, enzyme inactivation (deactivating), and membrane disruption. Although these methods can still be used to meet the necessary safety standards, they are hindered by heterogenous heat transfer patterns with significant thermal gradients and excessive cooking loss caused by moisture loss, color degradation, and textural hardening, which can cause "cold spots" that allow bacteria like *L. monocytogenes*, *E. coli*, and *C. perfringens* to survive. In addition, high-temperature treatments lead to the development of undesirable thermal reaction products, such as HAAs and AGEs, which have adverse effects on both nutritional and sensory quality.

In addition to the practical aspects of heating, there is also a mechanistic and predictive approach to meat's thermal processing. The use of mathematical and computational modeling has become a viable method to comprehend the magnitude of heat and mass transferred during cooking or sterilization. By analyzing the distribution of temperature and moisture within the product, these models enable

researchers and engineers to predict thermal behavior, optimize process parameters, and design more efficient heating systems. By simulating heat flow, moisture migration and structural changes while cooking these models offer valuable insights into achieving uniform cooking; conserving energy and improving sensory properties. Additionally, modeling helps with rational design of equipment, improves product quality, and ensures food safety in large-scale production.

Innovative thermal technologies such as OH, MW, RF, IR, and sous vide processing provide more uniform and volumetric heating mechanisms that reduce temperature gradients and time of processing by up to 60–80%. These technologies improve energy efficiency, maintain higher WHC, and minimize nutrient degradation. For example, OH at a field strength of 30 V/cm can reduce cooking loss from approximately 31% to below 10%, while sous vide processing preserves native protein structures and volatile flavor compounds, resulting in enhanced tenderness and palatability.

The ability of innovative thermal heating to rapidly transfer volumetric energy has been showed to inactivate both vegetative and spore-forming microorganisms. OH involves the direct flow of electric current through the meat matrix, which generates internal heat by means of ionic conduction and ensures that cold zones were minimized. Also, the use of electroporation with an electric field leads to more extensive microbial contamination by breaking down membranes and increasing denaturation rates. MW heating experiences rapid temperature increases (>20 °C/s) due to the dielectric polarization of water molecules, which causes frictional heating and the unfolding of cytoplasmic proteins, as well as the potential formation of DNA damage through reactive oxygen species. These innovative systems offer efficient microbial and parasitic inactivation, with processing time significantly reduced and product quality greatly improved. However, the cost of equipment, need for precise process control, and lack of comprehensive industrial standards still limit large-scale adoption. Nondestructive spectroscopic techniques have been developed to enable real-time monitoring and molecular characterization of meat during thermal treatment, in addition to these advancements. NIR, Raman, fluorescence, and low-field nuclear magnetic resonance (LF-NMR) spectroscopy enable the in-line detection of structural and physicochemical changes such as reductions in α-helix content, increases in β-sheet structures, moisture migration (decrease in T_2 relaxation time), and oxidative reactions associated with AGE formation. By using NIR spectroscopy, core temperature can be predicted with a root mean square error of prediction (RMSEP) below 2 °C, and Raman spectra reflect amide I and III band shifts with coefficients of determination (R^2) greater than or equal to 0.98. The use of these techniques provides fast, accurate, and noninvasive alternatives to conventional destructive analytical methods.

Nonetheless, the shift from laboratory experimentation to industrial application remains a significant hurdle. Due to the inherent heterogeneity of meat matrices, optical interference caused by fat and chromophores, the cost of advanced optical components, and industrial resistance to technological change, large-scale deployment is still a challenge. Future research should include the integration of these intelligent analytical systems with advanced thermal technologies and predictive modeling to achieve adaptive, automated process control. Through the integration of real-time sensing and computational simulations, it is possible to predict temperature changes and moisture levels, dynamically regulate heating intensity, and avoid overprocessing. The potential for online monitoring of meat's thermal and chemical changes is high due to the availability of high-resolution and high-speed data acquisition by hyperspectral imaging (HSI) systems. When coupled with machine learning and deep learning algorithms such as partial least squares regression (PLSR), support vector machines (SVM), and convolutional neural networks (CNN), HSI can predict moisture distribution, protein denaturation, and surface browning with remarkable accuracy. Through closed-loop feedback control, these systems can dynamically adjust processing parameters in real time, minimizing thermal overexposure and energy waste. Within the framework of Industry 4.0 and 5.0, the convergence of spectroscopic sensing, the Internet of Things (IoT), artificial intelligence (AI), and multiphysics computational modeling will revolutionize meat processing by enabling integrated digital twins that simulate heat and mass transfer, structural transformations, and quality evolution across nano- to macroscale dimensions. Furthermore, hybrid thermal heating processing systems, such as OH combined with IR (internal volumetric plus surface heating) or MW combined with RF (deep penetration and improved uniformity), are expected to enhance thermal efficiency by up to 70% while reducing processing time and carbon footprint.

Ultimately research efforts are expected to focus on adaptive, self-optimized thermal systems, real-time farm-to-fork quality monitoring and traceability via blockchain that ensures product authenticity and transparency of supply chain. The study of nontraditional meats like camel, venison, and kangaroo, along with the reduction of thermally induced toxicants using natural antioxidants, will contribute to nutritional safety and sustainability. The combination of advanced thermal technologies, intelligent spectroscopic monitoring, computational modeling, and digital infrastructure is ultimately leading to the transformation of red meat processing from experimental, trial-based methods to data-driven, self-regulated, undisrupted, or sustainable systems. Technological advancements not only improve both taste and nutrition but also stimulate a shift toward more environmentally responsible, resource-efficient undated meat production.

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17

Advances in Meat Smoking: Balancing Flavor and Preservation

Foteini Pavli and Theodoros Varzakas

17.1 Introduction

Meat smoking is a preservation method based on chemical compounds from smoke that influence the sensory properties of meat products with antimicrobial and antioxidative roles on the meat surface (McDonald, 2015; Qureshi *et al*., 2024; Teodorovic *et al*., 2015). Smoking is one of the oldest preservation methods developed by humans as an attempt to preserve meat-based products and extend their shelf life without any refrigeration involved (Cheng *et al*., 2023; Toldrá, 2002; Zhang *et al*., 2020). The smoking process has advanced throughout the years and has transitioned to a complex processing technology applied in both artisanal processes and industrial-scale meat processing, highlighting its technological and commercial relevance for the sector. Smoking acts as a multifunctional processing technique, extending the shelf life of meat products through dehydration and antimicrobial activity, while imparting specific changes on the flavor, texture, and color of the product that result in very distinctive sensory profiles (Cheng *et al*., 2023; Hitzel *et al*., 2013; Merlo *et al*., 2020). The use of smoking varies by product type and regional practices and is not always required. It is more frequently employed in northern regions, where climatic conditions make ripening and drying processes more challenging (Toldrá, 2002).

Smoking relies on wood combustion and a staged pyrolysis process. This process entails four key steps: the initial water evaporation followed by the successive decomposition of hemicellulose, cellulose, and lignin as temperatures rise. The relative proportions of lignin, cellulose, and hemicellulose vary significantly among different wood species used for smoking resulting in different smoke characteristics according to the specific botanical source used for the pyrolysis (Yin *et al*., 2021; Zhang *et al*., 2020). The thermal decomposition pathways of lignin, cellulose, and hemicellulose differ with cellulose and hemicellulose being the precursors of carbonyl formation, while lignin serves as the structural origin of the phenolic compounds present in smoke (Yin *et al*., 2021). Literature indicates that the wood smoke is a dense chemical matrix featuring over 400 volatile species out of a total of 1,100 identified chemical compounds. Phenolic compounds constitute the core aroma profile; however, the unique smoky character is a result of synergistic interactions between these phenols and other volatile groups such as carboxylic acids, aldehydes, ketones, esters, and alcohols (Ledesma, Rendueles and Díaz, 2014; Yin *et al*., 2021).

The efficacy of the smoking process depends on a complex interplay between wood type and specific environmental and processing parameters. Factors such as the thermal intensity of the wood combustion, the amount of water vapor available, the presence of oxygen, the airflow speed, as well as the duration of the smoking process critically influence the chemical signature of the produced smoke (Martuscelli *et al*., 2009; Yin *et al*., 2021; Zhang *et al*., 2020). Commercial smoking operations frequently utilize beech, apple, oak, and bamboo, with beech chips serving as the primary heat and smoke source globally due to their performance in imparting standardized color and flavor. In contrast, fruit-derived wood chips are incorporated for their unique volatile profiles, introducing specific aromatic esters and carbonyls that contribute to a more complex and desirable flavor perception in the finished product (Yin *et al*., 2021).

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17.2 Types of Smoking

Methods for pyrolyzing wood to produce smoke-flavor compounds have evolved significantly over time. Historically, meat smoking was performed in a rather primitive way where meat pieces were suspended from the ceiling allowing the generated smoke from the fire to naturally surround the products (direct method). In contrast, modern commercial settings utilize highly sophisticated technologies to generate smoke under precisely controlled conditions. Modern smoking systems typically generate smoke by pyrolyzing wood in a separate chamber and then channel the smoke into a food-holding chamber (indirect method). This differs from traditional methods in which smoke production and food exposure occur within the same chamber (Maga, 1988; Toldrá, 2007). Meat smoking encompasses a range of techniques that mainly differ in the temperature regime, the duration of the process, and the technological objectives that have to be achieved. The smoking methods are often classified into cold smoking, warm smoking, hot smoking, and alternative smoking approaches such as liquid smoke (Figure 17.1). Each of these types of smoking exerts distinct effects on the physicochemical properties, the microbiological stability, and the organoleptic attributes of meat products; therefore, the smoking method should be carefully selected taking into consideration the product formulation, the shelf life requirements, and any relevant regulatory considerations.

Cold smoking is performed at relatively low temperatures, typically below 30 °C and mainly in the range of 15–25 °C (Maga, 1988), while the relative humidity (RH) may be 70–80% (Ledesma, Rendueles and Díaz, 2016; Toldrá, 2007), or even as high as 95% (Šimko, 2005). Under these conditions, the thermal effect that the meat receives is minimal, and smoke particles are deposited on the surface of the product over prolonged periods of time that can range from several hours to several days (1–14 days), due to the low concentration of aromatic and preserving compounds. Cold smoking is primarily used for cured meat products, such as dry-cured hams and fermented sausages, fermented salamis and bacon, where preservation relies on multiple hurdles, including curing agents, reduced water activity (a_w), reduced pH, and less on the smoking itself. It has to be noted that the long duration of the process results in significant weight loss. The selection of the smoking process and its parameters determine the energy consumption and the waste generation (Nizio, Czwartkowski and Niedbała, 2023). The main technological functions of smoking are the development of a characteristic flavor and aroma, the formation of a darker surface color, and the enhancement of oxidative and microbial stability through the activity of the phenolic smoke compounds. It has to be noted that the cold smoking process does not achieve sufficient temperatures for pathogen inactivation. Cold-smoked products require strict control of the quality of raw materials, the conditions of curing, and the subsequent storage temperature to ensure safety.

Warm smoking is an intermediate process, between cold and hot smoking, typically performed at temperatures 25–50 °C, RH of about 80%, and lasts for 4 hours to two days. This method is less commonly standardized, but is still applied in certain traditional meat products where partial protein denaturation

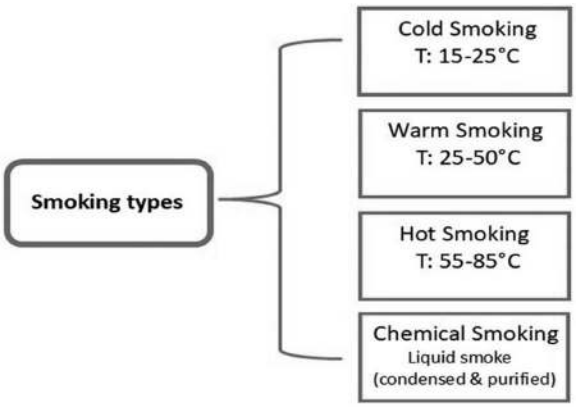

FIGURE 17.1 Types of smoking.

and moderate drying/dehydration is expected, without having the meat cooked. Warm smoking enables a greater diffusion of the smoke components into the meat matrix when compared to cold smoking, while still preserving some raw-like textural characteristics. The process contributes to flavor development and exerts limited microbial reduction, similarly to cold smoking, and is often combined with additional hurdles such as curing or drying steps or fermentation to achieve the desired shelf life and the safety objectives.

Hot smoking, on the other hand, is carried out normally at temperatures 55–85 °C (Ledesma, Rendueles and Díaz, 2016; Maga, 1988), while the RH is maintained at relatively high levels to avoid product dehydration (Toldrá, 2007), depending on the product type and the process design. In this case, smoking and cooking occur simultaneously, resulting in significant protein denaturation, fat melting, and moisture loss. Hot-smoked meat products such as cooked sausages (frankfurters) and cooked hams are typically ready-to-eat (RTE) and exhibit a shorter processing time compared to cold and warm smoking. The higher temperatures utilized in hot smoking enhance microbial inactivation and contribute to food safety, while smoke compounds provide flavor, color, and antioxidant effects. The higher temperatures used can also have an impact on the texture profile, resulting in firmer or drier products.

Beyond these three types of smoking, an alternative method for imparting smoke is the addition of liquid smoke, which has become important in modern meat processing and even cheese production. Liquid smoke is produced by capturing and condensing smoke vapors, followed by specific purification steps to remove undesirable compounds such as tar and ash (Aaslyng and Koch, 2018; Ledesma, Rendueles and Díaz, 2016). The application can take place via dipping, spraying, atomization, or incorporation directly into the meat formulation. Liquid smoke presents several advantages compared to the typical smoking process, rendering it very popular in industrial settings. The use of liquid smoke enables (1) uniform distribution of smoke flavor throughout a product rather than surface-heavy flavor, typical of traditional smoking; (2) enhancement of flavor intensity in conventionally smoked foods; (3) precise control over the level of smoke flavor applied; (4) the fractioning of the condensate to concentrate desirable components and remove potentially harmful substances prior to use; (5) the applicability to foods not traditionally subjected to smoking; (6) suitability for both consumer and commercial processing; (7) reduced costs due to elimination of wood and specialized smoking equipment; (8) lower environmental impact; and (9) flexibility in application methods, including spraying, dipping, or direct incorporation into foods (Ledesma, Rendueles and Díaz, 2016; Maga, 1988; Soares *et al.*, 2016). However, liquid smoke bears the limitation of not having the complexity and the strength of the traditional smoke flavor profiles.

Smoke is a two-phase system, composed of particulate and gaseous phases. The particulate phase consists mainly of tars, wood resins, and high-boiling phenolic compounds, existing as condensed liquid droplets averaging 0.196–0.346 μm. However, the most characteristic smoke flavor resides in the gaseous phase. Understanding these phenomena has led to the development of electrostatic smoking, where products pass through charged tunnels (20–60 kV) (Ledesma, Rendueles and Díaz, 2016), causing smoke components to deposit on meat surfaces, followed by infrared drying, altering volatile composition and reducing acids, phenols, and carbonyls overall significantly (Maga, 1988). Electrostatic smoking and other more advanced smoke delivery systems have been developed and proposed to improve smoke deposition efficiency and ultimately reduce smoking time (Toldrá, 2007). To conclude, the selection of the smoking method depends on the intended product characteristics, safety requirements, and the production capacity. It is crucial to understand the distinct principles and the outcomes of each smoking type to ultimately optimize quality and meet consumer expectations in smoked meat production.

17.3 Smoking Equipment

Smoking equipment and technology references span various domains, from food processing devices (electric/wood smokers, MAP packaging) and tobacco testing machine**s** (standardized puffing machines) to recreational/cannabis accessories (vapes, bongs, grinders, rolling papers), with research focusing on safer smoke generation, packaging innovations (vacuum, tray sealing), and digital cessation tools, often found in technical journals, patents, and industry sites.

Controlled slow combustion of the smoking material leads to smoke formation, greatly affected by the access of atmospheric oxygen. Two processes occur: thermal degradation of smoke (oxygen allowed) and pyrolysis, that is, combustion with oxygen limitations (Nizio, Czwartkowski and Niedbała, 2023).

Several methods of smoke production have been reported. Smoldering is one such method where pyrolysis at 400–800 °C of the crushed wood smoke–generating raw material occurs (Cheng *et al*., 2023; Varlet, Prost and Sérot, 2007). Smoke (smoldering) generators have the characteristic of power supply to one smoke-forming part of fuel being carried out at the expense of the energy allocated at burning of the other part. Pyrolysis or incomplete combustion of wood lead to the release of large amounts of heat from the exothermic decomposition of organic wood compounds to carbon and hydrogen. This heat warms part of the wood to a temperature of about 300 °C, at which self-ignition occurs (Shokina *et al*., 2019).

An open fireplace with an entire supply of oxygen is where combustion takes place. The smoke produced is thick and dry. A flame is visible during combustion. The combustion temperature is very high (even >1,000 °C). CO_2 and water steam are contained within smoke (Ekonomou *et al*., 2022; Rigling *et al*., 2023). Steaming, a flameless method, exposes wood chips to superheated steam heated at a temperature of 400 °C with a pressure of 0.13 MPa, and condenses on the product's surface along with the smoke (Li *et al*., 2023).

Simultaneous occurrence of the thermal decomposition of wood chips and the oxidation of particles in the fluidized state takes place when fluidized smoke generators operate. Introduction of the air into the smoking chamber and heating to 300 °C occur (Chua and Chou, 2003; Heo *et al*., 2010).

Pyrolysis of sawdust compressed into blocks is part of smelting. The constant parameters of the smoke generated and the possibility of exploiting wood waste constitute great advantages of this method (Essumang, Dodoo and Adjei, 2013; Shokin and Shokina, 2020). Burning of fuel in special apparatuses, such as smoke generators is reported by Shokin and Shokina (2020). It is from this area where the smoke is passed to the place of product processing by a chimney.

Smoke generation foreign brands include Autotherm (Germany), Vemag (Germany), Reich (Germany), Maurer (Germany), Bastra (Germany), and others.

Classification of operated smoke generators should follow the criteria below, characterizing their technological and ecological efficiency:

1. Energy source for fuel heating (external and internal heat generation)
2. Heating surface design
3. Operation principle (open and closed)
4. Automation and mechanization level of the smoke generation process
5. Pyrolysis temperature control
6. Environmental safety level of smoke (PAH content)

In the design of modern smoke generators, smoke can be obtained by smoldering, friction, and steam generation.

Finally, a two-step smoke development is being carried out due to pyrolysis in the presence of CO_2 or N_2 and then mixing with oxygen, leading to burn out of smoke, making it more dense and rich in smokeable substances (Ledesma, Rendueles and Díaz, 2016; Wang *et al*., 2021).

Besides the simple smoking room, there is a forced ventilation fumigation device where the air in the smokehouse is circulated by a fan, and the heating source of the product is gas or steam. This type of smokehouse has uniform airflow and good humidity control. It can correctly control not only the smoking process, but also the cooking temperature and the shrinkage of the finished product.

Another type is the tunnel-type continuous smoking furnace which can smoke 1.5–5 tons of products per hour. The heat treatment, smoking heating, hot water treatment, precooling, and rapid cooling of the products all are carried out continuously in the tunnel. The raw materials enter from one side and the products come out from the other side.

Finally, the fully automatic smoking oven is the most advanced meat-smoking equipment. In addition to drying, smoking, and cooking, it also has the functions of automatic spraying and automatic cleaning, which is suitable for the drying, smoking, and cooking processes of all smoked or unsmoked meat products.[1]

Another equipment mentioned in the bibliography is QUALISANI (FAQ) designed and manufactured for grilling of meat and smoking and smoking-drying of fish (Assogba *et al.*, 2024). Load capacity is estimated to be 20–30 kg against 5–10 kg for traditional equipment such as barrel kiln and clay grill with two chambers currently in use by processors. FAQ shows a combustion and a grilling/smoking chamber supplied with five grids. QUALISANI equipment is used as described in its invention patent (Assogba *et al.*, 2023).

17.4 Woods and Smoke Characteristics

The selection of wood fuels are the most important determinants of the resulting smoke composition, thermal behavior, and sensory outcomes in meat smoking. Wood serves as an energy source and also as a generator of chemically active smoke compounds that contribute to flavor and color and exert antimicrobial effects. It is of paramount importance to understand the physical and chemical properties of wood fuels, as well as the mechanism behind the smoke formation to produce consistent and well-controlled outcomes.

Hardwoods are almost exclusively used in meat smoking due to their favorable combustion characteristics and their chemical composition. Conifers are not ideal for smoke production due to the high levels of resins that generate harmful compounds during the process (Nizio, Czwartkowski and Niedbała, 2023). Unlike softwoods that contain high levels of resin and terpenes that produce acrid flavors and potentially harmful compounds, hardwoods generate smoke rich in desirable phenolic and carbonyl compounds. Common smoking woods include oak (*Quercus* spp.), alder, maple, acacia, hickory (*Carya* spp.,) beech (*Fagus* spp.), and some fruitwoods, including apple (*Malus domestica*), walnut, and cherry (*Prunus* spp.), which vary in lignin content, resulting in distinct smoke profiles. As an example, oak produces a honey flavor with a slight bitterness, whereas apple generates a milder smoke with subtle fruit flavor (Nizio, Czwartkowski and Niedbała, 2023).

Wood structure and moisture content significantly influence combustion behavior (Table 17.1). Cellulose and hemicellulose decompose at lower temperatures (180–350 °C) generating acids and carbonyls, while lignin degrades over a broader temperature range (300–500 °C), producing phenolic compounds responsible for the characteristic smoke aromas and high antioxidant activity (Du *et al.*, 2022). Excessively dry wood burns rapidly and may produce thin but hot smoke, whereas wood with high moisture content (>25%) results in an increased production of particulate matter, bitter-tasting compounds, and higher polycyclic aromatic hydrocarbons (PAHs) emissions. For most smoking applications, wood moisture content of 15–20% is considered ideal for stable combustion and balanced smoke generation.

Temperature is a critical determinant of the smoke characteristics, given the different temperatures required for degradation of hemicellulose and lignin, with hemicellulose fraction being the first major

TABLE 17.1

Wood Composition and Smoke Characteristics

	Wood Carbohydrate Composition (%)				
Wood	**Cellulose**	**Hemicellulose**	**Lignin**	**Characteristic**	**References**
Apple	20.7	6.9	37.9	Mild smoke with subtle fruit flavor	Lingbeck *et al.*, 2014; Nizio *et al.*, 2023
Cherry	20.7	3.4	13.8	Subtle fruit flavor with little bitterness	Lingbeck *et al.*, 2014; Nizio *et al.*, 2023
Hickory	41.4	1.7	24.1	Sweet, smoky flavor	Rizzo *et al.*, 2022; Nizio *et al.*, 2023
Mesquite	8	8	44	Smoky aroma, meaty/brothy flavor	Lingbeck *et al.*, 2014; Del-Toro Gipson *et al.*, 2020
Maple	17.2	17.2	55.2	Mild and slightly sweet taste	Lingbeck *et al.*, 2014; Nizio *et al.*, 2023

wood fraction to undergo degradation, while the lignin fraction is the most resistant. Consequently, at relatively low temperatures, lignin may not fully decompose, resulting in smoke with a chemical composition that differs from that produced at higher temperatures (Maga, 1988). Effective airflow management is critical especially in traditional smokehouse systems.

In summary, wood fuel selection and combustion management constitute a complex, interrelated system affecting environmental efficiency and the product quality. Knowledge of wood properties, combustion chemistry, and airflow control allows smoking to be performed in a reproducible manner and technically optimized, rather than being performed as an empirical process.

17.5 Antimicrobial Compounds in Smoke

Wood smoke contains more than 400 volatile compounds, including approximately 48 organic acids, 22 alcohols, 131 carbonyl compounds, 22 esters, 46 furans, 16 lactones, 75 phenols, and about 50 additional miscellaneous substances. Smoke condensates are mainly composed of water (82.4%), followed by tar (4.8%), residue (4.2%), activated charcoal extracts (4.1%), acetic acid and other higher-molecular-weight acids (1.7%), methanol (1.0%), ketones (0.7%), higher-molecular-weight aldehydes (0.6%), formic acid (0.4%), formaldehyde (0.1%), and phenolic compounds (0.1%) (Ledesma, Rendueles and Díaz, 2016). During the thermal decomposition of wood components, such as cellulose, hemicellulose, and lignin, a complex mixture of volatile and semivolatile compounds is generated. Particularly, the degradation of lignin is crucial as it produces phenolic compounds with strong antimicrobial properties. The generation of antioxidant and antimicrobial compounds during wood combustion, as well as the extent to which these substances deposit on the product surface, can significantly influence the shelf life of the product (Merlo *et al*., 2020). Optimal smoke generation aims to maximize antimicrobial compounds while minimizing harmful substances such as polycyclic aromatic hydrocarbons (PAHs), as will be discussed in the following section.

Several groups of compounds in smoke are responsible for antimicrobial activity, including phenolic compounds, organic acids, carbonyl compounds, alcohols, and hydrocarbons. The most important phenolic compounds found in smoke include phenol, guaiacol, and syringol. Phenols disrupt bacterial cytoplasmic membranes (Lingbeck *et al*., 2014), denature proteins, and interfere with enzyme activity. They are particularly effective against Gram-positive bacteria and contribute significantly to surface preservation. Organic acids such as acetic acid and formic acid contribute toward lowering the surface pH of meat products, creating unfavorable conditions for microbial growth. In their undissociated form, these acids can penetrate microbial cell membranes, inactivate internal enzymes (Lingbeck *et al*., 2014), and disrupt internal pH balance. Carbonyl compounds such as formaldehyde and acetaldehyde exhibit antimicrobial effects by reacting with proteins and nucleic acids in microbial cells. Even when carbonyl compounds are unable to penetrate the interior of microbial cells, they can still suppress microbial growth by disrupting nutrient uptake mechanisms (Lingbeck *et al*., 2014). Formaldehyde, although effective, is also associated with toxicity concerns and must be carefully controlled through smoke generation parameters. Additionally, alcohols and hydrocarbons have relatively weak antimicrobial effects individually but may contribute synergistically when combined with phenols and acids.

Despite its antimicrobial properties, smoking alone does not provide complete microbial safety. Smoke compounds can be effective against pathogenic microorganisms (*Staphylococcus aureus*, *Escherichia coli*, *Listeria monocytogenes*, and *Salmonella* spp.) and reduce the lipid oxidation (Gómez *et al*., 2020), while they are less effective against yeasts and molds (Maga, 1988). Cold-smoked products are especially vulnerable, as processing temperatures are insufficient to achieve microbial inactivation. Furthermore, post-smoking handling, slicing, and packaging can introduce contamination, reducing the effectiveness of smoke-derived antimicrobials. Because of these limitations, antimicrobial smoke compounds are most effective when used as part of a hurdle technology strategy. Smoking is commonly combined with curing (salt and nitrite), reduction of water activity through drying, refrigeration, pH control, hygienic processing, and appropriate packaging. Each hurdle targets different aspects of microbial survival, and their combined effect provides a higher level of safety than smoking alone. In this context, smoke compounds act as a complementary hurdle that enhances surface stability and contributes to shelf-life extension.

17.6 Food Safety and Health Considerations

Although smoking is a traditional preservation method that imparts unique characteristics to meat products, certain chemical risks are introduced during the smoking process which have to be considered. The most important category of chemical risks associated with smoking are the polycyclic aromatic hydrocarbons (PAHs), produced during uncontrolled smoking processes due to the incomplete combustion or the thermal decomposition of the wood fuel (Ledesma, Rendueles and Díaz, 2015). PAHs are organic compounds comprised of two or more fused aromatic rings (Škaljać *et al*., 2023). Carcinogenic, mutagenic, and bioaccumulative properties have been attributed to these compounds, with the European Commission setting the maximum levels of PAHs that can be contained in foods, which has further been reduced (Commission Regulation, 2023). Additionally, recent evidence indicates that repeated exposure may also increase the risk of oxidative stress, thrombosis, hypertension, myocardial infarction, and other cardiovascular diseases (Da Silva *et al*., 2024). An understanding of the conditions associated with higher PAH production is essential for food producers, who should apply appropriate controls to limit their formation (Ledesma, Rendueles and Díaz, 2016).

PAH contamination of meat products can arise from several sources. Raw materials may already be contaminated due to environmental pollution, as animals and plant ingredients can absorb PAHs from air, soil, or water originating from traffic emissions, industrial activities, and natural events such as forest fires (Da Silva *et al*., 2024). In addition, food processing methods other than smoking, including grilling, frying, roasting, baking, drying, and barbecuing, can contribute to PAH formation. During smoking, melted fat from products placed higher in the smoking chamber may drip onto heat sources or onto other products, increasing PAH levels in both the smoke and the meat. Finally, direct exposure to smoke leads to PAH contamination through the deposition of tar particles on the surface of meat products (Ledesma, Rendueles and Díaz, 2016). Tar is a black and highly viscous liquid that can be condensed and deposited into foods and form aerosols that polymerize into more complex structures. At temperatures above 750 °C, tertiary tar products increasingly form, and the condensation of these tertiary aromatic compounds results in the generation of PAHs (Ledesma, Rendueles and Díaz, 2014). Four PAHs—benzo(*a*)pyrene (BaP), chrysene (Chr), benz(*a*)anthracene (BaA) and benzo(*b*)fluoranthene (BbF)—have been considered as the most suitable indicators for PAHs presence in foods (Da Silva *et al*., 2024; Fuertes-Martínez *et al*., 2024).

The method of smoke generation, the characteristics related to the combustion of the wood material, the smoking technique applied (direct or indirect, cold, warm or hot, liquid smoking), the smoke generation temperature, the position of the food product within the smoke house, the duration of the smoking process, the humidity, the airflow rate, the type of wood being utilized, as well as any subsequent treatments determine the formation of PAHs (Cheng *et al*., 2023; Racovita *et al*., 2020; Singh, Varshney and Agarwal, 2016). To limit excessive PAH accumulation in smoked processed meats, it is recommended to avoid high pyrolysis temperatures and direct smoking. In modern smoking systems, the smoke generator is positioned separately from the smoking chamber. This design prevents fat from dripping onto the heat source and thereby reduces the formation of toxic compounds (Fraqueza *et al*., 2020).

In addition to PAHs, many studies have shown that smoking can also influence the formation of heterocyclic amines (HAs). HAs are toxic compounds found in meat and fish that have been processed at temperatures higher than 150 °C (Iko Afé *et al*., 2021). Their presence depends on specific smoking parameters such as the type of wood used, the method of smoke generation, and the duration and temperature of smoking. Based on their chemical structures, HAs can be classified into two main categories: pyrolytic HAs, also referred to as amino-carbolines, and thermally formed HAs, which mainly consist of imidazo-quinoline compounds. Imidazo-quinolines, imidazo-quinoxalines, and imidazo-pyridines represent three classes of compounds that originate from precursors naturally present in raw meat muscle. These compounds can be formed from creatine or creatinine, free amino acids, and sugars through Maillard reaction pathways (Iko Afé *et al*., 2021). However, residual levels of HAs in smoked meat products are generally considered to be relatively low (Cheng *et al*., 2023).

Another group of chemical compounds called nitrosamines may be present in smoked meat products as a result of both smoking and additional processing steps, particularly curing. Nitrosamines are a group of toxic compounds that are produced during heat processing in meat products. During curing, nitrites

are commonly added to control microbial growth and to develop the characteristic color and flavor, but under certain conditions they can react with amines naturally present in meat to form nitrosamines. The smoking process, especially when high temperatures are applied, may further promote these reactions. Other factors such as prolonged storage, low pH, and cooking can also influence nitrosamine formation. Therefore, controlling nitrite levels and processing conditions is essential to minimize potential health risks (Iko Afé *et al.*, 2021).

The microbiological safety of smoked meat products cannot rely on smoking as a sole preservation method. While smoking provides inhibitory effects through mild heat, surface drying, and antimicrobial smoke compounds, it is often insufficient to eliminate pathogens such as *L. monocytogenes*, *Salmonella* spp., *S. aureus*, and spore-forming bacteria such as *Clostridium botulinum*, particularly in cold-smoked products. For this reason, smoking is applied in combination with other preservation measures using the hurdle approach. This strategy integrates curing with salt and nitrite, reduction of water activity, refrigeration, pH control, hygienic handling, and suitable packaging to prevent microbial growth. The combined action of these hurdles is essential to ensure microbiological safety and product stability.

Note

1. https://landercn.com/blog/articles/the-ultimate-guide-to-food-smoking-technology/?srsltid=AfmBOoonZRIT1QxGZkOX1R_6dR40da0AL17a5yroTnoDIL5y-jMyo6gI (accessed January 2026).

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18

Additives in Meat Manufacturing: Key to Improving Appearance, Texture, Shelf Life, and Safety

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18.1 Introduction

Since the earliest stages of human development, the search for safe and durable food has driven the evolution of processing practices, ranging from primitive methods of drying and salting to the industrial-scale preservation and formulation techniques of the modern era. Over the centuries, these empirical techniques converged with advances in chemistry, industrialization, and food technology, giving rise to the systematic use of substances capable of preserving, stabilizing, or enhancing foods (Carocho *et al*., 2014).

Within this historical and technological *continuum*, the intentional incorporation of functional substances, now formally referred to as food additives, has become one of the most significant developments in food technology. The use of food additives is not arbitrary but must meet three fundamental and interrelated criteria: (1) technological need (must serve a purpose not easily met otherwise), (2) safety (must not harm health at intended levels, with a margin of safety), and (3) consumer benefit (must maintain quality, freshness, nutrition, or appeal without misleading people) (Figure 18.1) (European Commission, 2025). These foundational principles have progressively been translated into structured regulatory frameworks and classification systems that govern the authorization, usage, and monitoring of food additives in food, and also meat and meat products.

In meat manufacturing, additives are indispensable for stabilizing these highly complex and perishable matrices, controlling spoilage, improving sensory attributes, and guaranteeing microbiological and chemical safety across supply chains (Ursachi *et al*., 2020).

Indeed, meat and meat products represent a unique matrix owing to undoubted nutritional values and macromolecular complexity. However, they also function as an "optimum medium" for the propagation of several harmful microorganisms (Dave and Ghaly, 2011; Miedico *et al*., 2022). Fresh meat is a biologically active matrix, and its high water activity, protein and lipid richness, and structural susceptibility to oxidation and microbial growth render it one of the most perishable foods (Iammarino *et al*., 2021). As a consequence, meat and meat-based products are also among the food categories most frequently implicated in foodborne illness. According to the World Health Organization (WHO), unsafe food is responsible for an estimated 600 million cases of illness and 420,000 deaths globally each year, with bacteria representing the predominant causative agents. Pathogens such as *Salmonella* spp., *Campylobacter* spp., enterohemorrhagic *Escherichia coli*, and *Listeria monocytogenes* are commonly associated with products of animal origin, including raw or undercooked meat and ready-to-eat meat preparations, and may lead to severe outcomes in vulnerable populations (European Food Safety Authority (EFSA), European Centre for Disease Prevention and Control (ECDC), 2025). In addition to microbial hazards, meat can act as a vehicle for chemical contaminants and residues, while emerging concerns such as antimicrobial resistance further complicate risk management. As a result, the adoption of additives has become integral to both the technological performance and the safety management of meat matrices in modern industry (WHO Team, Nutrition and Food Safety (NFS), 2022).

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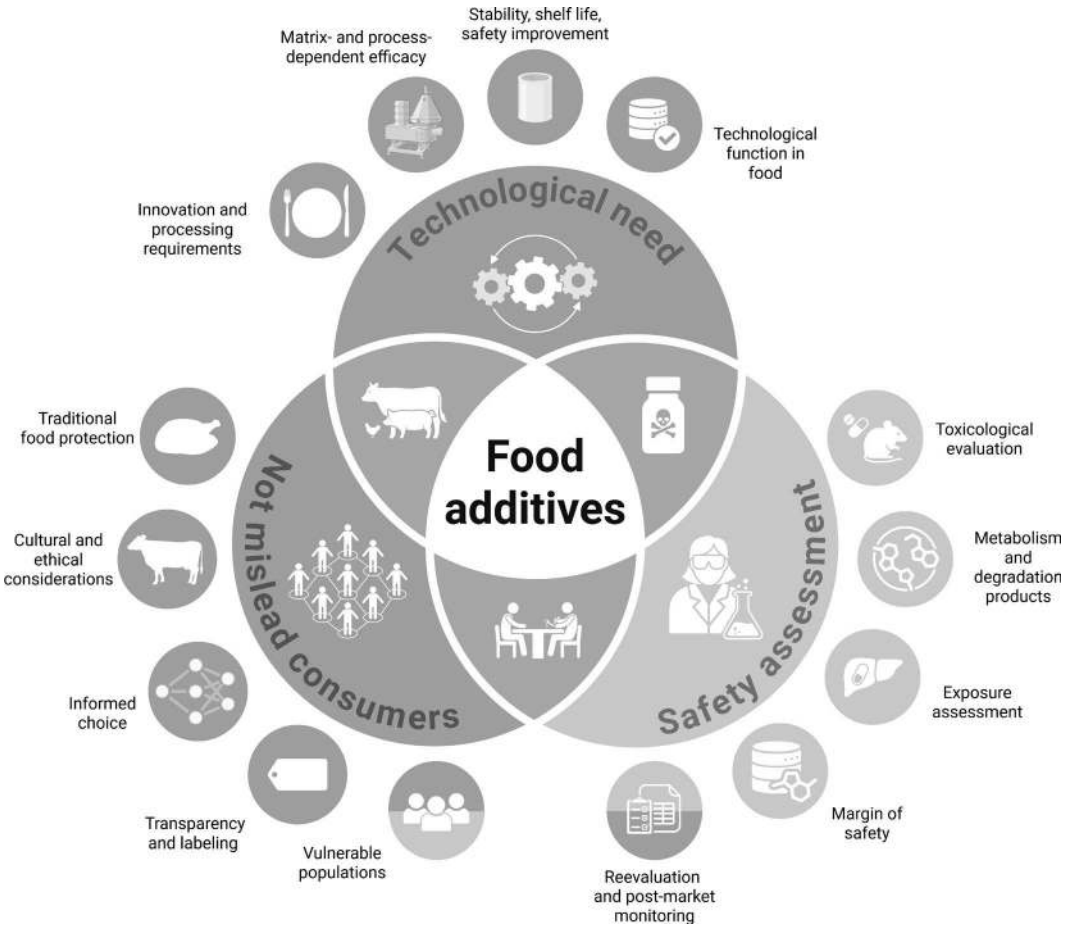

FIGURE 18.1 Main criteria governing the use of food additives. These criteria are particularly relevant in the EU regulatory framework; in fact, in the European Union, food additives are included in the positive list established under Regulation (EC) No. 1333/2008 only when three interrelated conditions are simultaneously fulfilled: (1) a demonstrated technological need that cannot be reasonably achieved by other means and is compatible with good manufacturing practice (2) a favorable safety assessment based on toxicological evaluation and dietary exposure, and (3) assurance that the intended use does not mislead consumers and preserves transparency through appropriate labeling.

Furthermore, over the past two decades, the meat industry has faced two major challenges: the advent of transformative technologies and the pervasive phenomenon of adulteration (Smaoui *et al.*, 2023; Sofos, 2008). These factors have precipitated the initial endeavors to delineate and regulate the legitimate additives permitted in food products. As an example, in Europe, the first directive on food additives was promulgated on December 21, 1988 (Directive 89/107/CEE). In fact, the deliberate addition of substances to meat, and more generally to food, has not always been associated with considerations of safety or quality (Balestra and Petracci, 2019). During the nineteenth century, the centralization of food production, the emergence of long-distance trade, and diversified regulatory oversight contributed to widespread adulteration of meat and other foods. Hazardous compounds were employed to mask spoilage or imitate desirable attributes, contributing to severe public health concerns and a progressive loss of consumer trust. The advent of new sensitive and selective technologies in analytical chemistry, in conjunction with regulatory interventions in the early twentieth century, signified a pivotal moment, facilitating systematic detection of adulterants and establishing the foundations for contemporary additive regulation, with the main objective to verify the correct use of additives. By the mid-twentieth century, processed foods had become a fundamental component of human diets worldwide. This development prompted a rapid expansion in the number and complexity of legally permitted additives and the establishment of structured

safety evaluation programs (Dusemund *et al*., 2012). Despite their indispensable role and the punctual process of pre-authorization evaluation, additives remain a subject of considerable debate. This is primarily due to new toxicological evidences and the differing interpretations adopted by regulatory authorities. In this context, a number of food additives have been investigated following experimental, clinical, or epidemiological observations suggesting potential health concerns, including the role of nitrates and nitrites in the endogenous formation of *N*-nitroso compounds (D'Amore *et al*., 2022), hypersensitivity reactions associated with sulfites (D'Amore *et al*., 2020), reported neurobehavioral effects for certain colorants and sweeteners (de Oliveira *et al*., 2024; Fadaei *et al*., 2025), and genotoxicity evidence observed for preservatives such as sorbates and benzoates in specific in vitro or model systems (D'Amore *et al*., 2021).

In addition, food additives have been observed to undergo chemical transformations during the processes of curing, heating, fermentation, or storage, resulting in the generation of compounds that exhibit altered biological activity and/or hazardous properties. A comprehensive understanding of these transformations is essential for conducting complete risk assessment and for the development of more predictable and sustainable formulations.

Currently, more than 4,000 additives are authorized globally, while many others have been progressively restricted or banned. The definition proposed by the Codex Alimentarius, originally adopted in 1995 and revised multiple times, remains the international reference (Codex Alimentarius—International Food Standards, 2024). Additives are defined as substances not normally consumed as foods nor used as typical food ingredients, but intentionally added for specific technological or organoleptic purposes during processing, preparation, packaging, or storage. The Codex also provides a framework for global standards and classification, to a certain extent harmonizing the work of major regulatory bodies (D'Amore, Smaoui and Agriopoulou, 2025).

Despite the fact that this framework has been extensively optimized over the years, periodic re-evaluations of all additives, refined monitoring studies, and ongoing research on new sources of active compounds indicate that it is still undergoing a profound transformation. The heightened level of consumer awareness and interest in "clean labels" and environmentally sustainable production has precipitated a rapid search for natural or minimally processed alternatives to synthetic and currently in use additives (Inguglia *et al*., 2023; Jung *et al*., 2024; Kurćubić *et al*., 2022). The use of plant extracts characterized by high concentrations of polyphenols, pigments, organic acids, functional peptides, and enzymes is currently under scrutiny as potential substitutes and/or lowering agents for synthetic additives. Concurrently, the proliferation of plant-based meat analogues and novel food products engenders novel formulation challenges. These matrices differ significantly from animal-derived proteins in terms of structure, water distribution, and oxidative behavior, necessitating tailored additive strategies.

The meat industry faces the challenge of reconciling innovation, technological performance, regulatory compliance, and societal expectations. This chapter provides a comprehensive review of the technological roles of additives in meat manufacturing. In addition, it offers a detailed analysis of the global regulatory and risk-assessment frameworks governing their use, as well as the emerging trends in this field. Special emphasis is placed on natural alternatives, reformulation strategies, and novel technologies.

18.2 Classification, Regulatory Framework, and Risk Assessment

18.2.1 Food Additive Functional Classes in Meat and Meat Products

The Codex definition of food additives is pivotal as it constitutes the basis upon which the majority of national and regional legislations are established. This development was the culmination of decades of research by the Codex Committee on Food Additives (CCFA) and the Joint FAO/WHO Expert Committee on Food Additives (JECFA). The primary mandates of these committees include the establishment of harmonized specifications, the evaluation of safety, the setting of maximum permitted levels (MPLs), and the promotion of fair practices in global food trade. Once the JECFA has concluded that an additive is safe for its intended uses and the CCFA has assigned MPLs, countries are expected to transpose these provisions into national legislation, unless more stringent local rules apply. This harmonized process assumes particular relevance in a globalized food system, where raw materials, ingredients, and

finished meat products routinely cross borders. Whereas JECFA provides global safety evaluations and establishes maximum permitted levels for food additives, the European Union operationalizes these principles through a highly structured regulatory framework. Specifically, the Common Authorization Procedure, codified in Regulation (EC) No. 1331/2008 and reinforced by Regulation (EU) 2019/1381, delineates the formal process for updating the Union list of authorized food additives, enzymes, and flavorings. This mechanism integrates risk assessment carried out by the European Food Safety Authority (EFSA) with Commission-led risk management and legislative adoption (European Commission, 2025).

Classification systems have been developed to support clarity and consistency in additive use. The most widely applied is the International Numbering System (INS) of the Codex GSFA, which categorizes additives according to functional class and assigns a unique numerical code. The European Union adopts this system but labels additives with the prefix "E", creating the familiar "E-number" system used in ingredient lists. In contrast, in the United States, Food and Drug Administration (FDA) operates under a distinct regulatory *corpus*, the Code of Federal Regulation (CFR), that distinguishes between food additives requiring premarket approval and substances "Generally Recognized as Safe" (GRAS), but functional overlaps remain significant.

Classification is complicated by the multifunctional nature of many additives: a single molecule may act simultaneously as an antioxidant, antimicrobial, color stabilizer, acidity regulator, or texturizing agent depending on the matrix and conditions. These pleiotropic functions are especially relevant for meat and cured meat products (Wu *et al*., 2022). A practical example is represented by nitrites and nitrates that are formally preservatives with bactericidal activity, but also flavoring modulators and coloring stabilizer and enhancer in cured meat products, thanks to the formation of nitric oxide (NO), which reacts with many macromolecules (e.g., heme group, proteins, enzymes) (D'Amore *et al*., 2022). Similarly, ascorbic acid can act both as an antioxidant and as a color stabilizer (Varvara *et al*., 2016).

Functional classes include, but are not limited to, preservatives, antioxidants, colorants, flavor enhancers, sweeteners, emulsifiers, stabilizers, thickeners, gelling agents, bulking agents, and anticaking agents. The Codex GSFA categorizes additives into 27 functional classes, as taken up by the European Reg. No. 1333/2008, whereas in the US CFR (Part 170), 32 classes are defined. With regard to meat and meat products, not all classes of additives are used or approved. Table 18.1 provides a concise overview of the various functional classes of additives and their respective roles in the context of meat manufacturing.

Acidity regulators (pH control agents), including lactic acid, phosphates, citrates, and sodium carbonates, are widely applied in processed meats to control pH, thereby improving water-holding capacity, texture, and microbial stability. Phosphates, for instance, are critical in cooked ham and emulsified sausages, where they enhance protein solubility and binding, while citrates and lactic acid can also act as mild antimicrobial agents (Bacak, 2017).

Antimicrobial agents or preservatives, such as nitrites, nitrates, sulfites, acetic acid, sorbates, natamycin, and ethyl lauroyl arginate, target spoilage and pathogenic microorganisms. Nitrites and nitrates are essential in cured meats, providing characteristic pink coloration and inhibiting *Clostridium botulinum*, and their use is strictly monitored (D'Amore *et al*., 2019). Sorbates and acetic acid are often applied in ready-to-eat meat products, where minimal thermal processing occurs, while natamycin is mainly permitted on surface-treated cheeses and some traditional fermented sausages (Bajcic *et al*., 2021). Antioxidants mitigate lipid oxidation and color deterioration. In minced meat and high-fat sausages, synthetic antioxidants like BHA or TBHQ are often restricted to industrially processed products, whereas natural antioxidants (e.g., rosemary extract, E392) are increasingly favored in clean label formulations. Coloring agents serve both appearance and functional purposes. Synthetic dyes, such as Allura Red (E129) or Ponceau 4R (E124), are permitted primarily in marked processed products, whereas natural pigments, such as beetroot red (E162), paprika extract (E160c), curcumin (E100), or annatto (E160b), are allowed in a wider range of fresh and processed meats. Some colors are limited to traditional or festive products due to allergenic potential or historical usage patterns (Czech-Załubska *et al*., 2023).

Emulsifiers and stabilizers, including sucrose esters, gum tragacanth, carrageenan, locust bean gum, and xanthan gum, are critical in finely comminuted or emulsified meats. They stabilize fat–water emulsions, enhance bite and mouthfeel, and reduce syneresis during thermal processing (Demirci, Yılmaz and Demirci, 2014). Similarly, gelling agents, mainly alginates and carrageenan, are used to structure reformed

TABLE 18.1

Functional Classes and Food Additives Authorized in Meat and Meat Products

Functional Class	Principal Authorized Additives in Meat and Meat Products	Description	Other Definition	Codex Class Number	EU Class Number	USA Class Number	INS Number Range
Acidity regulator (pH control agents)	Lactic acid Buffered vinegar Phosphoric acid—phosphates—di-, tri-, and polyphosphates Citric acid and citrates Sodium carbonates Tartaric acid and tartrates	Substance added to change or maintain active acidity or basicity, including buffers, acids, alkalis, and neutralizing agents	Acid, acidifier, alkali, base, buffer, buffering agent, pH adjusting agent	1	6–7	23	300–399 500–599
Antimicrobial agent or preservative	Sulfur dioxide—sulfites Nitrates and nitrites Acetic acid Acetates Lactic acid Buffered vinegar Sorbic acid and sorbates Phosphoric acid—phosphates—di-, tri-, and polyphosphates Natamycin Ethyl lauroyl arginate Tartaric acid and tartrates	Substance used to preserve food by preventing growth of microorganisms and subsequent spoilage	Preservative, antimicrobial Preservative, antimycotic agent Bacteriophage control agent, fungistatic agent, antimold, and antirape agent, antimicrobial synergist	21	3	2	200–299
Antioxidant	Ascorbic acid and ascorbates Lactates Citric acid and citrates Extracts of rosemary Propyl gallate TBHQ BHA Erythorbic acid Sodium erythorbate	Substance used to preserve food by retarding deterioration, rancidity, or discoloration due to oxidation	Antioxidant synergist Anti-browning agent	4	4	3	300–399

Color / color retention agent	Allura red AG Brilliant blue FCF Brown HT Curcumin Carminic acid Caramels Annatto bixin and norbixin Paprika extract Beetroot red Lycopene Quinoline yellow Riboflavins Sunset yellow FCF Ponceau 4R Carotenes EDTA	Substance used to impart, preserve, or enhance the color or shading of a food	Coloring agent, decorative pigment Surface colorant	9	2	4 (together with color retention agent)	100–199
Curing agent	*Included in preservative (nitrites)	Substance imparting a unique flavor and/or color to a food, usually producing an increase in shelf life stability	Pickling agent			5	249–252
Emulsifier	Sucrose esters of fatty acids Gum tragacanth	Substance able to modify surface tension in the component phase of an emulsion to establish a uniform dispersion or emulsion	Plasticizer, dispersing agent, surface active agent, crystallization inhibitor, density adjustment agent, suspension agent, clouding agent	11	11	8 (together with emulsifier salt)	400–499
Flavor enhancer	Neohesperidine DC	Substance added to supplement, enhance, or modify the original taste and/or aroma of a food, without imparting a characteristic taste or aroma of its own	Flavor synergist	14	14	11	600–699 900–999
Gelling agent	Alginates Carrageenan	A food additive, which gives a food texture through formation of a gel	–	17	16	–	400–499
Humectant	Xanthan gum Phosphoric acid—phosphates—di-, tri-, and polyphosphates Tartaric acid and tartrates	Hygroscopic substance incorporated in food to promote retention of moisture, including moisture-retention agents and anti-dusting agents	Moisture-retention agent, wetting agent	19	18	16	400–499

(Continued)

TABLE 18.1 ***(Continued)***

Functional Classes and Food Additives Authorized in Meat and Meat Products

Functional Class	Principal Authorized Additives in Meat and Meat Products	Description	Other Definition	Codex Class Number	EU Class Number	USA Class Number	INS Number Range
Modified starch	Acetylated distarch phosphate Hydroxypropyl distarch phosphate	Substance obtained by one or more chemical treatments of edible starches, which may have undergone a physical or enzymatic treatment, and may be acid or alkali thinned or bleached	–	–	19	–	1,400–1,452
Stabilizer	Stearoyl-2-lactylates Sucrose esters of fatty acids Cassia gum Alginates Carrageenan Processed *Eucheuma* seaweed Locust bean gum Guar gum Gum tragacanth Xanthan gum EDTA	Substance, which makes it possible to maintain a uniform dispersion of two or more components	Foam stabilizer, colloidal stabilizer, emulsion stabilizer, stabilizer synergist, binder	25	24	28	400–499
Surface-finishing agent	Talc	Substance used to increase palatability, preserve gloss, and inhibit discoloration of foods, including glazes, polishes, waxes, and protective coatings	Glazing agent, sealing agent, coating agent, surface-finishing agent, polishing agent, film-forming agent	18 (only glazing agent)	17 (only glazing agent)	30	400–499 910–919
Thickener	Cassia gum Alginates Carrageenan Locust bean gum Processed *Eucheuma* seaweed Guar gum Gum tragacanth Xanthan gum	Substance that affects the appearance or feel of the food (viscosity)	Texturizer, thickener, bodying agent, binder Texturizing agent, thickener synergist	27	25	32	400–499

BHA: butylated hydroxyanisole; TBHQ: tertiary butylhydroquinone.

or restructured meat products, while humectants, including phosphates and tartrates, retain moisture in cured and dried meats, preventing excessive dehydration and textural defects (Hashem *et al.*, 2022).

Flavor enhancers (e.g., neohesperidine DC, E959) are selectively used in processed meats where flavor loss occurs during cooking or extended storage. Modified starches are incorporated to enhance water-binding, texture, and emulsion stability, particularly in sausages, pâtés, and other processed meats (Gałkowska, Kapuśniak and Juszczak, 2023).

18.2.2 Regulatory Framework

More than 4,000 substances are employed worldwide for additive or additive-like functions across foods, feeds, and beverages; however, only a subset is authorized for direct use in human foods, and an even smaller subset is permitted in meat products. A considerable number of compounds that were previously authorized have undergone restrictions or ban following new toxicological evidences or shifts in risk–benefit evaluations. The dynamic nature of additive regulation is indicative of two interrelated factors: first, scientific progress, and second, the better consumer protection (D'Amore, Smaoui and Agriopoulou, 2025).

Despite the existence of internationally recognized standard, as previously described, the authorization, conditions of use, and monitoring of food additives remain regulated through distinct national and regional legislative frameworks. A comparative overview of the principal regulatory approaches governing food additives worldwide is presented in Table 18.2. These regulations define authorization procedures, usage conditions, monitoring requirements, and safety assessments for food additives.

TABLE 18.2

Principal National Regulations on Food Additives

Country/Nation	Regulation	Notes
Australia and New Zealand	FSANZ—Food Standards Code 1.3.1	In Section 2.2.1, there are requirements and definitions of meat and meat products and Section 1.3.1 is dedicated to additives
Brazil	ANVISA—Regulation No. 272, March 14, 2019	*Latest amendment*: 2022
Canada	CFIA—Food and Drug Regulation, Division 16	Under Canadian Minister of Justice
China	NHFPC—GB 2760 National Food Safety Standard for Uses of Food Additives	New additives evaluated by China National Centre for Food Safety Risk Assessment
Europe	Regulation (EC) No. 1333/2008; (EU) No. 1129/2011	Union list of food additives established Requirements for authorization procedures: Regulation EU 234/2011
India	FSSAI—Food Safety and Standards Rules	Under Ministry of Health and Family Welfare
Indonesia	NADFC—Regulation No. 36/2013	Under Ministry of Health, maximum limits for preservatives
Korea	MFDS—Food Additives Code 134-2019	Includes monographs for all additives
Saudi Arabia	SFDA—GSO-FDS-05-2019	Modeled on EU regulation
South Africa	SADOH—Foodstuffs, Cosmetics and Disinfectants Act 54/1972	January 1, 1973 (Gazette 3753 of December 29, 1972) *Last amendment*: Act 39 of 2007
Taiwan	TFDA—Standards for Specification, Scope, Application and Limitation of Food Additives	Under the Ministry of Health and Welfare
United States	USFDA CFR – Title 21	Replaced EAFUS; includes GRAS substances

Abbreviations: ANVISA: Agência Nacional de Vigilância Sanitária; CFIA: Canadian Food Inspection Agency; FSANZ: Food Standards Australia New Zealand; FSSAI: Food Safety and Standards Authority of India; MFDA: Ministry of Food and Drug Safety; NADFC: National Agency for Drug and Food Control; NHFPC: National Health and Family Planning Commission of the People's Republic of China; SADOH: South African Department of Health; SFDA: Saudi Food and Drug Authority; TFDA: Taiwan Food and Drug Administration; USFDA CFR: United States of Food and Drugs Administration Code of Federal Regulations.

In the European Union, the General Food Law (GFL, Reg. EC No. 178/2002) establishes overarching principles of food law and safety procedures. Complementary regulations include Reg. EC No. 852/2004 on food hygiene and Reg. EU No. 231/2012 on purity criteria, as well as Reg. EC No. 1333/2008 on food additives. Authorization of additives in the European Union is overseen by the European Commission (EC) with scientific advice from the EFSA. EFSA mandate includes premarket safety evaluation, periodic reevaluation of all approved additives, and issuing opinions in response to specific regulatory requests. A systematic reevaluation program for additives authorized prior to January 20, 2009, established under Reg. EU No. 257/2010, although scheduled for completion by 2020, is still ongoing (D'Amore, Smaoui and Varzakas, 2025; EFSA, 2025).

In the United States, the Title 21 of CFR, established by the FDA, outlines the procedures for additive approval. Part 170 lists all additives permitted for direct addition to foods, replacing the previous EAFUS (Everything Added to Food in the United States) inventory. Certain additives are classified as GRAS when evidence demonstrates safety under intended conditions. Examples include ascorbic acid and calcium alginate. The criteria for GRAS classification are detailed in 21 CFR Part 170.30 (Alger *et al.*, 2013; Burdock and Carabin, 2004).

The Food Standards Code 1.3.1 (FSANZ) in Australia and New Zealand establishes permitted additives and usage levels. Recent approvals include the new antioxidants rosemary extract (INS 392), which are applied in meat curing and processed meat products.

Brazilian ANVISA regulation No. 272 sets maximum limits and functional uses for additives in meat, with detailed guidance for preservatives, colorants, and antioxidants in processed and cured products.

Similarly, the Canadian Food Inspection Agency (CFIA) regulates additives through Division 16 of the Food and Drug Regulations. Approval relies on toxicological review and exposure assessment, consistent with Codex guidance.

In China, the GB 2760 National Food Safety Standard provides technical requirements for additive use. Approval of new additives requires assessment by the China National Centre for Food Safety Risk Assessment, and specific functional categories are tailored to traditional and processed meats. Finally, in other regions such as India (FSSAI), Indonesia (NADFC), Korea (MFDS), Saudi Arabia (SFDA), Taiwan (TFDA), and South Africa (SAMH), it is mainly adopted as EU-based system as a model or rely on Codex guidance, with regional modifications reflecting dietary patterns, traditional products, and national safety priorities.

This framework is distinguished by high dynamism. It is an example of the recent revision of the regulatory framework for nitrites (E249–250) in the European Union. This revision aims to optimize consumer exposure control while preserving the antimicrobial efficacy critical for meat safety. As of October 9, 2025, the maximum permitted levels of nitrites in general meat products have been reduced to 80 mg/kg (nitrite ion), and to 55 mg/kg for sterilized meat products. Traditional cured meats retain higher permitted levels (≈100–105 mg/kg) due to technological and cultural considerations. Of particular significance is the introduction of maximum residual levels, which are thresholds that must not be exceeded throughout the product shelf life. These levels typically range from 25–50 mg/kg, depending on the meat category (European Commission, 2023)).

18.3 Trends toward Sustainability and Clean Labels

In recent years, the phrase "clean label" has been recognized a significant market trend by food producers (Delgado-Pando *et al.*, 2021) in the official blog of the Institute of Food Technologists (2025): "Clean label means making a product using as few ingredients as possible, and making sure those ingredients are items that consumers recognize and think of as wholesome". As part of the food industry group, the meat industry faces significant challenges and must address changes toward clean label options (Delgado-Pando *et al.*, 2021). The shift toward clean label meat products necessitates the replacement of three major synthetic additives: sodium nitrite, ascorbate (and its stereoisomer erythorbate), and phosphate. These compounds play essential roles in microbial inhibition, pigment formation, antioxidation, and water retention and are increasingly scrutinized by both consumers and regulatory

authorities (Chen and Xia, 2024; Delgado-Pando *et al.*, 2021; Flores and Toldrá, 2021; Molina, Bohrer and Mejia, 2023). Nitrites are usually replaced by nitrate-rich vegetables, along with nitrate-reducing starter cultures or pre-converted nitrite powders, achieving adequate nitric oxide production and stabilizing meat color (Chaari *et al.*, 2023; Chaari *et al.*, 2023; Gassara *et al.*, 2016). Ascorbates are replaced by vitamin C–rich materials and polyphenol-based antioxidants from green tea and rosemary, achieving nitrite reduction and contributing to meat color and oxidative stability. Phosphates are replaced by natural substitutes such as hydrocolloids, dietary fibers, vegetable extracts, isolated proteins, and calcium powders from eggshells or oyster shells, achieving partial success in restoring water-holding capacity, pH regulation, and texture integrity (Kim *et al.*, 2025).

Several additives of natural origin are already authorized under EU legislation. Regulation (EU) No. 231/2012, the "identity card" of approved food additives, defines their sources, production processes, and purity criteria, including detailed derivation pathways for compounds such as annatto (*Bixa Orellana* L.), curcumin (*Curcuma longa* L.), lycopene (from several sorces such as red tomatoes or *Blakeslea trispora*), paprika and quillaia extracts.

However, the authorization of new additives or alternative natural sources intended to replace or reduce synthetic additives remains limited. (European Commission, 2012)). This is largely due to the length and complexity of the scientific evaluation and regulatory approval process. In most jurisdictions, clean label reformulation strategies rely on ingredients that are already approved within existing additive categories or are classified as food ingredients rather than additives, provided that their technological function can be justified without misleading consumers. Among the few plant-derived additives that have gained broad regulatory acceptance, rosemary extract represents a paradigmatic example. Rich in phenolic diterpenes such as carnosic acid and carnosol, rosemary extract has been authorized in several legislative frameworks as a natural antioxidant for use in meat and meat products, with defined purity criteria and maximum use levels (European Food Safety Authority, 2008). In the European Union, it is listed as a food additive (E 392) under Regulation (EC) No. 1333/2008, while similar approvals exist in Australia and New Zealand, the United States, and other national systems, reflecting a convergence toward its recognition as an effective and comparatively safe alternative to synthetic antioxidants.

Consequently, innovation in this area often progresses faster at the research and pilot scale than at the regulatory level, creating a gap between technological feasibility and market authorization (Figure 18.2).

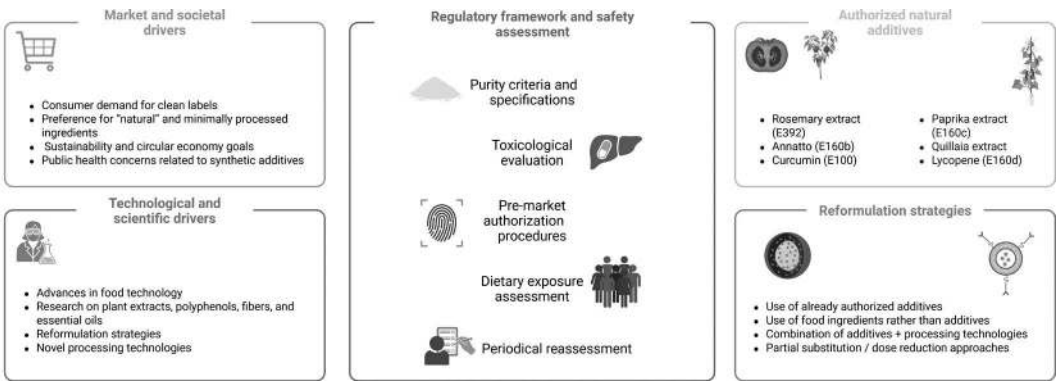

FIGURE 18.2 Interaction among technological innovation, regulatory frameworks, and clean label reformulation strategies of food additives in meat products. Consumer demand for clean labels and sustainability, together with advances in food technology, drives the development of natural alternatives to conventional synthetic additives. However, these innovations are filtered through regulatory frameworks requiring comprehensive safety, exposure, and technological assessments before authorization. Consequently, clean label reformulation in the meat sector largely relies on a limited number of already authorized natural additives or on ingredients classified as foods rather than additives, often combined with technological strategies to achieve functional equivalence.

18.3.1 Natural Alternatives and New Research

The increasing demand for clean label meat products by consumers has shown the importance of effective alternatives (Nottagh *et al*., 2025).

Fruit powders have been used as natural alternatives to sodium nitrite on lipid oxidation in clean label salami (Moraru Manea *et al*., 2025).

Essential oils (EOs) and plant extracts with potential antioxidant and antimicrobial properties maintain the quality attributes of meat products without the possible health risks related to synthetic preservatives (Zhang and Piao, 2023). In a recent review from Molina, Bohrer, and Mejia (2023), natural ingredients and others used to replace inorganic phosphates have been reported. Apple pomace and coffee silver skin, shiitake mushroom powder, chia mucilage (powder and gel), and winter mushroom powder were among them (Molina, Bohrer and Mejia, 2023). In the review article by Zhang *et al*. (2023), the replacement of nitrites in meat processing is studied. Bamboo leaf extracts, rose extracts, radish powder and oregano essential oil, mixed plant extracts (stinging nettle, olive leaves, and green tea) with nisin or nisin nanoparticles, guava epicarp flour extracts, and extracts from cruciferous vegetables were reviewed as alternative additives in order to reduce the addition of nitrite and nitrate to meat products (Zhang *et al*., 2023).

Effective dietary fibers that have been used in meat and meat analogues include seaweed-derived fibers, such as alginate and carrageenan, cereal- and grain-based fibers, fruit and vegetable fibers, and legume-based fibers. These fibers have been shown to improve water-holding capacity and emulsifying properties, enhancing mouthfeel and juiciness (Stanišić *et al*., 2025).

Natural phenolic compounds (NPCs) are secondary plant metabolites with at least one aromatic ring bearing one or more hydroxyl substituents. This category mainly includes phenolic acids, flavonoids, glycosides, terpenoids, and their derivatives, depending on their chemical structures. These compounds are characterized by abundance, variety, and wide distribution since they originate from both edible and non-edible plant materials. Their main sources are vegetables, fruits, medicinal plants, cereals, woody pores, bean sprouts, and roots and are found in various parts of plants, including leaves, bulbs, bark, seeds, roots, bark, and fruits, as well as in processing by-products, such as wastewater and slag (Bai *et al*., 2025). The application of olive polyphenols, specifically oleuropein, hydroxytyrosol, and tyrosol, to meat products led to the improvement of their oxidative stability, enhancing their shelf life and nutritional value (Munekata *et al*., 2020). Olive polyphenols and a mixture of rosemary, thyme, camellia, thyme, lemon balm, and turmeric were used in pork sausages and the results of the study found that they could be used as an alternative to nitrates to improve their oxidative stability (Kaloudi *et al*., 2025).

18.3.2 Reformulation Strategies

Current reformulation strategies in the meat industry include practices related to the reduction or replacement of animal fat with vegetable oils using microencapsulation or the elaboration of 3D gels using organogelants and hydrocolloids. The replacement of umami taste and salt is carried out using extracts from seafood and mushrooms, while the replacement of conventional approved additives is carried out with antioxidant and preservative extracts from plants and herbs. Also, the incorporation of dietary fiber is carried out through fruit peels and vegetable by-products (Ayuso, García-Pérez and Nieto, 2025).

Spices and herbs are ingredients that are widely used in the formulation of meat products, as they contain valuable antioxidant components such as phenolic acids (gallic acid, caffeic acid, and rosmarinic acid), flavonoids (catechin, quercetin, apigenin, kaempferol, naringenin, and hesperetin), phenolic diterpenes (carnosic acid and carnosol), and volatile oils (eugenol, carvacrol, thymol, and menthol) (Ayuso, García-Pérez and Nieto, 2025). Moreover, plant and fruit by-products or noncommercialized parts rich in bioactive compounds have also strong antioxidant properties, and have been used in the formulation of healthier and more environment-friendly meat products. Guarana seeds have been used in pork burgers, and their extract was able to enhance the color, while at the same time lower lipid oxidation values were observed (Pateiro *et al*., 2018). The use of organic hydroxytyrosol from olive leaves was examined in lamb burgers and the extract of this substance provided higher antioxidant and preservative capacity in maintaining nutritional value than the synthetic hydroxytyrosol used as a control (Martínez-Pineda, Vercet and Yagüe-Ruiz, 2021).

18.3.3 Role of Additives in Plant-Based and Meat Preparations

The use of additives plays a very important role in the physical, chemical and technological and sensory properties of both traditional meat products and plant-based meat alternatives. The addition of dietary fiber can modify textural characteristics such as hardness, chewiness, and consistency. Dietary fiber has also demonstrated significant water-binding properties as well as improved fat-binding properties. Significant improvement was shown in the stability of meat emulsions, ensuring a consistent texture. Dietary fiber also helps to stabilize emulsions by binding water and fat, forming a gel-like network that prevents separation. A consequence of the good emulsifying properties is their potential use as phosphate substitutes in emulsion-type sausages, aiming to create "clean label" products (Stanišić *et al.*, 2025). Moreover, many fibers have the ability to inhibit microbial growth, a property extremely useful in the preservation of meat products. Their content of flavonoids such as catechin, epicatechin, procyanidins, and other chemicals with antimicrobial properties may cause alteration of the cytoplasmic membrane and blockage of specific metabolic pathways and enzymes, leading to DNA damage or inhibition of nucleic acid synthesis by bacterial cells (Ayuso, García-Pérez and Nieto, 2025).

In the meat products industry, NPCs are applied to ham, dry fermented sausage, and frankfurter sausages to inhibit microbial growth, delay lipid rancidity, inhibit myoglobin oxidation, and stabilize meat color (Bai *et al.*, 2025). Several fruits and plants have been used as natural colorants in meat products due to both their coloring and antioxidant properties, improving the consumer acceptance (Ayuso, García-Pérez and Nieto, 2025).

18.4 New Technological Challenges

The transition toward more sustainable meat manufacturing poses significant technological challenges that directly impact the selection, performance, and usage of food additives. A decline in salt, nitrites, and synthetic antioxidants, driven by public health policies and the demand for clean labels, may compromise microbial stability, oxidative control, and sensory quality. This necessitates the development of alternative strategies capable of delivering equivalent functionality at lower doses. As previously described, although plant-derived extracts that are rich in polyphenols, organic acids, or antimicrobial peptides show promise in this field, they exhibit high variability in composition (so, difficulty compliance with regulatory requirements), limited stability under thermal processing, and strong interactions with meat proteins and lipids that may reduce bioavailability or technological efficacy (Chaari *et al.*, 2025).

Emerging technologies such as active and intelligent packaging, nano- and micro-encapsulation of additives, and controlled-release systems are being explored to enhance stability, target antimicrobial or antioxidant activity, and reduce overall additive loads. These technologies also permit to reduce the amount of additives added to foods (Ulloa-Saavedra *et al.*, 2022). As an example, nano- and micro-encapsulation are increasingly applied in meat products to stabilize and control the delivery of antioxidants, natural antimicrobials, and even traditional preservatives (nitrite, sulfites). Microencapsulation techniques (e.g., spray drying, coacervation, extrusion) protect labile polyphenols and pigments from heat and oxidation and facilitates incorporation into coatings or processed matrices, while nanosystems (liposomes, nanoemulsions, polymeric nanoparticles) enhance solubility, surface contact with microbes, and controlled release at the meat surface, boosting antimicrobial efficacy of essential oils and lowering off-flavor at effective doses (Domínguez *et al.*, 2021; Yong *et al.*, 2021). Similarly, the encapsulation of preservatives such as nitrite and sulfite can modulate release during processing and storage, potentially maintaining color and antimicrobial function with lower free residual levels and limiting rapid migration, degradation, or interaction with meat constituents that promote potentially hazardous and/or inactive compounds. Verlindo *et al.* (2024) used spray drying to encapsulate four different nitrite-based formulation (adding also porcine collagen, gum arabic, and maltodextrin) in mortadella: the use of microencapsulated materials improved mortadella stability by slowing sodium nitrite depletion, maintaining residual levels above 50 mg/kg up to 50 days of shelf life, whereas the control reached this threshold after 30 days (Verlindo *et al.*, 2024).

Analogously, nonthermal preservation strategies such as high-pressure processing, pulsed electric fields, ozonation, and plasma treatments are being increasingly combined with reduced additive formulations (Chaari *et al*., 2025). Nevertheless, the effects of these strategies on additive degradation, reaction pathways, and long-term safety remain, often, at a research level or insufficiently characterized.

18.5 Future Perspectives and Conclusions

Food additives remain indispensable in meat manufacturing, ensuring product safety, extended shelf life, and appearance/sensory quality in matrices that are inherently complex, heterogeneous, and highly perishable. As demonstrated throughout this chapter, their use is deeply rooted in both historical necessity and scientific advancement, evolving from empirical preservation practices into rigorously regulated technological interventions supported by toxicological risk assessment and exposure evaluation. In meat products, where microbial growth, lipid oxidation, and protein denaturation occur rapidly, additives continue to represent a critical interface between food safety, quality assurance, and industrial feasibility.

At the same time, the role of additives is undergoing a profound transformation. Regulatory frameworks have become increasingly stringent, as exemplified by the recent revision of nitrite limits in the European Union and the introduction of residual level requirements across the shelf life of meat products. These developments reflect a shift from static authorization toward dynamic risk management, where cumulative exposure, more attention to vulnerable populations, and real-life consumption scenarios are explicitly considered. Periodic reevaluation programs and harmonization efforts at international and national levels further underline the need for science-driven governance capable of adapting to new evidence and emerging risks.

In addition, consumer expectations have reshaped the technological framework of meat processing. The growing demand for clean label products and environmentally sustainable production systems challenges the conventional reliance on synthetic additives. While natural alternatives offer promising functional and sustainability benefits, their integration into meat matrices remains technically and regulatory demanding. Variability in composition, reduced stability under processing conditions, and complex interactions with proteins and lipids complicate formulation strategies and necessitate robust validation of efficacy and safety.

Future additive system will increasingly move away from single-function compounds toward integrated technological solutions. Emerging approaches such as nano- and micro-encapsulation, active and intelligent packaging, and controlled-release systems may allow for reduced additive levels while maintaining antimicrobial and antioxidant efficacy. Similarly, the combination of additives with nonthermal preservation technologies may open new avenues for minimizing the usage of synthetic additives without compromising safety. However, these innovations also raise new toxicological and regulatory questions, particularly concerning degradation products, migration phenomena, and long-term exposure, which must be addressed through targeted research and updated risk assessment. Sustainability considerations, for example, the adherence with specific Sustainable Developments Goals (SDGs), further complicate this scenario. The valorization of agri-food by-products as sources of substances or ingredients that exhibit functional activities analogous to those of additives aligns well with circular economy principles but introduces challenges related to standardization, contaminant control, and regulatory classification. Ensuring consistent quality and safety of such materials will be essential to their broader acceptance by regulators, industry, and consumers alike.

Looking ahead, the future of food additives in meat manufacturing will be defined by the ability to reconcile technological innovation with regulatory compliance, safety assurance, and societal trust. Advances in analytical chemistry, exposure modeling, and new integrated methodologies (e.g., in vitro, in silico, and, in general, new approach methodologies—NAMs) are expected to refine risk assessment approaches, enabling more predictive, human-relevant, and matrix-specific assessments. At the same time, interdisciplinary collaboration among food technologists, toxicologists, microbiologists, and regulatory scientists will be crucial to develop ad hoc strategies, monitoring programs and tailored plans, with an eye not only to food safety, but also to sustainability, transparency, and fair risk communication.

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19

Sausage Technology, Safety, Nutrition, and Authenticity

Theodoros Varzakas

19.1 Introduction

Around 340 megatons meat are produced globally annually; the number is expected to rise in the following years (FAO, 2022; OECD and FAO, 2022). Complex production processes and supply networks and an intense consumption of energy and environmental resources characterize the meat supply chain along with excessive land use for livestock farming and feed cultivation. More than 50% of the total emissions of greenhouse gases (GHG) in the agricultural sector arises from meat production (Benning, 2021; Godfray *et al*., 2018; Leip *et al*., 2015; Umweltbundesamt, 2018; Weiss and Leip, 2012) and contributes to nearly one-third of the global agricultural water food print.

More than 20% of the produced meat is wasted (Caldeira *et al*., 2019; Gustavsson, 2011; Karwowska, Łaba and Szczepański, 2021) due to insufficient cooling, temperature interruptions, and inadequate transport and storage conditions, resulting in spoilage and making it a hazard to product quality and safety (Bilska *et al*., 2020; Canali *et al*., 2017; Flanagan, Robertson and Hanson, 2019; Lipinski, 2020; Nychas *et al*., 2008; Parfitt, Barthel and Macnaughton, 2010). Other factors leading to food waste are inadequate control and information exchange (Canali *et al*., 2017; Muriana, 2017). Discarding of meat at the retailer and consumer level when the product's shelf life is expired is another significant factor (Karwowska, Łaba and Szczepański, 2021; Lebersorger and Schneider, 2014; Neff *et al*., 2019).

19.2 Classification of Sausages

Cured or uncured, nonfermented and often smoked meats are the origins of fermented sausages and are also not heat processed. Lactic acid produced by fermentation brings a distinctive tangy flavor. Casing has been used for stuffing of the meat and fermentation then takes place, where sugars are metabolized by bacteria and produce acids and other by-products. Genoa, salami, pepperoni, frizzes, Lebanon bologna, cervelat, thuringer, mortadella are considered as fermented sausages or known as "summer sausages" and are eaten cold.

Different casings exist such as natural ones, which are preserved in salt.

Special grade smooth polyethene or polyamide can be used in sausage casing. Reduction of *Listeria monocytogenes* surface contamination of hot dogs and other cooked sausages is carried out by cellulose casing with natural antimicrobial system.

Coextruded casing with collagen and alginate as the casing materials has also been employed.

Liquid form casing is an alginate-based casing applied in liquid form and encases both ends of the sausage and has a natural taste and texture.

Kielbasas (Polish sausage), Chinese sausage, mettwurst, teawurst, and smoked country-styled pork sausage are uncooked smoked sausages, mostly cured, nonfermented products, with an increase in shelf life by heating due to partial reduction of their moisture content (FAO, 2022, 2026; Modzelewska-Kapituła *et al*., 2022).

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Cured or uncured cooked smoked sausages are heat processed and sometimes smoked. They are usually served cold and may be refrigerated for up to seven days after opening the package and are considered ready to eat products such as Frankfurters, Cotto salami, and Berliner. Cooked sausages are heat-treated to ensure the microbiological safety (Korkeala and Bjorkroth, 1997; Lyng, 2014). In this category, frankfurters, wieners, hot dogs, mortadella, and Bologna-style sausages exist, representing approximately 45% of all sausage products sold in the United States (Knipes, 2014; Steven, Topel and Marple, 2019). Other technologies such as ohmic heating (OH) can be employed versus traditional ones. Heating meat emulsion batters (e.g., Bologna-style sausages) by OH has been investigated by Shirsat *et al.* (2004a, 2004b, 2004c) and Piette *et al.* (2004), who analyzed parameters such as color, texture, water-holding capacity, sensory attributes, and microbiological inactivation of OH-treated versus COV-treated sausages.

A vacuum chopper has been used to prepare the meat emulsion batter by addition of the following ingredients: 50 wt% lean pork meat SIII, 15 wt% pork cheeks, 15 wt% pork back fat, 17.5 wt% crushed ice, 1 wt% NaCl, and 1 wt% sodium nitrite salt. Additional additives are added such as 0.002 wt% sodium diphosphate, 0.0005 wt% sodium ascorbate, and 0.005 wt% seasoning. Premixing and subsequent vacuum-chopping is carried out for 3 minutes. Filling of the resulting meat emulsion batter into polyamide casings follows, as reported by Joeres *et al.* (2024).

Cooked sausages are subjected to final cooking following stuffing without additional smoking, for example, liverswurst, Braunschweiger, and blood sausage.

Cured, uncured, smoked, and nonsmoked meats that do not readily fit into other category could refer to specialty sausages. Seasoning is their characteristic and often their formation into loaves, for example, olive loaf, head cheese, jellied corned beef, scrapple souse, and sausage rolls.

Fresh sausages should be kept refrigerated prior to eating. Heating is carried out by the consumer before serving, for example, fresh pork, breakfast, sausage, Italian sausage, and fresh chorizo (Akpan, 2017).

19.3 Safety

The safety of the sausages has also been the subject of many studies recently and for many years. *L. monocytogenes*, *Staphylococcus aureus*, *Escherichia coli*, *Salmonella* spp., and *Yersinia enterocolitica* are common foodborne pathogens that can be found in sausages. Even less frequent pathogenic agents such as *Mycobacterium avium* subsp. *Paratuberculosis* and *Aeromonas* spp. can be found in sausages along hepatitis E virus.

Chemical hazards constitute mainly biogenic amines, nitrosamines, mycotoxins, and polycyclic aromatic hydrocarbons. These have been found specifically in smoked sausages, as reported by Carballo (2021). Biogenic amines (BA), as derived from the conversion of amino acids, are nitrogenous low-molecular-weight compounds that participate in several biological functions in animals, plants, and microorganisms. Following ingestion in higher amounts, BA may pose a potential risk to consumers' health.

BA affect the nervous and vascular systems due to their toxicity and cause allergic reactions due to their vasoactive and psychoactive activities. They are known for their carcinogenic action since they are precursors of *N*-nitrosamines.

Polycyclic aromatic hydrocarbons are also carcinogenic and they can be avoided by the use of liquid smoke flavoring (LSF), although traditional Portuguese dry-fermented producers use wood smoking as a traditional practice (Gomes-Bispo *et al.*, 2025).

Moreover, control and prevention of both microbiological and chemical hazards can occur by the selection of starter cultures. They usually contain lactic acid bacteria (LAB)—mainly a *Lactobacillus* strain and a coagulase-negative staphylococci (CNS), and can aid color improvement and flavor development, safety, and extension of shelf life in the manufacture of fermented sausages.

A *Lactobacillus* strain has been used in the production of raw-cured sausages, as reported by Jensen and Paddock (1940). Starter cultures can standardize the process and the quality of the end products by controlling fermentation and maturation of raw-cured sausages.

Nutritional and sensory qualities of the product can be improved by the fermentative, proteolytic, and lipolytic activities of microorganisms. Hence, the speed and homogeneity of drying can be affected. Commercial starter cultures in terms of safety should not contain toxic or pathogenic activities and should also be free of biological or chemical pollution. Technological competitiveness and economic viability are also additional factors that should be taken into account.

19.4 Diet and Nutrition Strategies

High salt and fat contents constitute the characteristics of traditional sausages in order to maintain their typical sensory attributes. However, cardiovascular diseases and certain types of cancer are the risk factors associated with their consumption.

Hence, the reduction of NaCl and/or its partial replacement with other salts, mainly KCl, $CaCl_2$, $MgCl_2$, and/or sodium ascorbate, has been one strategy in order to achieve acceptable organoleptic characteristics (Karwowska, Łaba and Szczepański, 2021; Laranjo *et al.*, 2016).

For reduction of the fat content, the replacement with non-lipid substitutes has been another strategy. However, it is well-known that texture, flavor, and mouthfeel of these meat products are highly correlated with fat making this strategy not appropriate. The application of fat substitutes, fat mimetics, and emulsions for the reduction of the fat content leaving the organoleptic characteristics intact has been investigated by the industry (Palavecino Prpich et al., 2021).

Carbohydrates have also been used as fat replacers in cooked meat products, or proteins (Paglarini *et al.*, 2022).

Inulin or other dietary fibers from fruits or cereals as fat replacers have been alternatively employed in raw fermented sausages, affecting texture and sensory properties satisfactorily. Added health benefits such as reduction of the risk of colon cancer as well as elimination of cardiovascular disease and obesity might arise from dietary fibers.

Finally, modification of the fatty acid profile of sausages by substitution of animal fat by olive oil or oleogels has been reported (Carballo, 2021).

19.5 Pork Sausage

Pork sausage as produced in Germany consists of finely chopped sausage meat (87% pork, water, table salt, spices, caraway, dextrose, sugar, glucose syrup, sodium acetate, sodium citrate, and diphosphate) wrapped in pork skin, as reported by Waldhans *et al.* (2025). They developed a dynamic TTI (time–temperature indicator) model based on TTI data from application and validation on a laboratory scale for pilot study preparation.

The spoilage of modified atmosphere (MA)-packed products is dominated by LAB (Koutsoumanis and Taoukis, 2005; O'Sullivan, 2016) and refers to as the specific spoilage organism (SSO) on MA-packed raw pork sausage, showing bacterial counts in the range of 3.5–8.5 log10 CFU/g (Bouju-Albert, Pilet and Guillou, 2018; Cocolin *et al.*, 2004; Raimondi *et al.*, 2018). They also appear on MA-packed poultry sausages (Lerasle *et al.*, 2014).

19.6 Salami Sausages

Spontaneous fermentation is the method used to produce traditional salami sausages but with no guarantee on the quality and safety of the final products. Starter cultures (LAB, staphylococci, and molds) in sausage production is a common practice ensuring quality and safety (extending the shelf life) (Bal-Prylypko *et al.*, 2024; Carballo, 2021; Ezzaky *et al.*, 2024; Laranjo, Elias and Fraqueza, 2017; Montanari *et al.*, 2021). They are used everywhere in the world from Europe to Thailand and China (Bratulic *et al.*, 2021; García-Díez and Saraiva, 2021; Ikonic *et al.*, 2023; Kaban *et al.*, 2022; Mao *et al.*, 2024; Rocchetti *et al.*, 2023; Wang *et al.*, 2018; Yilmaz Topcam, Arslan and Soyer, 2024).

The natural microflora present in the raw materials constitute the main characteristic of Mediterranean technology (Barbieri *et al.*, 2021; Lorenzo *et al.* 2022; Oliveira *et al.*, 2018).

Two groups of starter cultures exist: acidifying bacteria and the family of LAB, such as *Lactobacillus*, *Lactococcus*, and *Pediococcus*, with a primary role of acidification for inhibition of microbiological spoilage and attainment of safety.

Production of various bacteriocins by LAB exerts a high degree of competitiveness against *L. monocytogenes, S. aureus*, and *Bacillus cereus.* Coagulase-negative cocci (CNC), such as *Staphylococcus*, *Kocuria*, and *Micrococcus* strains, belong to the second group (Aguero *et al.*, 2020; Hwang *et al.*, 2023). Reduction of nitrates(V) to nitrates(III), for stabilization of the specific red color of meat products, leads to the formation of nitrosomyoglobin (Amadoro *et al.*, 2022; Leroy, Vermassen and Talon, 2016).

Salami-type sausages in Poland are made according to the recipe provided by Dasiewicz *et al.* (2024). This uses lean pork meat from the shoulder cut (80% w/w) and pork back fat from the thoracic region (20% w/w).

Supporting raw materials are curing salt (2.6% w/w), ascorbic acid (0.2% w/w), dextrose (0.1% w/w), milled black pepper (0.12% w/w), and garlic (0.035% w/w).

Different starter cultures can be employed in different fermentation technologies. In the case of so-called "warm" fermentation, starter cultures (*Lactobacillus sakei* and *Staphylococcus carnosus* with a total cell count $\geq 4.5 \times 10^{10}$ CFU/g) are used. In "cold" fermentation, *L. sakei*, *Pediococcus acidilactici*, and *S. carnosus* with a total cell count of $\geq 3.8 \times 10^{10}$ CFU/g have been employed.

A homogeneous meat batter is obtained by grinding of lean pork meat and pork back fat through a 3-mm diameter cutting plate and chopping in a cutter with other ingredients for 3 minutes. Addition of starter cultures took place at a concentration of 25 g/100 kg. Natural porcine casings can be used to stuff the batter with a diameter of 45 mm. Fermentation of prepared semi-finished products is carried out for five days with medium air circulation. "Warm" fermentation is conducted at an initial temperature of 24–26 °C, followed by 20–21 °C, with a relative humidity of 85–90% for the first three days, with maintenance of temperature at 16–18 °C and a relative humidity of about 85% for the fourth and fifth day. "Cold" fermentation, with temperature around 12–15 °C and a relative humidity of 85–90% lasts, for three days. The temperature is set at approximately 15 °C, with a relative humidity of around 85% during the fourth and fifth day.

Ripening/maturation of the fermented sausages lasts for 14 days with an air humidity of 70–80%. Smoking takes place during the first day (with oak chips) for 30 minutes at 25 °C, and the fourth day, for 3 hours at 25 °C. The temperature in the chamber was gradually lowered to approximately 16 °C during ripening. Finally, drying of the salami-type sausages takes place at 15 °C with a relative air humidity of approximately 75% during the last stage.

19.7 Spanish *Salchichon*

The 100% Iberian acorn-fed *salchichon*, sliced and vacuum-packed, as supplied by the company Ibericos Rivas (Spain), has the following formulation: Iberian pork meat, salt, sugar, natural flavoring, garlic and spices (black pepper and nutmeg), stuffed into natural pork casing, and free of additives, as reported by Sanchez-Gutierrez *et al.* (2024).

They evaluated the stability of sliced 100% Iberian Spanish *salchichon* without added additives. It was wrapped in a biodegradable nanocellulose films incorporating olive leaf extract and then vacuum-packaged and stored at 5 °C and 25 °C for 90 days.

19.8 "Salsiccia Sarda" or Sardinian Fermented Sausage (SFS)

It is a traditional ready-to-eat (RTE) pork meat product typical of Sardinia (Italy) and belongs to traditional food products (Italian Republic, 2020).

SFS production seems to vary from small and artisanal establishments to larger plants with industrial processing, showing high variability in the manufacturing process (Siddi *et al.,* 2022). This fermented

sausage is manufactured as a semidry sausage made of pork meat and fat following fermentation, drying, and ripening. LAB and nitrate-reducing coagulase-negative staphylococci comprise SFS typical microflora, and could be naturally found in the meat or added by starter cultures (Greco *et al.,* 2005).

Proper acidification and drying are essential in the manufacturing process (Piras *et al*., 2019).

Presence of *L. monocytogenes* could occur by inadequate fermentation or inappropriate dry-curing duration and cross-contamination (Mureddu *et al.,* 2014), and this could be a public health risk (EFSA, 2018). Vacuum packaging is followed for SFS, with a shelf life of 120 days (Siddi *et al*., 2023), or could be sold without any packaging, and a shelf life of not higher than 20 days (Siddi *et al*., 2024).

Positive environmental samples accounted for 45.8% of *Listeria* spp. and 16.7% of *L. monocytogenes*. Correct drying and ripening, applied for at least 20 days, constitute some of the critical hurdles required to guarantee the safety of fermented sausages. Environmental contamination could be reduced by application of proper hygiene and cleaning procedures (Siddi *et al*., 2024).

19.9 Secondary Collagen-Containing Raw Materials for Processing of Sausages

Gizatova *et al.* (2021) employed secondary meat raw materials of the meat processing industry: horse meat, flank, and other beef muscle tissue of the second grade, which, after fermentation by *Lactobacillus bulgaricus*, *Bifidobacterium siccum*, and *S. carnosus*, were used instead of the main meat raw materials in the production of sausages.

It was made possible to use secondary collagen-containing raw materials for processing. Quality increased and the cost of production was reduced.

19.10 Dry and Semidry Sausages

Microbial fermentation needs to be applied for dry and semidry sausages and this makes them distinct compared with other types of sausage. This fermentation reduces the pH of the product to 5.0 to 5.3 for dry sausage and 4.6 to 5.2 in the case of semi-dry sausage. A relatively low water activity (a_w) of approximately 0.85 in the case of dry sausage and 0.85–0.91 in the case of semidry sausage is attained by drying.

Spoilage of raw materials seems to be a problem and most specifically "greening" is related to spoilage. The result of a white sausage appearing to be mostly fat, development of a mushy texture due to proteolysis, and an oiling out of the fat due to lipolysis arise from a bleaching effect on the lean. Peroxides produced by bacteria growing in the meat usually prior to processing cause this phenomenon. These microorganisms are fairly heat resistant but heat treatment could eliminate them. Heating needs to be carried out to kill *E. coli* 0157:H7, *Salmonella*, and *L. monocytogenes.*

Starter cultures ensure that pH drop will inhibit the growth of undesirable organisms. Low-temperature cultures, with best growth at 21–27 °C, may give the most preferred flavors, but with longer fermentation times.

Chemical acidulants, such as GDL (glucono delta lactone) or encapsulated lactic acid, could be employed. Normally acidulants tend to have a somewhat harsh flavor. If GDL is being used, stuffing of the product should be carried out immediately after addition followed by immediate heat processing. Heating of the product to a temperature that will release the acid is significant when acid encapsulation is applied (Rust, 2025).

Regarding stuffing, proper casing is used for the product. Depending on the type of product, natural, collagen, or cellulose casings could be used. Stuffing to the proper diameter should be carried out avoiding double-walled sewed bungs with large-diameter natural casings, which develop rancidity of the adhering fat.

Optimum conditions of temperature, humidity, and time should be provided for lactic acid–producing bacteria by fermentation, in order to produce lactic acid and other metabolic products and also overgrow any food spoilage or pathogenic microorganisms. The conditions need to be favorable to the starter culture.

For semidry sausage, the fermentation temperatures would range between 27 °C and 43 °C with a 95% relative humidity, appropriate conditions for a starter culture to attain fermentation in less than 24 hours. For dry sausage, fermentation is conducted at a lower temperature between 24 °C and 27°C, with a longer period of time of 48 hours to achieve appropriate fermentation (Rust, 2025).

Drying of dry sausage is very critical in the sense that rate of moisture removal carried out from the surface of the sausage should be the same as that transferred from the interior following moisture balance and air circulation. Excess drying rates will result in case hardening, hence leading to suspension of the moisture loss from the surface. The net result deep creases and often voids in the interior of the product as it begins to shrink.

The drying room temperature are normally maintained in the range of (15–18 °C). Placement of the sausages under dry conditions with a water activity of 0.90 leads to an 85% room humidity. As the product loses moisture and there is reduction in water activity, the relative humidity of the drying room can be decreased accordingly.

An example of sausage technology is described in this flow diagram (Figure 19.1).

The flow diagram of boiled sausage is given in Figure 19.2.

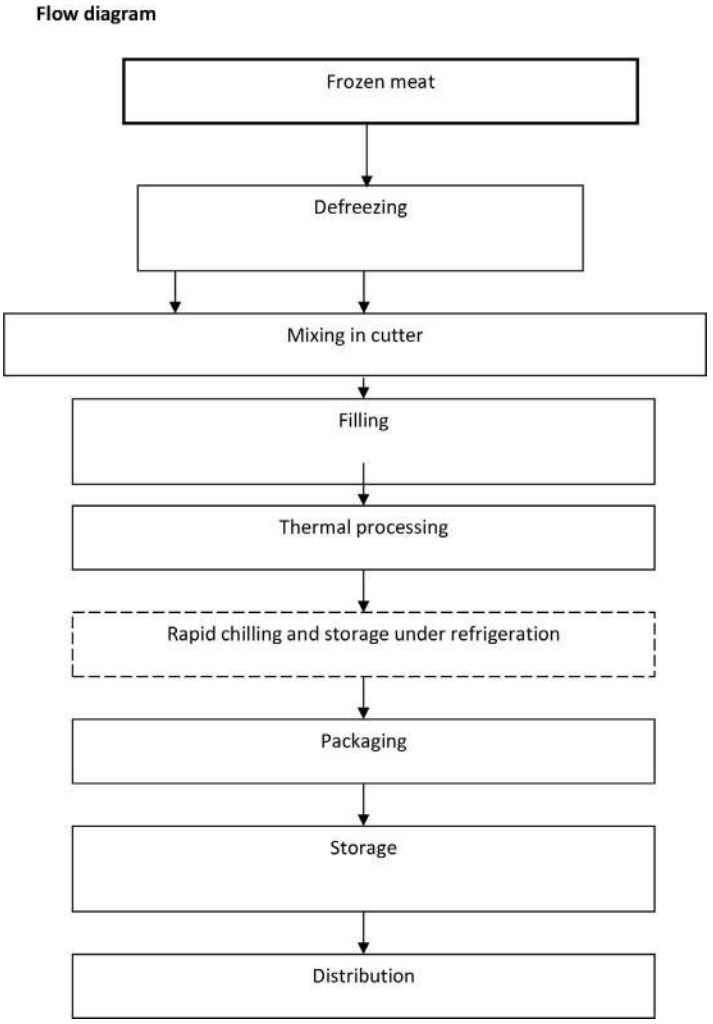

FIGURE 19.1 Flow diagram of sausage technology. (From Arvanitoyannis, Varzakas and Tserkezou, 2009.)

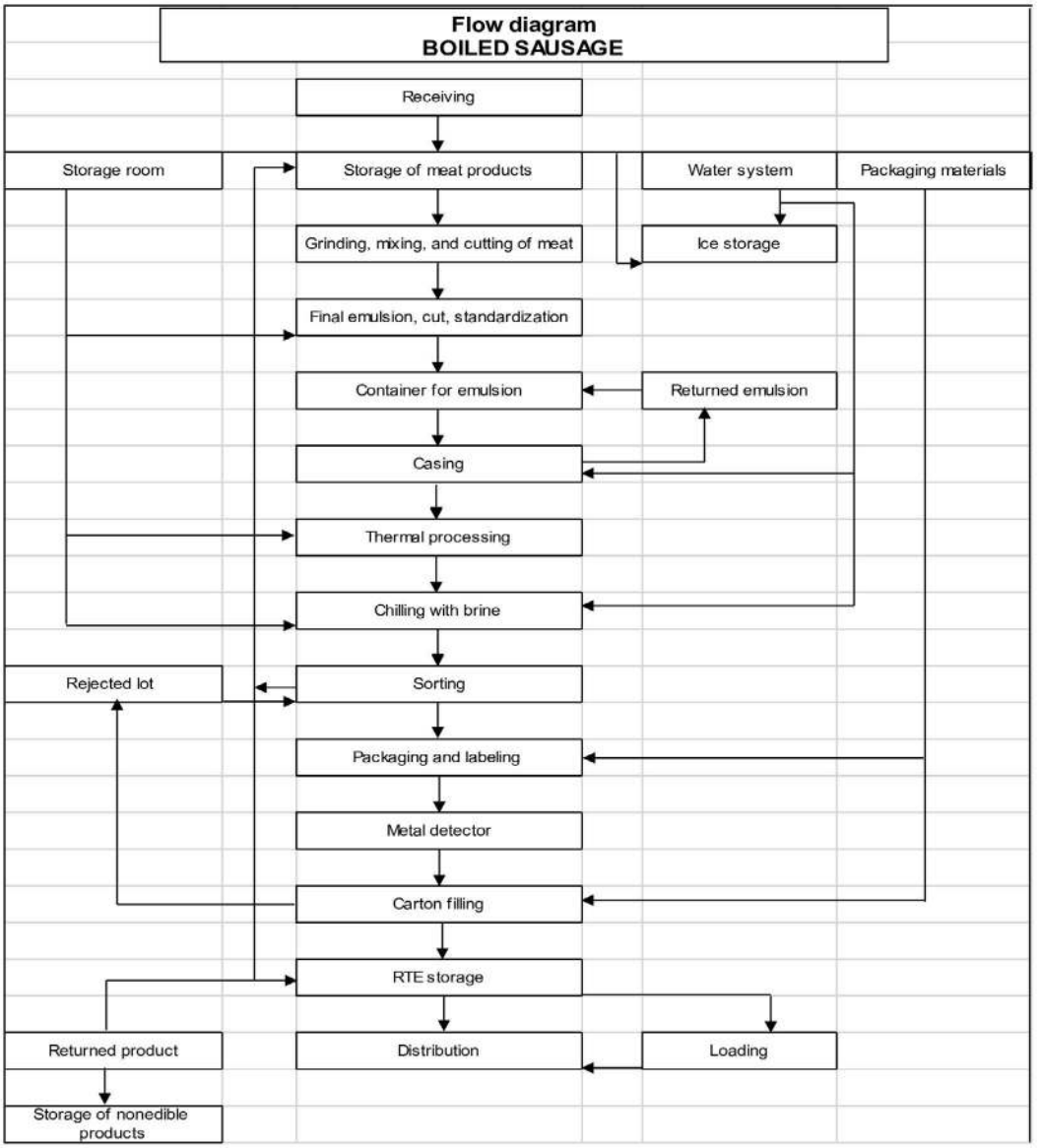

FIGURE 19.2 Flow diagram of boiled sausage.

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20

Innovations in Salami Fermentation and Quality Control

Ilyes Dammak

20.1 Introduction

20.1.1 Historical Context and Industrial Significance

Although the practice of fermenting and drying meat dates back thousands of years, since before written history, it remains one of the most advanced and enduring techniques of preserving meat ever developed by humans. In fact, the earliest evidence of the use of fermentation to preserve meats comes from Mediterranean societies dating to well before the recorded history of those regions. In terms of basic biochemical principles, our understanding of how to utilize microbial metabolism and physicochemical changes to convert fresh meat into stable, long-shelf-life products has changed little. What has changed substantially over the intervening time span is the degree to which we understand the science behind this preservation process and the tools we employ to manage and improve these processes (Toldrá, 2017; Lücke, 2000).

As of today, the modern fermented meat industry generates a substantial portion of the world's economy. Fermented sausage alone is estimated to be an $85 billion per year global market in 2023, with continued growth expected throughout the decade (Global Market Insights, 2024). The market for meat starter cultures is also growing. In 2023, the global market for meat starter cultures is expected to be worth $70.3 million, with a CAGR of 4.8% through 2032 (Global Market Insights, 2024). Both markets are driven by consumers' desire for convenient, high-protein food products and for traditional and artisanal foods that reflect their region of origin and provide a connection to their cultural heritage.

Europe currently accounts for the majority of the world's fermented sausage production, with Italy, Spain, France, and Germany accounting for the largest share of that production. Each of these countries has a rich tradition of specialty fermented sausage products that have been produced for generations in specific geographic areas. Many of these products are protected by EU geographical designation laws, such as PDO and PGI designations. These laws give them a better position in the market and help to preserve the cultural and economic heritage of each country. Examples of such products include several types of salami from Italy (Salame Milano, Salame Napoli, and Ventricina), Spanish chorizo and fuet, French saucisson sec, and German Landjäger.

The development of starter culture technology is one of the greatest advancements in fermented meat processing over the last 50 years. Until the introduction of commercially available starter cultures in the late 1950s and early 1960s, fermented products relied entirely upon the natural microbiota found in raw materials and in the environment of the processing facility. While the natural flora provided each product with its unique characteristics associated with a particular geographical area, it also contributed to considerable variability in final products and occasional failures related to food safety. Starter cultures enabled manufacturers to transform an art form into a controlled industrial process capable of consistently producing safe and uniform products from batch to batch. The market for meat starter cultures is valued at $70.3 million in 2023 with a projected CAGR of 4.8% through 2032, reflecting the industry's ongoing commitment to utilizing culture-based process management (Global Market Insights, 2024).

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Although the fermented sausage industry has experienced significant success recently, it faces several major challenges that require creative solutions. When a microbiological safety incident does occur, although relatively rare considering the number of products being produced, it can cause severe damage to a company's reputation and result in financial losses. Several outbreaks of *Salmonella* and *Escherichia coli* O157:H7 linked to the consumption of fermented sausage products have resulted in the imposition of more stringent validation procedures and additional process controls by regulatory agencies in multiple jurisdictions. Additionally, the IARC classification of processed meat as a Group 1 carcinogen (IARC Working Group on the Evaluation of Carcinogenic Risks to Humans, 2015) has increased public scrutiny regarding the ingredients commonly used in fermented sausage production, specifically nitrite and nitrate curing agents.

20.1.2 Scope and Objectives of This Chapter

This chapter comprehensively examines recent innovations in salami fermentation technology and quality control, focusing on advancements with current or near-term industrial applicability. It encompasses the entire production chain, including raw material selection, fermentation, ripening, and final product evaluation, synthesizing insights from microbiology, biochemistry, food engineering, and quality management. It synthesizes insights from peer-reviewed research, industry reports, and regulatory guidance to offer a cohesive overview of the latest knowledge and future trends.

This chapter focuses on three converging streams of innovation. The progression of starter culture technology from basic acidification agents to multifunctional systems with bioprotective activity, biogenic amine control, and potential probiotic benefits signifies a significant transformation in fermentation conceptualization and management. Second, the utilization of omics technologies, particularly metabolomics, to comprehensively assess quality has introduced novel insights into understanding fermentation dynamics and predicting product outcomes. Third, advances in safety control strategies addressing both microbiological hazards and chemical risks have enhanced the scientific foundation for process validation and risk management.

Section 20.2 shows how to make salami, including a full process flow diagram that uses hazard analysis and critical control points (HACCP) principles. Section 20.3 examines innovations in starter culture technology. Section 20.4 addresses metabolomic profiling applications for quality assessment. Section 20.5 reviews advances in safety control strategies. Section 20.6 identifies persistent challenges and future research directions. Section 20.7 synthesizes key conclusions and implications for industry practice.

20.1.3 Innovation Drivers and Emerging Paradigms

Numerous technological, regulatory, and consumer trends are driving salami fermentation. In terms of regulatory influences, mandatory HACCP implementation has been the primary driver of regulatory changes. In addition to basic HACCP compliance, many countries are now requiring manufacturers to demonstrate lethality through nonthermal processing of their meat products. As such, manufacturers will need to characterize their processes and provide documented evidence of the effectiveness of their pathogen control measures (USDA-FSIS, 2017).

As consumers' expectations move beyond food safety to include functional benefits, clean label formulations, and sustainability attributes, manufacturers are finding it necessary to expand their offerings to meet this demand. Companies are using functional ingredients to set themselves apart in a crowded market. For example, they are adding probiotics to fermented meats. However, there are several technical challenges associated with the use of probiotics in fermented meats due to the low water activity levels that are present in most ripened sausages. Research has shown that several different probiotic strains (including *Lacticaseibacillus rhamnosus*, *Lactiplantibacillus plantarum*, and *Bifidobacterium lactis*) can be successfully used in fermented sausage without negatively impacting consumer acceptance (Mani-López *et al.*, 2024; Tukel, 2024). There are also several other factors, aside from taste, that affect whether or not consumers will accept new functional features, including price, perceived healthfulness, and cultural context (Section 20.3.9).

Advances in analytical instrumentation and computational methodologies have greatly increased the ability of manufacturers to better understand and control fermentation. High-throughput DNA sequencing technologies have enabled manufacturers to identify microorganisms at previously unattainable resolutions. Metabolomics based on mass spectrometry allows manufacturers to perform comprehensive biochemical phenotyping and measure the presence of hundreds of different biochemicals at once. Using machine learning techniques, manufacturers can analyze large amounts of complex data and develop predictive models that can identify relationships between variables that may not be apparent when analyzing the data statistically (Tao *et al*., 2020).

The combination of the above-mentioned technologies provides the foundational elements needed to establish "precision fermentation" as a viable approach to manufacturing. Precision fermentation is the use of data to improve and predict the results of fermentation processes that take into account differences in raw materials and the natural differences between microorganisms. Research has already identified the potential for machine learning models to predict the quality of fermented products during the early stages of fermentation (Woldemariam, 2024).

20.2 Salami Manufacturing Methodology

20.2.1 Raw Material Selection and Preparation

Regardless of how well the final processed product is made, the quality of the unprocessed ingredients selected at the start will always be the limiting factor in determining the quality of the final product. Therefore, there is no room for error when selecting the raw materials for traditional salami production. The four primary components of salami include lean meat (pork, beef, or a combination of two or more); backfat or adipose tissue; salt; and a combination of curing agents, sugars, and spices. These four components provide each individual ingredient's unique functional properties that work together to determine the final product's microbiological safety, functional characteristics, and sensory quality (Feiner, 2016; Toldrá, 2017).

In addition to providing the visual appearance of the meat, the biochemical characteristics of the lean meat also affect the fermentation process of the meat. One of the most important factors in the selection of lean meat is postmortem pH. Meat that falls within the pH range of 5.5–5.8 will ferment best since it has an ideal pH for acid formation, while meat with a pH higher than 6.0 will resist pH drops and create an environment where pathogens can survive. The level of contamination present in the lean meat will also have a significant impact on the overall safety of the final product. The sanitation of the carcass during slaughter and cutting will establish the initial level of contamination that the processor must then manage.

The processor should place equal importance on the selection of fat. Pork backfat has historically been the preferred fat because of its firmness at processing temperatures and lower content of polyunsaturated fats, which are prone to oxidative rancidification during longer periods of ripening. It is essential to maintain temperature control throughout the preparation of both the meat and the fat to preserve their structure and to protect them from becoming too soft. Typical procedure calls for the tempering of the meat and the fat to temperatures ranging from –2 °C to –4 °C prior to grinding. The particle size of the ground meat and fat will ultimately determine the texture of the final product, the rate at which the product loses moisture (water activity) during drying, and the extent to which microorganisms can access the nutrients present in the product. Particle size is dependent upon the diameter of the grinding plates used (typically 3–8 mm for coarsely ground salamis).

20.2.2 Formulation and Ingredient Functionality

Standard salami formulations typically comprise 65–80% lean meat, 20–35% fat, 2.5–3.0% sodium chloride, 100–200 mg/kg sodium nitrite (or equivalent nitrate quantities for slow-fermented varieties), and 0.3–0.5% glucose or dextrose as fermentable carbohydrate substrate (Cocconcelli and Fontana, 2015). Sodium chloride serves multiple essential functions: salt extracts myofibrillar proteins that bind

meat particles together, reduces water activity creating conditions unfavorable for pathogen growth, and influences enzyme activity during ripening.

Nitrite, typically incorporated as sodium nitrite at 100–150 mg/kg in contemporary formulations, performs critical functions that no single alternative has successfully replicated. Antimicrobial activity against *Clostridium botulinum* constitutes the most important safety function. Color stabilization through nitrosomyoglobin formation produces the characteristic pink-red hue of cured meats. Antioxidant activity inhibits lipid oxidation, preventing development of rancid off-flavors (De Mey *et al*., 2014; Honikel, 2008).

Starter cultures represent perhaps the most significant technological advancement in modern salami production. Commercial starter formulations typically combine lactic acid bacteria (LAB) to drive acidification with coagulase-negative staphylococci (CNS) to enhance color development and flavor formation (Leroy, Verluyten and De Vuyst, 2006). LAB species commonly employed include *Lp. plantarum*, *Lactobacillus sakei*, *Lacticaseibacillus casei*, *Pediococcus acidilactici*, and *Pediococcus pentosaceus*. CNS species, primarily *Staphylococcus xylosus* and *Staphylococcus carnosus*, contribute nitrate reductase activity for color formation along with lipase and protease activities that generate flavor precursors (Dasiewicz *et al*., 2024).

The functional properties of contemporary starter cultures extend well beyond simple acidification. Mani-López *et al*. (2024) demonstrated that *Lp. plantarum* (as a starter) and *Lactobacillus acidophilus* (as a probiotic) maintained viability throughout the fermentation and ripening of salami-type products while achieving pH values of 5.1–5.2 after 15 days of fermentation. These results align with findings by Stangierski *et al*. (2023), who observed similar pH profiles in commercial salami production. The multifunctionality of modern starters reflects decades of strain selection and characterization, moving from organisms selected solely for acid production toward systems delivering bioprotective activity, flavor enhancement, and potentially probiotic health benefits.

Predictable interactions occur in LAB and CNS populations throughout fermentation, which will have a direct impact on product formulation. LAB quickly outnumbers CNS during fermentation's beginning stages due to an increase in populations of 10^8–10^9 CFU/g within 24–48 hours given an ideal environment. An abundance of LABs quickly consumes all available fermentable carbohydrates and results in acidic conditions that create a negative effect on CNS populations as the pH decreases. Before the pH level drops below the ideal level for CNS activity, CNS populations usually reach a maximum of 10^6–10^7 CFU/g. The timing of changes in LAB and CNS populations has a big effect on flavor development. This is because the enzymatic activities of CNS create flavors that are directly linked to products made from fermentation that happens in the early stages, before pH-related inhibitions take effect. This optimization can enhance both safety (through LAB-related enzymes) and quality (by improving flavor development via CNS enzymes).

20.2.3 Mixing, Stuffing, and Casing Selection

Following the preparation of each individual component, the mixing process unites all ingredients to create a uniform batter. This mixing process also extracts the proteins that will be used to hold the final product together in future processes.

The mixing process takes place under either vacuum or at very low oxygen levels, with the goal of minimizing the amount of air incorporated into the batter. A typical range for mixing times is between 3 and 8 minutes; this allows sufficient time for uniform ingredient distribution but does not allow excessive mixing, which can generate too much heat and damage the integrity of the fats.

The batter is stuffed into casings that define the final product's shape and drying rate. Natural casings are often still used today as casings for high-end products, as they have properties such as permeability that permit optimal moisture movement and the ability to develop the normal surface mold flora.

A second aspect of casings is the diameter of the casing itself. The diameter of the casing determines the drying rate of the product. For example, products made in smaller diameters (30–40 mm) require 2–4 weeks to achieve the desired water activity level, whereas larger diameter products (80–120 mm) can take 60–120 days to dry completely (Zanardi *et al*., 2002).

20.2.4 Fermentation Phase

Fermentation is the most important step in the production process, where microbial processes convert uncooked, raw batter into a preserved food item with a low pH level. Rapid fermentation techniques are used in US manufacturing facilities employing high-temperature (35–40 °C) fermentation periods ranging from 12 hours to 24 hours; these methods achieve desired pH levels of less than 5. On the other hand, slower fermentation processes employed in European-style sausage production involve lower temperatures (18–24 °C) for longer fermentation periods (48–96 hours), allowing for a gradual pH drop, which promotes an increase in flavor complexity development (Aquilanti *et al.*, 2007).

In addition to differences in manufacturing time, the use of either rapid or slow fermentation processes also represents trade-offs regarding the inherent quality of the final product. In their research paper, Dasiewicz *et al.* (2024) investigated the effects of cold fermentation versus warm fermentation on the microbiological, chemical, and sensorial properties of sausages during 63 days of storage after the ripening process. The results of the study indicated that fermentation technology affected the types of microorganisms produced as well as the quality characteristics of the final products. While the study demonstrated that cold fermentation enhanced flavor complexity, it also resulted in extended processing times.

Modulation of temperature during fermentation has become an attractive option for many producers who seek to find a balance between ensuring the safety of the products they produce and meeting the desired quality standards. Initial temperatures of 24–28 °C promote the growth of the starter culture and the initial phases of acidification that provide the environment required for the control of pathogens. Reducing the temperature of the fermentation process to 18–20 °C creates an environment that allows for the continuation of fermentation while continuing to allow for the growth of CNS cultures and the synthesis of flavor precursors. Utilizing the stepped temperature fermentation method provides for safe and quality products similar to those obtained using rapid high-temperature fermentation processes while retaining some of the quality characteristics of the slow fermentation processes.

20.2.5 Drying and Ripening

Post-drying of fermented foods removes water from them, progressively decreasing the water activity of those foods until they are in a state where no microorganisms can grow (microbiologically stable) and the desired texture is created. Generally, target water activities for dried products are between 0.85 and 0.91, and they will generally be reached once the product has lost between 30% and 40% of its original weight. Typical standard drying conditions consist of 12–15 °C temperature and 70–80% relative humidity, and these conditions create a "driving force" for water removal from the food product without excessively drying out the surfaces of the product (Toldrá and Flores, 1998).

During the post-drying ripening phase of salami production, many biochemical changes occur due to the actions of both endogenous and microbial enzymes that degrade lipids and proteins. The enzymes break down proteins into free amino acids and peptides, which add to the salami's flavor. For example, the buildup of glutamic acid makes the salami taste umami. The enzymatic action on lipids results in the formation of free fatty acids from triglycerides; the oxidation of these free fatty acids produces aldehydes, ketones, and other volatile compounds that contribute to the aromatic complexity of the salami. Figure 20.1 provides an overview of all processes involved in the manufacture of salami, including operational steps as well as hazard analysis and critical control point (HACCP) identification.

20.2.6 Hazard Analysis and Critical Control Points

EU Regulation 852/2004, USDA-FSIS guidelines, and similar international regulations mandate HACCP implementation in salami production. However, due to the fermented meat matrix, there are unique obstacles when attempting to ensure that a product will be safe, since it receives no final heat treatment. Therefore, several barriers need to be used together to provide assurance that a product will be safe to consume. These barriers include lowering the pH of the meat, reducing the water activity, increasing the

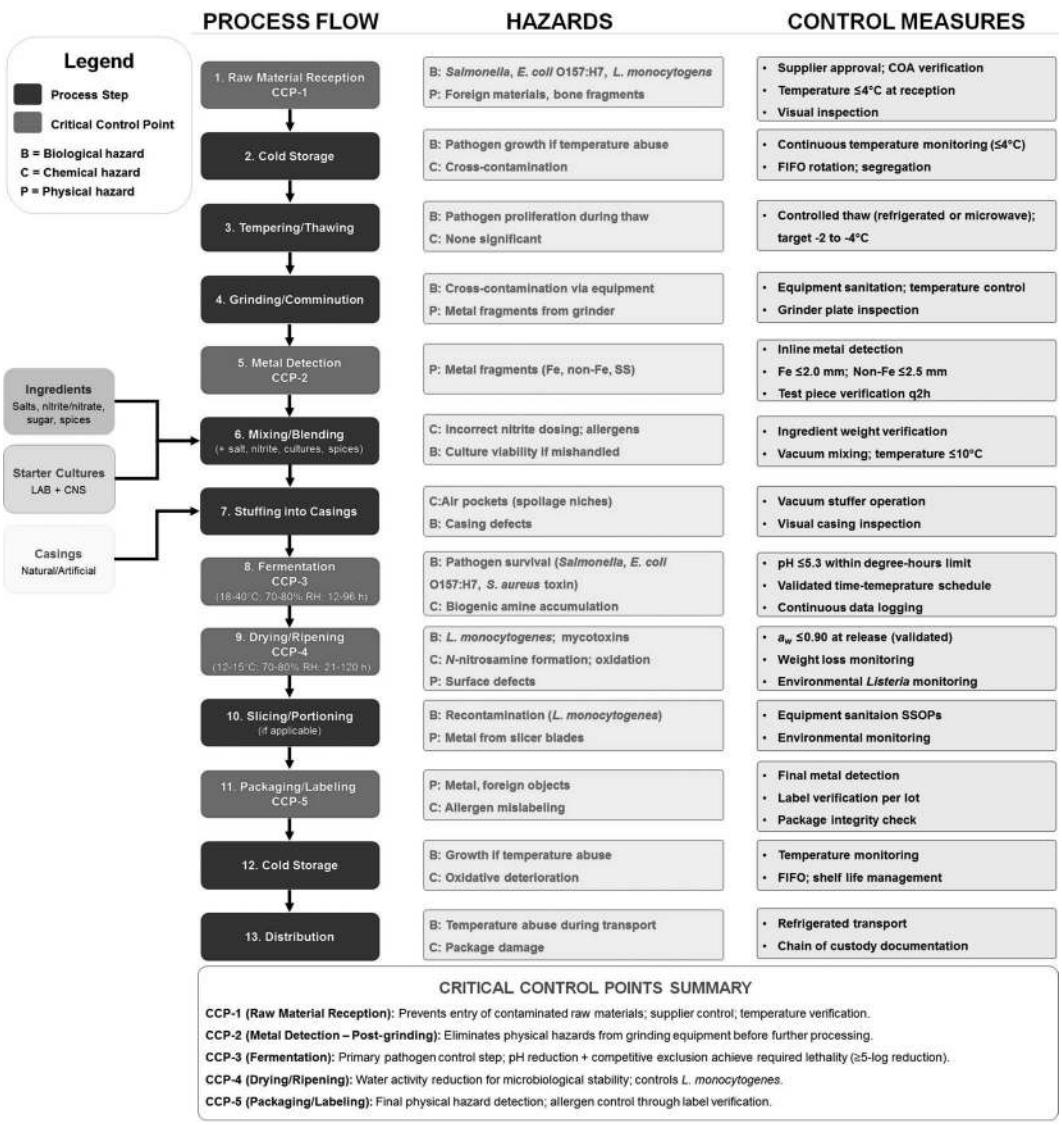

FIGURE 20.1 Process flow diagram for salami manufacturing with integrated hazard analysis and critical control points (CCPs). Biological (B), chemical (C), and physical (P) hazards are identified at each production stage. *Abbreviations:* CCP: critical control point; CQA: certificate of quality assurance; Fe: iron; FIFO: first in, first out; SS: stainless steel.

antimicrobial action of both sodium chloride and sodium nitrite, and using large enough populations of the starter cultures to competitively exclude pathogenic bacteria (ICMSF, 2005; Leistner, 2000).

The primary biological hazards in salamis include *Salmonella* spp., *Listeria monocytogenes*, *E. coli* O157:H7, all Shiga toxin-producing *E. coli* (STEC), *Staphylococcus aureus*, and *C. botulinum*. USDA-FSIS, in its Appendix A, lists combinations of pH, water activity, and time that demonstrate at least a five-log reduction in *Salmonella* and STEC. Any process that does not meet these criteria can use an alternative scientific approach to justify the claim that the product is safe to eat (USDA-FSIS, 2017). EFSA has also published scientific opinions regarding *S. aureus* risk in ready-to-eat foods, with the most recent opinion offering additional direction for control measures (EFSA Panel on Biological Hazards, 2020).

Table 20.1 outlines the typical critical control points (CCPs) in salami production, including the associated hazards, critical limits, monitoring procedures, and corrective actions.

TABLE 20.1

Critical Control Points (CCPs) in Salami Manufacturing with Hazards, Critical Limits, Monitoring Procedures, and Corrective Actions

CCP	Process Step	Hazards	Critical Limits	Monitoring Procedure	Corrective Action
1	Raw material reception	**B:** *Salmonella* spp., *E. coli* O157:H7, *L. monocytogenes* on incoming meat **P:** Foreign materials, bone fragments	• Meat temperature ≤4 °C at receipt • Supplier COA for each lot • No visible contamination, off-odors, or package damage	• Temperature measurement (calibrated probe) for each delivery • Visual inspection of all incoming lots • COA review and documentation • Frequency: Every delivery	• Reject nonconforming lots • Notify supplier and document deviation • Increase inspection frequency for repeat offenders • Segregate suspect materials pending evaluation
2	Metal detection (post-grinding)	**P:** Metal fragments from grinding equipment (blades, plates, wear particles)	*Detection sensitivity*: • Ferrous (Fe): ≤2.0 mm • Nonferrous (non-Fe): ≤2.5 mm • Stainless steel (SS): ≤3.0 mm	• Continuous inline metal detection • Test piece verification using certified standards every 2 hours and at start/end of production • Automatic reject mechanism functional check • Daily sensitivity calibration	• Hold and segregate all product since last conforming test • Reinspect held product through functioning detector • Recalibrate or repair detector • Investigate source of contamination • Document and trend analysis
3	Fermentation	**B:** Pathogen survival/growth (*Salmonella* spp., *E. coli* O157:H7, *S. aureus* enterotoxin production) **C:** Biogenic amine accumulation (histamine, tyramine)	• pH ≤5.3 achieved within validated degree-hours • Temperature per validated schedule (e.g., ≤24 °C for slow fermentation; ≤40 °C for rapid) • Time–temperature combination per USDA-FSIS Appendix A/B equivalency or validated alternative	• pH measurement at defined intervals (minimum every 12 hours during fermentation) • Continuous chamber temperature recording (data logger) • Batch records with time stamps • Starter culture viability verification (periodic)	• Extend fermentation time if pH target not met • Apply validated thermal kill step (e.g., 54.4 °C/4 min) if pH/time targets unachievable • Hold batch for QA evaluation • Destroy product if safety parameters cannot be achieved • Root cause investigation
4	Drying/ ripening	**B:** *L. monocytogenes* survival/growth; mycotoxin production from uncontrolled mold **C:** *N*-Nitrosamine (NA) formation; lipid oxidation **P:** Surface defects (casing failure)	• a_w ≤0.90 at release (or per validated HACCP plan) • Temperature: 12–15 °C • RH: 70–80% • Weight loss per product specification (typically 30–40%)	• a_w measurement at product release (representative samples) • Weight loss tracking throughout ripening • Continuous environmental monitoring (temperature/RH) • Visual inspection for surface defects • Environmental *Listeria* monitoring program	• Extend drying period if a_w target not achieved • Hold for further evaluation • Divert to cooked product line if safety limits unachievable • Destroy product if parameters cannot be met • Sanitation review if environmental positives detected

(Continued)

TABLE 20.1 ***(Continued)***

Critical Control Points (CCPs) in Salami Manufacturing with Hazards, Critical Limits, Monitoring Procedures, and Corrective Actions

CCP	Process Step	Hazards	Critical Limits	Monitoring Procedure	Corrective Action
5	Final inspection and packaging	**P:** Metal fragments, foreign objects introduced post-fermentation **C:** Allergen cross-contact; incorrect allergen labeling	• Metal detection sensitivity as per CCP-2 • Correct allergen declaration verified against formulation • Label legibility and accuracy confirmed • Package seal integrity	• 100% product through metal detector • Test piece verification per CCP-2 schedule • Label verification check per production lot (first piece, periodic, last piece) • Visual/automated seal inspection	• Reject units triggering metal detector • Recalibrate detector; hold and reinspect product since last conforming test • Relabel or repackage if labeling error • Quarantine and evaluate for allergen cross-contact • Customer notification if distributed product affected

Abbreviations: B, biological hazard; C, chemical hazard, P, physical hazard; a_w, water activity; COA, certificate of analysis; Fe, ferrous metal; NA, *N*-nitrosamines; non-Fe, nonferrous metal; RH, relative humidity; SS, stainless steel.

Source: Adapted from USDA-FSIS (2017) and Codex Alimentarius Commission (2003) guidelines for fermented meat products.

20.2.7 Process Validation and Verification

Process validation establishes scientific evidence that the manufacturing process consistently achieves intended safety outcomes. For fermented sausages, validation typically involves challenge studies where products are deliberately inoculated with target pathogens at levels exceeding those expected in commercial production, then processed according to defined protocols with pathogen reduction measured to confirm achievement of regulatory requirements.

Verification activities confirm that validated processes operate as intended during routine production through monitoring record review, periodic product testing, and environmental monitoring programs. Environmental monitoring detects the emergence of niches where pathogens like *L. monocytogenes* might establish residence, enabling corrective sanitation before product contamination occurs.

20.3 Innovations in Starter Culture Technology

20.3.1 Evolution from Traditional to Functional Starter Cultures

Commercial fermentation technology development for fermented sausage is analogous to other areas within food biotechnology in that it has progressed from a trial-and-error process using initial empirical selections based on primary functionality to a process of rational design for multifunctional products. First-generation commercial starters were largely selected for their ability to produce acids as rapidly as possible and with reliability. Second-generation starters have been selected to provide both an increase in rate of acidification and contribute to the color and flavor of the final product by incorporating coagulase-negative staphylococcus species along with LAB. The current third generation of starters are being designed to address additional functions, including bioprotection through the use of bacteriocins, competitive exclusion, and probiotics, as well as controlling levels of biogenic amines (Gaggia *et al.*, 2011; Munekata *et al.*, 2022).

20.3.2 LAB: Contemporary Strain Selection

The 2020 taxonomic revision of the *Lactobacillus* genus (Zheng *et al.*, 2020) reorganized species relevant to meat fermentation into several new genera. *L. sakei* remains the species most frequently isolated from traditional European fermented sausages, reflecting its exceptional ecological adaptation to the meat environment. *Lp. plantarum* has gained prominence because certain strains combine robust acidification capabilities with documented probiotic properties and bacteriocin production.

P. acidilactici and *P. pentosaceus* feature prominently in rapid-fermentation systems. Their homofermentative metabolism efficiently converts glucose to lactic acid, driving rapid pH decline at elevated temperatures. Certain strains produce pediocin PA-1, a Class IIa bacteriocin with strong anti-listerial activity. Recent selection of autochthonous *P. pentosaceus* strains demonstrated improved sensory properties compared to commercial cultures while maintaining food safety characteristics (Ferrocino *et al.*, 2022).

Table 20.2 summarizes the principal LAB and CNS species employed in contemporary starter culture formulations.

TABLE 20.2

Lactic Acid Bacteria and Coagulase-Negative Staphylococci Species Used as Starter Cultures in Salami Fermentation: Technological Functions, Bioprotective Mechanisms, and Limitations

Species	Group	Primary Technological Functions	Bioprotective Mechanisms	Probiotic Potential	Key Limitations
Latilactobacillus sakei	LAB	Rapid acidification Dominant meat-adapted species Cryotolerant Arginine deiminase pathway for pH buffering	Sakacin A, P, K production (strain-dependent) Competitive exclusion Organic acid production	Limited Not among established probiotic species	Variable bacteriocin production Some strains BA-positive Requires glucose supplementation
Latilactobacillus curvatus	LAB	Acidification Psychrotrophic growth Frequent co-dominant with *Lt. sakei*	Curvacin A (sakacin A homologue) Curvaticin production Competitive exclusion	Limited evidence	Higher frequency of tyramine production than *Lt. sakei* Slower acidification rate
Lactiplantibacillus plantarum	LAB	Versatile acidification Broad temperature range Robust stress tolerance Antioxidant production	Plantaricins (class IIb) Phenyllactic acid Amine oxidase activity (strain-specific) Competitive exclusion	High Multiple strains with documented probiotic attributes Good GI survival potential	Not meat-specific adaptation Variable performance across strains Some strains produce BA
P. acidilactici	LAB	Fast acidification at elevated temperatures (up to 50 °C) Homofermentative Thermotolerant	Pediocin PA-1 (potent anti-listerial class IIa bacteriocin) Organic acids	Moderate Some strains evaluated for probiotic application	Limited flavor contribution May produce excessive acidity Narrow metabolic repertoire
P. pentosaceus	LAB	Rapid acidification Thermotolerant Broad carbohydrate utilization	Pediocin production (strain-dependent) Competitive exclusion	Moderate Fewer characterized probiotic strains than *P. acidilactici*	Variable bacteriocin production Less common in traditional products
Lacticaseibacillus rhamnosus	LAB	Moderate acidification Adjunct for probiotic function rather than primary fermentation	Competitive exclusion Organic acids Strain-specific antimicrobial peptides	High Includes strain GG with extensive clinical documentation	Poor survival during extended ripening Not meat-adapted Requires protective strategies

(Continued)

TABLE 20.2 ***(Continued)***

Lactic Acid Bacteria and Coagulase-Negative Staphylococci Species Used as Starter Cultures in Salami Fermentation: Technological Functions, Bioprotective Mechanisms, and Limitations

Species	Group	Primary Technological Functions	Bioprotective Mechanisms	Probiotic Potential	Key Limitations
L. casei/paracasei	LAB	Moderate acidification Flavor development through proteolysis Adjunct starter	Competitive exclusion BA degradation (strain-specific amine oxidases)	High Well-established probiotic species with commercial applications	Variable a_w tolerance Viability decline during ripening
Staphylococcus xylosus	CNS	Nitrate reductase (color) Strong lipolytic activity Proteolysis Aroma compound generation	Catalase (oxidative stability) Nitrite reduction may inhibit *Clostridium* spp.	None Not considered probiotic	Variable lipase expression May produce BA Some strains carry antibiotic resistance genes
Staphylococcus carnosus	CNS	Nitrate reductase Color development Proteolysis Moderate lipolytic activity QPS status (EFSA)	Catalase Superoxide dismutase production	None	Lower lipase activity than *S. xylosus* Limited flavor impact in some studies
Staphylococcus equorum	CNS	Nitrate reductase Lipolytic activity Halotolerant Common in Mediterranean-style products	Catalase production	None	Less extensively characterized than *S. xylosus* or *S. carnosus* Safety assessment ongoing for some strains

Note: Taxonomic nomenclature follows Zheng *et al.* (2020) for reclassified *Lactobacillus* species.

Abbreviations: a_w, water activity; BA, biogenic amine-producing strains; CNS, coagulase-negative staphylococci; LAB, lactic acid bacteria; QPS, qualified presumption of safety.

Sources: Compiled from Leroy, Verluyten and De Vuyst (2006), Talon and Leroy (2011), Zdolec *et al.* (2022), and references cited therein.

Recent investigations have substantially expanded understanding of LAB functionality in meat fermentation. Woldemariam (2024) screened LAB strains based on acid production, nitrite degradation, and bacteriostatic capacity, identifying strains H1-5, N102, YL-1, and YL-2 with excellent fermentation characteristics and inhibitory activity against both *E. coli* and *S. aureus*. These strains were applied to salami production, reducing pH to 5.2 while generating distinctive flavor profiles. Metagenomic analysis revealed that salami prepared with selected strains showed distinctive metabolic profiles, with key volatiles including linalool, 1-octen-3-ol, 3-methylbutyric acid, and hexanal contributing to characteristic flavor.

The flavor contribution of different LAB species and strains has received increasing attention as manufacturers seek to differentiate products in competitive markets. Key volatiles identified in well-fermented salami include linalool, 1-octen-3-ol, 3-methylbutyric acid, butyric acid, hexanal, heptanal, phenylacetaldehyde, 2-methylbutanol aldehydes, and *p*-cresol. The YL-1 salami in the Woldemariam (2024) study showed high concentrations of linalool (0.15 mg/kg), 1-octen-3-ol (0.04 mg/kg), and 3-methylbutyric acid (1.08 mg/kg), illustrating the strain-specific nature of flavor compound generation.

20.3.3 Coagulase-Negative Staphylococci

CNS contributes enzymatic activities that LAB cannot provide. Their nitrate reductase activity converts nitrate to nitrite, lipases hydrolyze triglycerides, releasing free fatty acids, and proteases generate peptides and amino acids. Catabolism of branched chain amino acids yields characteristic volatile aldehydes

(Sánchez Mainar, Weckx and Leroy, 2017; Stahnke, 1995). *S. xylosus* and *S. carnosus* are most commonly employed. Recent studies with *Staphylococcus simulans* demonstrated promotion of free amino acid formation with slight biogenic amine-reducing activity (Li *et al*., 2024).

20.3.4 Bioprotective Cultures: Mechanisms and Applications

Beyond acidification, certain starter strains inhibit undesirable microorganisms through bacteriocin production and competitive exclusion. Class IIa bacteriocins, including pediocin PA-1 and sakacin A, kill sensitive cells by forming pores in their membranes. Studies have documented one to three log additional pathogen reduction when bacteriocin-producing strains are employed (Hugas, Garriga and Aymerich, 2003; Fraqueza, Patarata and Lauková, 2016).

The integration of bioprotective cultures with other safety hurdles has been systematically evaluated through meta-analysis. Stegmayer *et al.* (2023) systematically reviewed the effects of LAB and CNS on dry-fermented sausage quality and safety, finding consistent evidence for enhanced pathogen control when appropriate cultures are employed. The presence of bacteriocinogenic strains has been shown to reduce pathogen counts by more than six logs compared to controls. The analysis confirmed that bioprotective efficacy depends not only on antimicrobial compound production but also on ecological factors, including inoculation level, competitive fitness under fermentation conditions, and interaction with indigenous microflora. Hashemi, Gholamhosseinpour, and Khaneghah (2023) demonstrated that LAB strains caused pH reduction that inhibited pathogen growth (*Salmonella typhi* and *S. aureus*), improving food safety.

Probiotic colonization of fermentation environments represents an emerging strategy for bioprotection. Hashemi, Gholamhosseinpour, and Khaneghah (2023) demonstrated that LAB strains (*Lp. pentosus* PTCC 1872, *Lp. paraplantarum* PTCC 1965, and *Lp. plantarum* PTCC 1745) established on surfaces caused pH reduction that inhibited pathogen growth (*S. typhi* PTCC 1609 and *S. aureus* PTCC 1826), improving consumer health and food safety. This approach extends bioprotection beyond batch-specific starter inoculation toward facility-wide ecological management.

20.3.5 Probiotic Starter Cultures: Potential and Limitations

Probiotics, as a food additive, are being used increasingly in fermented meat products, which has prompted several researchers to investigate how they can deliver the same level of health benefits in these types of products as they do in dairy. For probiotics to work in a fermented meat product, it is essential that the probiotics maintain their viability in numbers sufficient to meet or exceed the recommended levels of viable cells throughout the entire shelf life of the product. There is currently no regulatory agency that mandates the amount of viable cells that must be present in a probiotic-fermented meat product. However, based on science and extrapolation from dairy standards, it is generally agreed upon that a minimum of 10^6 viable cells per gram (CFU/g) must be present at the time of consumption, whereas 10^7–10^8 CFU/g would be ideal for providing demonstrable health benefits. According to the Codex Alimentarius Commission Standards, specifically CXS 243-2003, there are mandatory amounts of starter culture (10^7 CFU/g) and other probiotic microorganisms (10^6 CFU/g) for fermented milk products. These standards are often cited for use in probiotic meat products because of the lack of specific regulatory standards for probiotic meat products.

Recently, research in this area has greatly enhanced our knowledge of the potential risks and strain-specific survival of probiotics. Tukel (2024) conducted a study involving the production of fermented salami using four different strains of probiotics: *L. rhamnosus* LR32 200B, *Lp. plantarum* LP115 400B, *B. lactis* BB12, and combinations thereof. During the course of the experiment, samples were stored at 4 °C for 60 days with regular assessments made of the viability of each strain of probiotics, along with the physical and chemical properties and sensory qualities of the fermented salami. All of the tested strains of probiotics were able to achieve and sustain viable counts greater than 10^6 CFU/g after 60 days of storage, thus meeting the minimum requirements for the probiotic function. Of the two strains that demonstrated the greatest increase in growth rate, *Lp. plantarum* LP115 and *L. rhamnosus* LR32 200B, they also demonstrated a greater tolerance to the high-salt, low-pH, and nitrate-rich environment found in

fermented sausages. Mani-López *et al.* (2024) demonstrated that it is possible to successfully incorporate *Lp. plantarum* and *L. acidophilus* in salami-type products without negatively affecting consumer acceptance. It was noted that the probiotic counts had grown two to three log cycles during the manufacturing process, from approximately 10^5 CFU/g at the time of inoculation to 10^8–10^9 CFU/g at the completion of the product, although the water activity had dropped to 0.83–0.84 by day 15. This growth trend contradicts the long-held assumption that the viability of the probiotics will decline during fermentation and ripening. A mixture of the two probiotic strains resulted in significantly higher counts of total microbes ($p < 0.05$) compared to the control, indicating that if the proper strain of product match is selected, then you can develop probiotic-enriched fermented meat products that contain viable counts of probiotics that are substantially higher than the minimum required for a beneficial effect. Overall acceptability scores were similar between the products containing probiotics and those without, indicating that it is feasible to successfully add probiotics to functional meat products (Sirini *et al.*, 2023).

The main issue hindering viability during ripening is that cells undergo severe osmotic shock when water activity drops to 0.85–0.91 in the completed product. Viability losses of two to four log cycles are typically observed; however, viability retention among different strains can vary drastically. *Lactobacillus plantarum* and *L. rhamnosus* strains have demonstrated extraordinary resistance and retained greater than 10^7 CFU/g at water activities of 0.83–0.89 for longer storage times. On the other hand, *Bifidobacterium* strains have shown the worst survivability and have experienced approximately a 3-log reduction during the ripening process, regardless of protective encapsulation methods employed, resulting in approximately only 50% of encapsulated cells surviving the low water activity environment.

Protective encapsulation within matrices provides significant protection against viability loss. Research with *Lactobacillus reuteri* has demonstrated that encapsulating alginate protects cells from viability loss by reducing losses from 2.6 log to ≤0.5 log under the same processing conditions (Gaggia *et al.*, 2011). Other protective approaches include supplementation with prebiotics such as fructooligosaccharides, glycerol cryoprotection for encapsulated *Bifidobacterium*, and optimized cold storage procedures. Screening for naturally resistant strains is another option that does not require additional processing costs and complexity.

The sensory effects of incorporating probiotics in fermented sausage products have been assessed extensively. Sirini *et al.* (2023) determined that probiotic strains can be successfully integrated into fermented sausages without decreasing consumer preference. Overall acceptability scores showed no significant difference between probiotic-containing and control products, indicating that probiotics can be viable options for developing functional meat products with added health benefits that consumers desire. This is consistent with growing consumer interest in gut health foods and enables producers to create probiotic-enriched salami with valid functionality claims in countries with permissive regulatory environments. However, the absence of standardized regulatory frameworks for probiotic meats presents both opportunities and challenges for manufacturers. Manufacturers must provide substantiation for the viability claims through the appropriate challenge studies, documenting the maintenance of minimum viable counts throughout the shelf life of the product under normal storage conditions.

20.3.6 Starter Culture Strategies for Biogenic Amine Mitigation

Biogenic amines accumulate when microbial decarboxylases convert amino acids to corresponding amines (Bover-Cid *et al.*, 2012). A recent comprehensive review by Özogul and Özogul (2024) examined biogenic amine occurrences and health effects in fermented foods, documenting that dietary exposure to foods containing high biogenic amine (BA) levels is associated with migraines, elevated blood pressure, tachycardia, and other adverse effects. Importantly, BA-mediated toxicity may occur at levels substantially below suggested toxic thresholds, depending on individual sensitivity and concurrent factors such as alcohol consumption and certain medications. Control strategies begin with the selection of strains lacking decarboxylase genes.

Spice extracts have also shown inhibitory effects. García-López *et al.* (2023) demonstrated that autochthonous bacteriocinogenic strains could simultaneously improve safety and quality while controlling biogenic amine formation.

Recent research has explored multiple approaches to biogenic amine reduction. Liu *et al.* (2023) demonstrated that *Lp. plantarum* X22-2 effectively increased LAB populations while significantly inhibiting the formation of putrescine, histamine, cadaverine, and tyramine in fermented lamb sausage. Total volatile basic nitrogen content, peroxide value of fat, pH, water activity, and viscosity were lower in samples fermented with this strain compared to commercial starter and natural fermentation groups. The efficacy of spice extracts for biogenic amine control has also received attention. Ma *et al.* (2020) found that cassia and fennel extracts showed the best inhibitory effects, with maximum inhibition rates of 21.8% for tryptamine, 19.3% for putrescine, 27.5% for spermidine, 24.6% for 2-phenylethylamine, 18.7% for tyramine, and 24.4% for histamine.

20.3.7 Autochthonous versus Commercial Starter Cultures

Although autochthonous strains present in traditional products offer a rich source of new strains, this resource has been largely underutilized. Ferrocino *et al.* (2022) demonstrated how specific strains of *P. pentosaceus* and *S. xylosus* selected from Salame Piemonte PGI could improve the sensory characteristics when used as an alternative to commercial strains. Montanari *et al.* (2021) have demonstrated that wild microbial flora compete with commercial starter cultures during fermentation of Italian Ventricina salami.

However, the transition of autochthonous strains to commercial production is expensive and time-consuming due to the need to characterize the strains from a food safety perspective, evaluate their use as a starter culture or ingredient in product formulation, and provide regulatory documentation. A large number of strains with potential for commercial development exist within culture collections but lack the resources necessary to begin commercialization.

20.3.8 Emerging Approaches and Future Directions

Emerging approaches exploit advances in genomics and synthetic biology (Woldemariam, 2024). Whole-genome sequencing enables comprehensive characterization of functional potential (Zheng *et al.*, 2020). Synthetic ecology approaches design multi-strain consortia with complementary functions (Leroy, Verluyten and De Vuyst, 2006). Adaptive laboratory evolution generates improved variants through iterative selection under defined stress conditions (Tao *et al.*, 2020).

20.3.9 Consumer Acceptance and Market Considerations

Consumer acceptance is a key to the commercial success of probiotic and clean-label fermented meat innovation. Research has indicated that consumers are willing to purchase probiotic-fermented sausages and have an intention to do so when the health benefit is aligned with their preferences for sensory attributes. In Brazil, 45% of consumers surveyed who were interested in purchasing probiotic dry-fermented sausage stated that they would be motivated to purchase due to the "healthiness" of the product, and 42% stated that they would be motivated to purchase out of curiosity. The results also indicated that health-conscious consumer segments accepted the product at a much higher rate than did moderately health-conscious consumers (da Silva *et al.*, 2024). Consumers' willingness to spend money on a premium for healthier fermented sausages varies by demographics and product positioning. Specifically, research demonstrated that women are willing to spend 20% more for low-nitrate salami than men (Hung, de Kok and Verbeke, 2016). Additionally, consumers are willing to spend 10–40% more on products that they perceive as natural or organic despite having similar nutritional profiles (Sebranek and Bacus, 2007). Despite this information, there are still significant knowledge gaps that exist related to consumer acceptance. For example, many consumers do not understand the definition of the term "probiotic" in the context of meats, which could limit market potential unless specific educational campaigns are implemented (Greis *et al.*, 2024). Sensory attributes continue to be the most influential attribute in determining consumer preference. Even products with beneficial health claims can be unsuccessful commercially if the taste, texture, or visual appearance of the product does not meet the consumer's expectations (Hung *et al.*, 2017).

The reaction to clean-label and nitrite-free product positioning is influenced by various tiers of consumer perceptions and discrepancies in reality. Cross-cultural research (n = 2,057) from four countries (Italy, Belgium, Germany, and the Netherlands) indicates that consumers lack an awareness about how many processed foods contain nitrites but will respond favorably to "less nitrite" or "natural compounds" labeling (Hung, de Kok and Verbeke, 2016). Perceived sensory quality can influence consumers' willingness to pay for nitrite-free products, according to auction-based experimental research. Additionally, with elastic net regression and decision trees, researchers have identified that both flavor and color have been identified as critical factors that influence a consumer's willingness to pay for a nitrite-free product (Hung *et al*., 2017). The way we describe the product also confuses consumers; they tend to believe "salt" is natural but "sodium chloride" is unnatural (65.6% acceptance versus 32% acceptance even though they are chemically equivalent) (Asioli *et al*., 2017). Vegetable-derived nitrate sources may provide nitrite-free alternatives, but this does not mean they provide the same functionality at the same rate. As a result, costs become an issue and may make it difficult for companies to produce these types of products due to the higher costs of vegetable juice powder. For example, to substitute vegetable juice powder for synthetic nitrite, you would need to apply four times the amount of the juice powder at a cost of >$44/kg versus <$2.5/kg for synthetic nitrite. Such expenses could lead to increased prices in stores by up to 15–30%, which only 11% of Italian consumers were willing to accept (Hung, de Kok and Verbeke, 2016; Sebranek and Bacus, 2007). Surveys of the meat industry found that 53% of consumers in developing countries expressed discontent with meat products, stating health concerns, and suggesting there is a large potential for reformulated products in emerging economies (Niyonzima *et al*., 2019).

Differing regional and cultural patterns have a significant impact on how quickly people will accept new functional meat products. Cross-cultural studies indicate that, when it comes to new meat technologies, consumers from China are the most open to them compared to their European and Latin American counterparts. This variation is largely because of Chinese consumers' perceptions of the health and nutritional value of new technologies and their focus on food safety concerns versus concerns about ethics (Bryant *et al*., 2019; Chong *et al*., 2025). In contrast, European consumers (especially Belgian, Dutch, and German) place emphasis on the "naturalness" of the product as well as the clarity of labeling and ethics of the production process versus the use of new technology (Verbeke *et al*., 2015). As a result, there tends to be less food neophobia toward fermented functional foods in Asia due to historical cultural practices of consuming fermented foods compared to Western countries, where there appears to be an increased amount of skepticism toward using probiotics in meats compared to more traditional dairy applications (Greis *et al*., 2024). When looking at demographic factors, regardless of location, young consumers (18–35 years), female consumers, and those with higher educational levels tend to be more accepting of new functional foods across all geographic locations. However, when considering gender as a variable, some research indicates that, in certain areas, this assumption may not always hold true (Bryant *et al*., 2019). Religious and political beliefs can also affect how open people are to new products. For example, studies found that self-identified religious people in the United States were 60% less likely to be open to new meat technologies (Wilks and Phillips, 2017), and politically conservative people in different countries were more likely to be disgusted by nontraditional products (Bryant *et al*., 2019). These studies' results underscore the necessity for tailored marketing strategies and product positioning, as opposed to a universal approach.

20.4 Metabolomic Profiling and Quality Assessment

20.4.1 Foodomics Approaches in Fermented Meat Research

A metabolomic study can provide a complete snapshot of the biochemistry present in fermented sausages. While traditional targeted studies are designed to measure a limited number of specific compounds, metabolomics is able to measure all of the small molecules that are produced as part of the fermentation process and discover new, unanticipated relationships (Cifuentes, 2009; Rocchetti *et al*., 2023). It is very effective to combine a metabolomics approach with an examination of the microorganisms present during the fermentation process to identify which organisms produce which compounds.

20.4.2 Analytical Platforms for Salami Metabolomics

Liquid chromatography–mass spectrometry (LC-MS) has become the workhorse platform for nonvolatile metabolite analysis (Doğan, 2024). Modern high-resolution instruments achieve mass accuracy below 5 ppm. Quality assurance and quality control practices for LC-MS metabolomics have been systematically addressed through community consensus efforts. The Metabolomics Quality Assurance and Quality Control Consortium (mQACC) presented workshop findings at Metabolomics 2023, focusing on reference materials, data quality review, metabolite identification/annotation, and quality assurance practices (Mosley *et al*., 2024). Key recommendations emphasize the use of pooled quality control samples, appropriate reference materials, and standardized reporting practices to enable meaningful comparison across studies and laboratories.

Current practices in untargeted metabolomics have been comprehensively reviewed by Broeckling *et al*. (2023), who conducted a scoping literature review detailing pooled QC sample use in published untargeted LC-MS metabolomics studies. While pooled QC samples are relatively widely adopted, relatively few studies use them for data quality improvement, demonstrating a clear opportunity for increased utilization in quality reporting, feature filtering, analytical drift correction, and metabolite annotation. These best practices frameworks offer direction for metabolomics researchers aiming to improve data quality and reproducibility. Gas chromatography–mass spectrometry (GC-MS) remains the reference technique for volatile compound analysis. GC-IMS offers rapid fingerprinting capabilities potentially applicable to online process monitoring.

20.4.3 Key Metabolite Classes in Salami Quality

Concentrations of free amino acids significantly rise throughout the ripening process due to proteolytic activity. The presence of glutamic acid has been reported to provide an umami taste, while γ-glutamyl peptides have also been shown to improve overall taste by enhancing kokumi mechanisms (Toelstede and Hofmann, 2008). The organic acids found in salami represent the metabolic products of the salami's microbial fermentation history; lactic acid is the most common organic acid produced and is generally present at levels from 0.5% to 1.5% (wet wt.). Lipid-derived metabolites constitute the majority of a salami's aroma compounds, and branched-chain aldehydes are responsible for producing a distinct malty salami-like aroma.

20.4.4 Microbial–Metabolite–Sensory Correlations

Integrating metabolomic data with microbiome analysis and sensory evaluation enables researchers to trace quality attributes to their microbial origins. Studies have demonstrated that different starter strains produce distinct metabolite fingerprints correlating with sensory descriptors. Rocchetti *et al*. (2023) examined the impacts of axenic and mixed starter cultures on the metabolomic and sensory profiles of ripened Italian salami. Figure 20.2 illustrates an integrated multiomics workflow for salami quality characterization.

20.4.5 Biomarker Discovery for Quality and Authenticity

Biomarker discovery applies statistical methods to identify metabolites distinguishing product categories (Rocchetti *et al*., 2023). Researchers have successfully discriminated PDO products from nonprotected alternatives based on metabolite profiles (Cifuentes, 2009). Quality grading applications remain less developed but show promise (Doğan, 2024).

20.4.6 Predictive Modeling and Precision Fermentation

Machine learning algorithms trained on integrated datasets can predict quality outcomes from early-stage measurements. Random forest, gradient boosting, and neural networks have been applied with promising results (Tao *et al*., 2020). Digital twin concepts offer promising approaches where virtual representations of fermentation systems enable simulation of control scenarios before implementation.

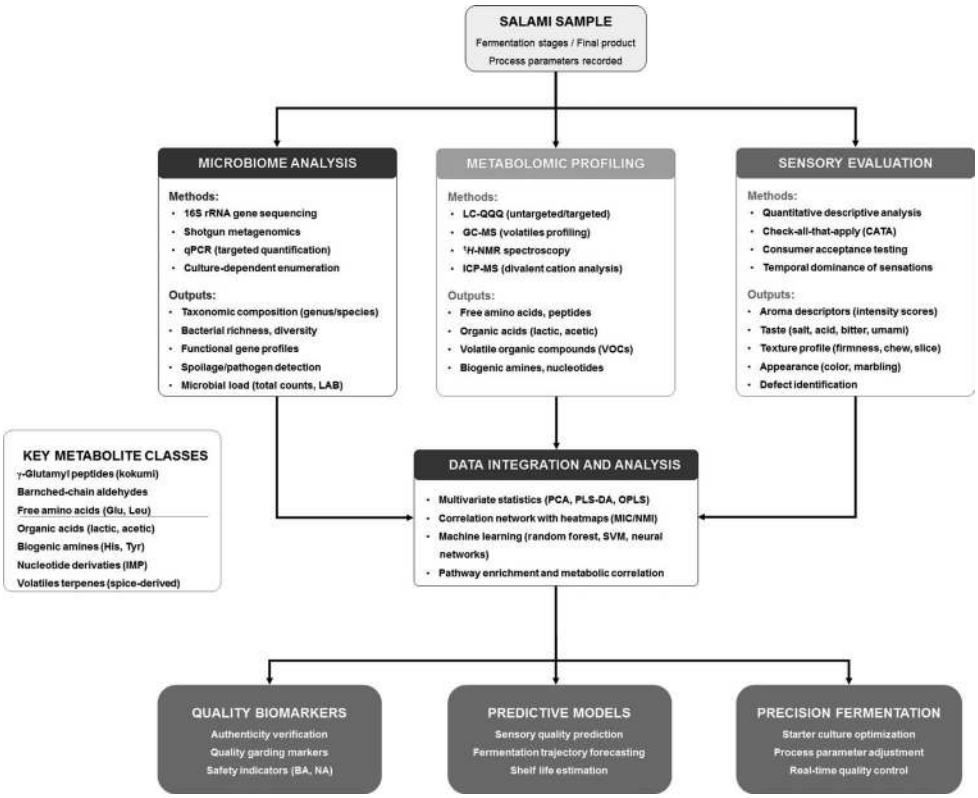

FIGURE 20.2 Integrated multiomics workflow for salami quality characterization. *Abbreviations:* 16S rRNA: 16S ribosomal RNA; BA: biogenic amines; CATA: check-all-that-apply; GC-MS: gas chromatography–mass spectrometry; ^{1}H-NMR: proton nuclear magnetic resonance; ICP-MS: inductively coupled plasma–mass spectrometry; IMP: inosine monophosphate; LAB: lactic acid bacteria; LC-QQQ: liquid chromatography-triple quadrupole; MIC: maximal information coefficient; NA: *N*-nitrosamines; NMI: normalized mutual information; OPLS: orthogonal partial least squares; PCA: principal component analysis; PLS-DA: partial least squares–discriminant analysis; qPCR: quantitative polymerase chain reaction; SVM: support vector machine; VOCs: volatile organic compounds.

Artificial intelligence applications in fermented meat production represent a rapidly developing field with transformative potential. Tao *et al*. (2020) reviewed smart processing approaches, including predictive quality modeling, real-time process optimization via closed-loop control, and digital twins for simulation. Machine learning algorithms, including random forest, gradient boosting, and neural networks, have been applied to fermented food systems with promising results for quality prediction and process optimization.

The practical implementation of AI-based fermentation management requires consideration of regulatory acceptance, process validation, and operator training. Explainable AI approaches that provide interpretable outputs rather than black-box predictions facilitate regulatory review and operator confidence. SHAP (SHapley Additive exPlanations) values enable attribution of model predictions to specific input features, identifying which measurements most influence quality predictions and supporting rational process optimization decisions.

20.4.7 Current Challenges and Future Directions

Annotation rates in untargeted metabolomics typically reach only 30–50% of detected features (Broeckling *et al*., 2023). Standardization of sample preparation, data acquisition, and bioinformatic workflows remains incomplete (Mosley *et al*., 2024). Multi-laboratory validation studies are needed to establish reproducibility (Broeckling *et al*., 2023).

20.5 Advances in Safety Control Strategies

20.5.1 Pathogen Control: Hurdle Technology

Fermented sausage safety depends on hurdle technology: the combined action of multiple preservation factors. Principal hurdles are pH, water activity, salt, nitrite, and competitive exclusion (Leistner, 2000). *Salmonella* and STEC represent primary concerns during fermentation; both organisms decline as pH drops and water activity decreases. *L. monocytogenes* presents different challenges due to its psychrotrophic nature and high tolerance for reduced water activity (Thévenot *et al.*, 2006).

20.5.2 Biogenic Amine Formation and Mitigation

A comprehensive review of biogenic amine occurrences has highlighted the importance of control strategies. The relationship between processing parameters and biogenic amine formation has been systematically characterized. Komprda *et al.* (2004) demonstrated that tyramine and putrescine content followed polynomial relationships with ripening time, enabling prediction of amine accumulation under specific processing conditions. Factors including smaller casing diameter, specific spice mixtures (containing red pepper), and certain starter cultures significantly reduced amine content.

García-López *et al.* (2023) evaluated two autochthonous bacteriocinogenic strains for production of salchichónes (Spanish fermented sausages), demonstrating that appropriate strain selection can simultaneously improve safety and quality while controlling biogenic amine formation. Co-inoculation with *Staphylococcus equorum* and *L. sakei* reduces vasoactive biogenic amines in traditional dry-cured sausages (Dias *et al.*, 2021), suggesting potential for combined LAB-CNS approaches specifically targeting amine control.

20.5.3 *N*-Nitrosamine Formation and Reduction

When nitrite reacts with secondary amines in an acid environment, it forms nitrosamines. The concentrations of nitrosamines within correctly produced products are generally extremely low, being less than 10 µg/kg. Strategies to decrease levels of nitrosamines can be achieved by reducing the amount of nitrite used in the product, adding ascorbate to inhibit nitrosation, and controlling environmental factors that enhance the rate of nitrosation. Clean-label alternative sources for vegetable-derived nitrates come from using celery powder or beetroot extract (De Mey *et al.*, 2014; Sebranek and Bacus, 2007).

20.5.4 Advanced Glycation End Products

AGEs form through Maillard-type reactions during extended ripening. Fermented sausages present intermediate AGE concentrations between fresh meat and heavily heat-processed products (Uribarri *et al.*, 2010). Control strategies focus on limiting sugar availability and managing temperature during ripening.

20.5.5 Oxidative Stability and Lipid Oxidation Control

Lipid oxidation generates off-flavors and potentially harmful compounds (Toldrá and Flores, 1998). Natural antioxidants (rosemary extract, green tea catechins) and appropriate packaging (vacuum, modified atmosphere) provide control (Munekata *et al.*, 2022). Selection of CNS strains with antioxidant activity offers additional protection (Talon and Leroy, 2011).

20.5.6 Integrated Risk Assessment

Quantitative microbiological risk assessment models combine contamination data, pathogen behavior during processing, consumption patterns, and dose–response relationships. Such models have been developed for *Salmonella* and *Listeria* in fermented sausages (Mataragas *et al.*, 2006).

20.5.7 Regulatory Developments and Industry Standards

The following regulatory guidelines and third-party certification schemes allow for some consistency across the world regarding fermented meat safety: USDA-FSIS Appendix A and EU Regulations 853/2004 and 2073/2005; SQF, BRC, and FSSC 22000.

20.6 Current Challenges and Future Directions

20.6.1 Persistent Research Gaps

There is no way to predict how probiotics will behave when introduced into the complex matrix of meat products using data obtained from laboratory media studies (Leroy, Verluyten and De Vuyst, 2006). The spatial heterogeneity within meat products allows for microenvironments that are obscured by bulk product analysis (Leistner, 2000). Additionally, the temporal nature of the fermentation process introduces an additional layer of complexity that cannot be captured with a single sample time point (Toldrá, 2017).

20.6.2 Probiotic Viability: The Persistence Challenge

At this time, there is little available information on the successful large-scale use of probiotics in low-moisture fermented meats (Gaggia *et al.*, 2011). Although microencapsulation technology offers much promise as a method to increase probiotic viability, it also adds cost and complexity (Sirini *et al.*, 2023). Some screening programs have identified candidate strains that appear to have inherent levels of stress tolerance (Tukel, 2024); however, there appears to be a trade-off between stress tolerance and other desirable characteristics.

20.6.3 Regulatory Frameworks: Gaps and Inconsistencies

The variability in regulatory approaches and inconsistencies between jurisdictions for functional or probiotic claims continue to exist. For example, although EFSA has rejected virtually all health claim applications for probiotics (EFSA Panel on Dietetic Products, Nutrition and Allergies, 2016), the FDA has allowed structure/function claims for dietary supplements (including fermented foods) without prior approval (FDA, 2013). As of today, no jurisdiction has established a specific limit for biogenic amines in fermented meats (Özogul and Özogul, 2024).

20.6.4 Autochthonous Strain Exploitation

The disconnect between academic research on the characterization of probiotic strains and their commercial use is an ongoing barrier (Ferrocino *et al.*, 2022). The characterization of local strains requires resources (i.e., financial and personnel) that few academic laboratories possess to perform the necessary evaluations for technological capability, regulatory compliance, and safe use (Montanari *et al.*, 2021). New collaborative models may be required.

20.6.5 Artificial Intelligence and Digital Fermentation

AI has tremendous capabilities as a method to optimize fermentation monitoring and control. AI machine learning models can predict quality output based upon early indicators. AI digital twins are able to simulate a control scenario. There will need to be proof of equivalency to traditional methods for regulatory approval of AI-controlled fermentation processes. Explainable AI models will be crucial to this process, as they allow regulatory bodies to review the decision-making process of an AI model (Tao *et al.*, 2020).

Digital twin concepts have significant potential for optimizing fermentation processing systems. The concept of a digital twin is that of a virtual representation of a physical fermentation system that is constantly being updated with real-time data from sensors, allowing for the evaluation of the effectiveness of simulated control scenarios prior to implementation. For example, salami production could utilize a

digital twin to combine the real-time measurement of the fermentation process (i.e., temperature, humidity, pH, etc.) and quality outcome predictions utilizing predictive models; the digital twin would allow for the virtual testing of various simulated intervention strategies (e.g., adjusting temperature, modifying humidity levels, extending ripening periods) before they were implemented in a product.

The regulatory framework for the use of AI-controlled food manufacturing processes is currently still in development. In order for regulatory authorities to accept the use of AI to control fermentation processes, there needs to be documented evidence of the safety and quality performance of these processes compared to their traditional counterparts. This documentation of comparative performance will require the completion of validation studies demonstrating that AI-controlled fermentation processes can produce quality outcomes at least comparable to those achieved by traditional methods. Additionally, transparency requirements may mandate the use of understandable AI models versus black box–type neural network models, thereby providing regulatory authorities with the ability to review and understand the decision-making logic behind the process control actions of an AI model.

20.6.6 Low-Nitrite and Nitrite-Free Production

Consumer demand for cleaner labels drives interest in nitrite reduction (Sebranek and Bacus, 2007). Vegetable-derived nitrate represents the current commercial solution (De Mey *et al.*, 2014). True nitrite-free formulations require alternative hurdles, particularly against *C. botulinum* (Leistner, 2000).

20.6.7 Sustainability and Environmental Considerations

The dominant contributor to the environmental footprint of fermented meat products is the extraction and processing of its raw materials, as shown by life cycle assessments (Thornton *et al.*, 2022). Better insulation and heating/cooling of fermentation and ripening chambers, using less water for washing and cleaning, and using biodegradable packaging can all help make energy use more efficient.

Climate change presents a significant challenge to sustainably addressing other aspects of sustainability, as proactive measures are required. Increasing ambient temperature requires increasing amounts of energy to maintain the same levels of temperature-controlled operation: refrigeration systems require 2–4% more energy to cool for each 1 °C increase in condensation temperature (Bilgili *et al.*, 2023). Cold storage facilities in warmer climates are already running for longer periods of time than those in cooler climates (18–20 hours versus 12–14 hours) (Bilgili *et al.*, 2023). The Intergovernmental Panel on Climate Change has projected 1.5–2 °C of global warming by the middle of this century (IPCC, 2021). This could result in increased costs associated with cooling fermentation chambers by 3–8% and may render the current ripening protocols economically unviable due to their reliance on consistent 12–15 °C temperatures. Approximately 5% of the world's total energy and 2.5% of the world's total GHG emissions are attributed to the world's total refrigeration needs in the global food system. However, by 2050, the expanded cold chain will necessitate up to 14 billion cooling appliances (IEA, 2018; FAO and UNEP, 2022).

Raw materials are being negatively impacted concurrently by heat stress among livestock that results in pale, soft, exudative (PSE) defects in meat when exposed to extreme heat prior to slaughter or dark, firm, dry (DFD) defects resulting from chronic thermal stress, both of which compromise the quality of the substrates used for fermentation and the performance of starter cultures (Gonzalez-Rivas *et al.*, 2020; Zhang *et al.*, 2024). Animals subjected to heat stress also demonstrate reduced feed conversion ratios, decreased growth rates, elevated pathogen excretion (primarily *Salmonella* and *E. coli* O157:H7), and changes to the biochemical composition of their muscles, which affect the rate of pH decline during fermentation (Henry *et al.*, 2012; Mayorga *et al.*, 2019). Already, the US livestock industry experiences estimated annual heat-related losses of approximately $1.7–2.4 billion ($369 million beef, $900 million swine, and $128 million poultry) (St-Pierre, Cobanov and Schnitkey, 2003). Experts anticipate a continued increase in the frequency and severity of extreme heat events.

Extreme weather events caused by climate change will create additional vulnerability to supply chains (FAO and UNEP, 2022). Transportation networks that are vital to the delivery of perishable meats are disrupted by flooding, drought limits the availability of water required for sanitation in processing plants,

and damage to infrastructure from storm events disrupts the continuity of the cold chain (Henry *et al.*, 2012). There have been documented impacts to food supply chains caused by climate-related disruptions (Forzieri *et al.*, 2018), including extreme precipitation, wildfires, and temperature anomalies resulting in localized shortages and price volatility. Adaptation strategies should consider integrating climate-resilient refrigeration technologies (natural refrigerants with low GWP, assisted cooling systems, and thermal energy storage) into the existing refrigeration systems of dairy processors, diversifying sources to mitigate against regional failures of production, and developing long-term plans for future investments in facilities based on temperature projections (FAO and UNEP, 2022).

20.6.8 Multiomics Integration

Full integration of metagenomics, metatranscriptomics, metaproteomics, and metabolomics remains technically challenging (Rocchetti *et al.*, 2023). Standardized workflows enabling data integration across platforms are needed (Cifuentes, 2009). Systems biology approaches promise holistic understanding of fermentation ecosystems (Tao *et al.*, 2020).

20.7 Conclusions

The technology associated with salami fermentation has progressed significantly since the early days of artisanal manufacture. Modern manufacturing combines the use of a defined starter culture and HACCP-based food safety and security protocols, as well as continually advancing technologies for quality analysis (e.g., metabolomics and spectroscopy). Despite this evolution, the primary goal of salami manufacture has remained constant—that is, to convert unstable, unsafe raw materials into shelf-stable, safe, palatable products via controlled microbial and enzymatic reactions.

New developments in salami starter cultures are moving beyond simple acidification to include cultures that provide multiple functions, including bioprotection against pathogens, biogenic amine formation prevention, and potentially probiotic function. The issue of maintaining viable probiotics throughout the low-moisture ripening process still exists. Metabolomics research has evolved from mere curiosity into a valuable instrument for the authentication and quality assessment of fermented sausages.

Safety practices for food management have improved by the consistent application of HACCP principles and validated processing techniques that have demonstrated a significant reduction in pathogen presence. We also need to continue paying attention to chemical hazards. Future opportunities for advances in food science for the development of fermented sausage exist within the areas of artificial intelligence and multiomics technology. As the regulatory environment evolves to reflect new technological advancements, it can be expected that the "clean label" movement will continue to grow in importance and may necessitate innovative methods for ensuring food safety while avoiding synthetic ingredients. Through these challenges, fermented sausages will evolve further and will continue to bridge the gap between culinary traditions and current food science to support the needs of future generations of consumers.

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21

Pasteurization and Aging in Processed Meat: Technologies for Quality and Flavor Enhancement

Theodoros Varzakas

21.1 Introduction

Pasteurization in processed meats uses heat (steam, hot water) or high-pressure processing (HPP) post-cooking/packaging to control pathogens like *Listeria*, extend shelf life, with typical temperatures around 70–85 °C and specific time-temperature profiles (e.g., 55 °C+ for *Listeria* control). These strategies are crucial for effectiveness, balancing safety with quality (Bolumar et al. 2021). Other nonthermal technologies have been employed such as irradiation, light pulses, and natural biopreservatives together with active packaging (Aymerich, Picouet and Monfort, 2008; Beckwith, 1995).

One of the most widely used methods for food preservation is pasteurization (Arias-Mendez *et al*., 2014; Silva and Gibbs, 2012).

Pasteurization refers to a relatively mild heat treatment of food, usually lower than 100 °C, aimed at destroying the vegetative cells of all pathogenic as well as most nonpathogenic microorganisms.

According to Stumbo (1973):

> Whether the term sterilization or pasteurization is used to label a heat treatment designed to reduce the microbial population of a food, the basic purpose of the heat treatment is the same—that is, to free the food of microorganisms that may endanger the health of food consumers or cause economically important spoilage of the food in storage and distribution.
>
> **(Stoforos, 2016)**

A new smart time–temperature indicator (TTI) of pasteurization has been reported by Brizio and Prentice (2015) that operates based on the complex reaction between starch and iodine, and the subsequent action of an amylase on this complex causing its discoloration.

21.2 Surface Pasteurization of Ready-to-Eat (RTE) Meat Products

Non–spore-forming pathogens should not be present in RTE meat products at the end of cooking; however, contamination may occur before packaging in the final retail wrap. As contamination can take place at the surface, the product's outer layer needs to be decontaminated. Post-package pasteurization technologies are applied in this case: thermal treatment, irradiation, and exposure to ultrahigh pressure (Rhodehamel and Beckwith, 1999; Rourke, 2001; Zhu *et al*., 2005). This along with proper sanitation practices should be followed and applied.

Listeria monocytogenes, a heat-resistant contaminant in the food processing environment, is commonly chosen for evaluation in post-package pasteurization.

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Houben and Eckenhausen (2006) reported on post-package pasteurization of fully cooked meat products (weighing up to 9 kg) by water submersion (96° C) for about 10 minutes in order to achieve a 2- to 4-log destruction of *L. monocytogenes* on the product surface.

Knowledge of the *D*- and *z*-values for a particular microorganism helps in the design of thermal processes that target that specific organism (Stumbo, 1973).

The thermal decimal reduction time (*D*-value) is the time necessary to reduce a microbial population present in a well-defined medium by 90%, and indicates the thermal resistance of a microorganism at a constant temperature. The temperature increase necessary to reduce the *D*-value by 90% represents the *z*-value, and shows the temperature dependence of microbial inactivation.

P_{70} value expresses the heating time in minutes at 70 °C at a certain location in the coldest spot of a product and is named as lethality of pasteurization. This is required to achieve equal lethality to microorganisms with a given *z*-value (Houben and Eckenhausen, 2006).

L. monocytogenes count should be less than 100 CFU/g in RTE products at the time of consumption as proposed by the Codex Committee on Food Hygiene. Regulation (EU) No. 2024/2895, amending Regulation (EC) No. 2073/2005 (Official Journal of the EU Commission, 2024), requires that RTE foods capable of supporting *L. monocytogenes* growth ensure absence in 25 g throughout their shelf life, unless levels will remain below 100 CFU/g until consumption as shown by validated evidence (EURL Lm, 2023; Dufour, 2011; Lee *et al.*, 2021).

At least a sevenfold decimal reduction in *L. monocytogenes* in potentially contaminated areas of a particular food should be achieved during pasteurization as a worst-case scenario.

Based on the calculations of the highest observed thermal resistance levels of the microorganism, the efficacy of pasteurization can be increased. This means conditions of 70 °C for 2 minutes for the potentially contaminated parts of a food or the receiving of a lethality heat treatment.

Effects of surface pasteurization on inactivation of *Listeria innocua* were investigated. The lethality of *L. monocytogenes* was predicted by surface temperature, monitored during post-packaging pasteurization. Temperatures reached 70 °C for lean and fat sausages within 9 minutes of treatment. The efficacy of post-processing and the thermal lethality of *L. monocytogenes* was validated by an inoculation study (Ahn *et al.*, 2014).

The destruction of *Enterococcus faecium* according to the 5D concept, which is >40, refers also to the lethality of the pasteurization process (Raseta *et al.*, 2021).

Finely and coarsely chopped sausages and canned meat in pieces packed in polyamide casings with diameters of 75 and 90 mm have been exposed to a shortening of the effective heat treatment time by 15 minutes. A decrease in *p*-values for finely chopped sausages was the result of optimization (diameter 90: 148.8 → 97.64 minutes; diameter 75: 111.2 → 58.4 min) for coarsely chopped cooked sausages (diameter 90: 115.5 → 79.1 min; diameter 75: 245.3 → 106.6 min) and for canned meat in pieces (diameter 90: 249.7 → 95.91 min; diameter 75: 213.9 → 48.42 min). Safety of the product is acquired by pasteurization and confirmed/validated by the use of *p*-value in optimization.

21.3 Ultrahigh Temperature (UHT) Pasteurization of Meat Products

Mendenhall (1995) treated meat at UHT, for example, 900–1,200 °C, for a time sufficient to denature proteins, without burning, to a depth of up to about 2 mm. In this context, they reported acceleration of the aging process and sterilization of raw meat for extended storage at refrigerated temperatures. Cooling at a refrigerated temperature is followed after UHT treatment. Packaging is the final step in the process carried out in a hermetically sealed container. Subjecting the hermetically sealed meat to electron beam radiation (EBR) at an irradiating dosage sufficient to destroy all mesophilic vegetative pathogens, spores of pathogens, toxins, and spoilage microorganisms which grow at ambient temperatures renders the meat stable for storage at ambient temperatures. Tender and flavored meat equivalent to meat aged under refrigeration for 30–60 days result from UHT pasteurization along with high temperature aging for 12–24 hours. UHT pasteurization followed by packaging of meat in a modified atmosphere can be employed in a ready-to-cook retail cut with a shelf life of up to about 60 days.

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22

Innovative Meat Packaging: Boosting Freshness, Safety, and Sustainability

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22.1 Introduction

Recently, the global meat sector has continued to expand in response to population growth, rising incomes, urbanisation, and increasing demand for animal-source foods. According to the OECD–FAO Agricultural Outlook 2025–2034, global meat production increased by an estimated 1.3% in 2024, reaching 365 Mt, mainly driven by poultry meat and beef (OECD/FAO, 2025). Over the next decade, global meat output is projected to increase by 13%, with poultry expected to account for 62% of the additional meat produced due to its production efficiency, lower cost, and suitability for rapidly growing urban markets. Recently, the global meat sector has continued to expand in response to population growth, rising incomes, urbanization, and increasing demand for animal-source foods. According to the OECD–FAO Agricultural Outlook 2025–2034, global meat production increased by an estimated 1.3% in 2024, reaching 365 Mt, primarily driven by poultry meat and beef (OECD/FAO, 2025). Over the next decade, global meat output is projected to increase by 13%, with poultry expected to account for 62% of the additional production due to its production efficiency, lower cost, and suitability for rapidly growing urban markets. Global meat consumption is also projected to rise by 47.9 Mt by 2034, underscoring the continued importance of meat in global food systems and the consequent need for effective preservation and packaging strategies (OECD/FAO, 2025). The primary driving force behind this expansion is the steadily increasing demand for meat and meat products. While population growth remains a key factor, rising income levels and increased consumer purchasing power have also significantly influenced meat consumption patterns and product choices (Jo and Lusk, 2023). Despite this rapid growth, the meat industry faces substantial challenges related to quality assurance, safety, and fraud prevention. The sector is increasingly required not only to meet rising demand but also to ensure that meat products comply with stringent safety and quality standards to avoid contamination and fraudulent practices that have been reported recently (Manyi-Loh and Lues, 2023). Meat and meat products are among the leading contributors to foodborne illnesses worldwide, with an estimated 600 million cases and 420,000 deaths reported annually, resulting in the loss of approximately 300 million tons of food each year (Zhang *et al.*, 2021). In the United States alone, foodborne illnesses account for healthcare costs exceeding US$5 billion annually and more than 3,000 deaths. Pathogens such as *Escherichia coli* (STEC), *Salmonella*, *Campylobacter*, and Shiga toxin-producing bacteria are frequently implicated in meat-related outbreaks (Conter, 2024). These safety risks, combined with the inherent perishability of meat, make packaging a critical determinant of product quality, safety, and shelf life. Packaging plays a key role in regulating oxygen availability, moisture migration, and microbial contamination during storage and distribution (Figueroa-Enríquez, Rodríguez-Félix *et al.* 2024). In response to increasing global demand for fresh meat products and rising sustainability expectations, the industry has intensified efforts to develop advanced packaging systems that preserve quality, reduce waste, and align with environmental priorities (Spada *et al.*, 2024).

Traditional packaging methods provide limited control over chemical, microbiological, and biochemical degradations and do not offer real-time information on product freshness or handling conditions,

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prompting the development of more interactive technologies (Mohebi and Marquez, 2015). Modified atmosphere packaging (MAP) and vacuum packaging (VP) remain fundamental approaches in food preservation, as they manipulate the gaseous environment to control oxidation and microbial growth (Łopacka, Półtorak and Wierzbicka, 2016). Building on these systems, active packaging technologies, such as oxygen scavengers, antimicrobials, antioxidants, and moisture regulators, have been introduced to further stabilize color, inhibit oxidation, control microbial growth, and extend shelf life. However, inappropriate oxygen levels may trigger abnormal physiological conditions that still accelerate quality deterioration, highlighting the need for improved control strategies (Lee *et al.*, 2024).

Recent advances in nanotechnology have further enhanced packaging performance by improving barrier properties, enabling controlled release of active agents (El-Sherif et al., 2026), and increasing sensor sensitivity, thereby supporting the development of multifunctional packaging solutions (Lamri *et al.*, 2021). In parallel, intelligent packaging technologies—including time–temperature indicators, gas sensors, colorimetric indicators, and RFID-based systems—provide real-time information on freshness, spoilage, and handling conditions, addressing key limitations of conventional MAP and VP formats (Khodaei *et al.*, 2023). These innovations respond directly to growing consumer demand for transparency, safety assurance, and trust in food quality information (Spada *et al.*, 2024).

Sustainability considerations have further shaped packaging innovation, driving the adoption of biodegradable materials, renewable biopolymers, and life cycle–informed design strategies (Lisboa *et al.*, 2024). Beyond material innovation, the integration of intelligent packaging with emerging digital technologies—such as biosensors, digital indicators, the Internet of Things (IoT), and decentralized data systems like blockchain—offers a transformative approach to monitoring and tracking meat products from farm to fork. These technologies enable secure, transparent, immutable, and tamper-proof data exchange across the supply chain, significantly enhancing traceability and accountability (Rahman, Sobhan and Sadak, 2026).

Concerns related to food safety and fraudulent practices remain major obstacles for the meat industry, as they directly affect consumer confidence and purchasing decisions (Tang, 2025). Traditional traceability systems, often based on paper records or fragmented digital platforms, are increasingly inadequate due to poor interoperability, limited transparency, and delayed response capabilities (Vasileiou *et al.*, 2025). Consequently, there is a growing global trend toward adopting integrated, secure, and transparent digital tracking systems that can effectively manage information flow across the meat supply chain and support timely interventions to prevent spoilage and fraud (Caccialanza, Cerrato and Galli, 2023), all of which improve the safety and security of products and consumer trust.

This chapter provides a comprehensive overview of recent advances in meat packaging technologies aimed at enhancing product quality, safety, shelf life, and sustainability in response to the growing global demand for meat and increasing concerns related to foodborne illnesses, spoilage, and fraud. By addressing these objectives, the chapter positions modern meat packaging as a multifunctional interface that integrates material innovation, microbial control, digital monitoring, and sustainable practices to support safer, higher-quality, and more transparent meat supply chains.

22.2 Advanced and Emerging Meat Packaging Systems

22.2.1 Modified Atmosphere and VP

MAP and VP are widely recognized as essential meat preservation strategies because they actively control the gaseous or pressure environment surrounding the product to slow spoilage processes and maintain desirable quality attributes. Their effectiveness stems from the manipulation of O_2, CO_2, and nitrogen (N_2) concentrations, or from the complete removal of air, to influence microbial growth, oxidative stability, and the progression of postmortem biochemical changes (Kandeepan and Tahseen, 2022).

22.2.1.1 Physicochemical Effects on Meat Quality

The physicochemical behavior of meat during storage is strongly shaped by MAP and VP, which influence oxidation pathways, pigment dynamics, water-holding capacity, microbial ecology, and textural development. These processes are regulated by the interaction between muscle biochemistry and the

conditions imposed by MAP and VP environments, and understanding these mechanisms is essential for optimizing shelf life and ensuring product quality in commercial settings. For instance, a central quality determinant in fresh red meat is color, governed largely by the redox state of myoglobin. High-O_2 MPA, commonly containing 60–80% O_2, enhances the formation of oxymyoglobin and creates the bright-red color preferred by consumers. McMillin (2017) noted that high-O_2 MAP systems consistently exhibit faster oxidative degradation compared to VP, resulting in shorter color life despite strong initial visual impact. Several experimental studies demonstrate this oxidation dynamic in practice. Łopacka, Półtorak, and Wierzbicka (2016) found that beef stored under high-O_2 MAP showed significantly higher TBARS values and faster metmyoglobin formation compared with VSP and low-O_2 MAP, confirming the oxidative liability of O_2-rich environments. These observations highlight the inherent trade-off between maintaining a desirable red color and minimizing oxidative deterioration. In contrast, VP elicits physicochemical responses conducive to lipid stability and prevention of pigment oxidation. Protection against oxidative processes has been observed in VP beef and lamb, where lipid stability is enhanced and discoloration is minimized across extended storage periods (Ząbek *et al.*, 2021). Furthermore, the interaction between packaging atmosphere and display conditions adds complexity. Wagoner *et al.* (2022) demonstrated that previously frozen beef packaged under VP displayed under simulated retail conditions maintained acceptable redness and minimal purge when low-OTR films were used, emphasizing the importance of film selection in protecting the physicochemical integrity of beef. Illumination conditions and temperature further affect pigment stability and lipid oxidation, suggesting that packaging atmosphere must be understood within the context of the entire cold-chain environment.

Protein stability and tenderness are also strongly influenced by MAP and VP. Zhao *et al.* (2022) demonstrated that early postmortem VP enhances calpain-mediated proteolysis, improves tenderness, and reduces purge, likely because vacuum conditions support a more favorable biochemical environment for endogenous enzymes to function efficiently during aging. These findings indicate that packaging can modulate proteolytic pathways and texture development, linking physical preservation strategies directly to postmortem muscle chemistry. Beyond tenderness regulation, MAP and VP also exert measurable effects on protein oxidation, structural integrity, and water–protein interactions, which collectively determine texture, juiciness, and overall mouthfeel. For example, electromagnetic field–assisted MAP substantially limited protein oxidation in chilled pork, maintaining higher α-helix and β-sheet proportions and reducing random coil formation—an indication that myofibrillar proteins retained their native conformation under combined electromagnetic field and modified atmosphere conditions (Chen *et al.*, 2025). This treatment also preserved water-holding capacity by restricting water mobility within the protein matrix, demonstrating that packaging can directly stabilize protein–water interactions, thereby slowing structural degradation. Similarly, studies on MAP pork patties showed that elevated CO_2 concentrations (40–60%) influenced endogenous antioxidant enzyme systems, where excessive CO_2 reduced activities of superoxide dismutase and glutathione peroxidase, indirectly promoting protein and lipid oxidative reactions when CO_2 exceeded optimal thresholds (Liang *et al.*, 2024). This highlights that gas composition not only affects microbial ecology and color but also modulates oxidative stability of muscle proteins. In VP and irradiated pork, irradiation alone accelerated protein oxidation, reflected by increased carbonyl formation and decreased sulfhydryl groups, whereas adding antioxidants such as tea polyphenols, grape seed extract, or date seed extract effectively mitigated these protein-damaging effects (Chen *et al.*, 2023). These results emphasized that VP can protect proteins from aerobic oxidative mechanisms, but when combined with high-energy processing, protein integrity requires biochemical reinforcement.

Water-holding capacity and purge formation present additional physicochemical challenges in meat storage. High-CO_2 MAP can increase drip loss by altering muscle protein interactions and lowering intracellular pH. Ząbek *et al.* (2021) observed greater drip accumulation in lamb under MAP (80% N_2/20% CO_2) compared with VP, demonstrating the impact of CO_2 solubility and muscle fluid dynamics under MAP. Conversely, VP significantly reduces purge by forming a conforming film around the product, which stabilizes muscle structure and minimizes fluid migration. Table 22.1 provides a summary of the effects of MAP and VP systems on the physicochemical properties of meat and its quality and outlines gas compositions, key quality indicators, major physicochemical outcomes, and recommended packaging conditions that optimize color stability, oxidative resistance, water retention, and overall quality during storage.

TABLE 22.1

A Summary of Physicochemical Effects of MAP and VP on Meat Quality

Food Type and Packaging System	Gas Composition/ Packaging Variant	Key Physicochemical Indicators	Condensed Scientific Outcomes	Interpretation/ Recommendation	Reference
Goat meat—MAP and VP	CO_2-MAP (30/70), O_2-MAP (70/30), CO-MAP (0.4 CO/30 CO_2/ 69.6 N_2), VP	pH, color (a^*), TBARS, TVB-N, cooking loss	CO-MAP produced highest redness, lowest oxidation, and TVB-N O_2-MAP increased oxidation VP showed elevated TVB-N	CO-MAP yields the best physicochemical stability up to ~14 days O_2-MAP and VP less suitable beyond short storage	Zhang *et al.*, 2025
Beef steaks—MAP	20%, 50%, 80% O_2	Color stability, myoglobin forms, TBARS	High O_2 accelerated lipid oxidation during display Long superchill weakened color regardless of O_2 level	For extended storage, avoid very high O_2 Moderate O_2 preferable to delay oxidation	Yang *et al.*, 2024
Beef steaks—MAP	MAP70, MAP50, MAP30	Color (a^*, chroma), lipid and protein oxidation	Lower O_2 (30%) minimized oxidation without major color loss when initial hygiene was good 50% O_2 preserved color better than 30% in less ideal conditions	O_2 optimization should match raw material quality ~50% O_2 offers balanced color and oxidative control	Feng *et al.*, 2025
Marinated pork chops—MAP	Hi-O_2 (70/20/10), High-CO_2 (80/20)	Carbonyls, TBARS, TVB-N	High-CO_2 MAP and superchill (–2 °C) markedly reduced oxidation and nitrogenous spoilage indicators	High-CO_2 MAP with superchilling is superior for oxidative and physicochemical stability	Shi *et al.*, 2025
Pork longissimus—MAP	M40 (40/60) versus M80 (80/20)	Color, pH, shear force, TBARS	M40 lowered oxidation and maintained pH with extended stability M80 enhanced redness but deteriorated faster	M40 recommended where oxidative preservation outweighs extreme redness	Wang *et al.*, 2025
Lamb loin and topside—MAP	0–80% O_2	Redness (a^*), MDA	Redness maintained even at moderate O_2 (40%) Oxidation remained low across treatments	Reducing O_2 to ~40% maintains color while minimizing oxidative stress	Corlett *et al.*, 2024
Analogue meats—MAP	Not fully specified (O_2 and CO_2 varied)	TBARS, FFA, antioxidant indices	Mince had strongest oxidative stability Filet showed highest oxidation and lowest antioxidant capacity	Product formulation strongly dictates oxidative sensitivity MAP must be tailored by matrix type	Abdullah, Dordevic and Kabourkova, 2024
Goat meat—MAP	Hi-O_2 with 20–40% CO_2	TVB-N, TBARS, shear force	Higher CO_2 (40%) minimized oxidation and improved texture but reduced redness	CO_2-rich MAP (~40%) best suppresses physicochemical deterioration, at the cost of color	Sai-Ut *et al.*, 2025

(Continued)

TABLE 22.1 ***(Continued)***

A Summary of Physicochemical Effects of MAP and VP on Meat Quality

Food Type and Packaging System	**Gas Composition/ Packaging Variant**	**Key Physicochemical Indicators**	**Condensed Scientific Outcomes**	**Interpretation/ Recommendation**	**Reference**
Beef steaks—MAP (smart indicators)	Not specified	Surface color, ΔE	ΔE changes reflected chemical shifts in the package headspace linked to quality decline	MAP supports colorimetric monitoring of chemical freshness indicators	Bhadury *et al.*, 2024
Pork—MAP and EMF	MAP, EMF, EMF-MAP	pH, TBARS, WHC, protein oxidation	EMF-MAP best preserved pH, minimized oxidation, and maintained WHC and protein structure	EMF enhances MAP performance for oxidative and structural stability	Chen *et al.*, 2025
Pork ham—MAP and VP	80/20, 70/30, 60/40, 50/50, VP/ VPS	Drip loss, pH, color, TBARS	High O_2 increased oxidation VP/VPS maintained drip and color but not ideal for long storage 60/40 balanced attributes best	MAP60/40 offers optimal physicochemical retention over 28 days	Chmiel *et al.*, 2025
Pork patties—MAP	80/20 40/20/40 40/40/20 40/60	pH, color, TBARS, FA profile	Lowering O_2 reduced oxidation; raising CO_2 improved stability until >40%, where oxidation increased	*Optimal mix*: 40% O_2/40% CO_2/20% N_2 for balanced oxidative and color stability	Liang *et al.*, 2024
Pork loin slices—MAP	55/40/5 versus 75/20/5	Color, pH, WHC	Gas ratio had minimal effect on pH and WHC Moderate O_2 (55%) maintained quality	Lower O_2 reduces O_2 demand without compromising quality	Zduńczyk, Modzelewska-Kapituła and Tkacz, 2024
Cooked low-salt pork belly—VP	VP at 4 °C and 25 °C	pH, TVB-N, TBARS	Higher temperature, accelerated oxidation, and nitrogenous spoilage markers	VP effective only if low temperature strictly maintained	Bassey *et al.*, 2022
Deer meat—VP	VP	Color, sensory quality	Rapid sensory and color decline after about three weeks linked to biochemical deterioration	VP deer not suitable for long chilled storage Freeze for stability	Sauvala *et al.*, 2023
Beef—VP with antioxidants	VP + Linalool/ eugenol	TBARS, texture, color	Essential oils reduce oxidation without negative effects on texture or color	Natural antioxidants under VP are effective against oxidative degradation	Bilen *et al.*, 2024
Chicken breast—MAP, VP, HPP, MVH, SGS	MAP (40/60), VP, SGS, HPP, MVH combinations	Color, texture, pH, drip loss, lipid oxidation	Physicochemical traits generally stable HPP and SGS minimized initial oxidation	Advanced technologies (HPP/SGS) enhance stability beyond MAP/ VP alone	Dang, Rode and Skipnes, 2021

(Continued)

TABLE 22.1 ***(Continued)***

A Summary of Physicochemical Effects of MAP and VP on Meat Quality

Food Type and Packaging System	Gas Composition/ Packaging Variant	Key Physicochemical Indicators	Condensed Scientific Outcomes	Interpretation/ Recommendation	Reference
Pork—VP + irradiation and antioxidants	VP + e-beam ± TP/GSE/DSE	TBARS, carbonyls, sulfhydryls	Irradiation alone increased oxidation Antioxidants mitigated these effects	Use antioxidants when applying irradiation to avoid oxidative damage	Chen *et al.*, 2023
Beef—AP versus VP with olive oil	AP, VP ± EVOO	WHC, TBARS, cooking loss	EVOO improved oxidative stability and WHC, especially under VP	EVOO acts as natural antioxidant enhancing VP performance	Hashem *et al.*, 2023
Cooked sausages—VP	VP	pH, syneresis	Higher temperature caused faster physicochemical decline	Physicochemical stability is highly temperature-dependent under VP	Lemos Junior *et al.*, 2024
Beef steaks—VRF versus PVC	VRF (vacuum-like), PVC (aerobic)	Color (L^*, a^*, browning), TBARS	VRF maintained redness and lower oxidation compared to PVC	VRF superior for color preservation over aerobic films	Reyes *et al.*, 2022
Ground beef—thermoformed VP	VP (T1, T2, T3 films)	Color indices, TBARS	Film properties influenced color, but oxidation remained controlled during display	High-barrier VP films enhance color stability during mixed frozen/chilled storage	Bernardez-Morales *et al.*, 2024
Mianning ham—VP and MAP	VP; MAP with CO_2	Color, Aw, volatiles	VP maintained redness MAP stabilized Aw and altered volatiles	VP for color retention; MAP for moisture and compositional stability	Chen *et al.*, 2025
Beef—VP versus VPAM	VP, VPAM	Color, TBARS, thiols	Minor differences in oxidation Color is slightly better under chilled VP than frozen-thawed cycles	Both systems preserve oxidative quality over long storage	Luzardo *et al.*, 2024
Semi-finished pork—VP	VP versus traditional	pH	pH shifts remained within acceptable range	VP maintains physicochemical acceptability for about eight days	Nikulina *et al.*, 2021
Chicken breast—VP/AP + EVOO	AP/VP ± EVOO	pH, WHC, TBARS	EVOO + VP gave best oxidative and water-retention profile	Combining VP with EVOO yields superior physicochemical stability	Hashem *et al.*, 2023
Pork—VAP (TiO_2 film), VP, AP	VP, VAP, AP	pH, TVB-N, WHC, redness	VAP improved color (a^*) and slowed chemical spoilage indicators	TiO_2 antimicrobial films enhance vacuum physicochemical performance	Chai *et al.*, 2024

Abbreviations: a^*, redness coordinate; AP, aerobic packaging; b^*, yellowness coordinate; CO, carbon monoxide; CO_2, carbon dioxide; CO-MAP, carbon monoxide modified atmosphere packaging; DMB, deoxymyoglobin; DSE, date seed extract; ΔE, total color difference; EVOO, extra virgin olive oil; FFA, free fatty acids; GSE, grape seed extract; HPP, high-pressure processing; L^*, lightness; MAP, modified atmosphere packaging; MDA, malondialdehyde; MET, metmyoglobin; MVH, microwave volumetric heating; N_2, nitrogen; O_2, oxygen; OMB, oxymyoglobin; RI, redness index; SGS, soluble-gas stabilization; TBARS, thiobarbituric acid reactive substances; TiO_2, titanium dioxide; TP, tea polyphenols; TVB-N, total volatile basic nitrogen; VOCs, volatile organic compounds; VP, vacuum packaging; VRF, vacuum-ready film; VSP/VPS, vacuum skin packaging; WHC, water-holding capacity.

22.2.1.2 Microbial Dynamics and Shelf Life Outcomes

Microbial dynamics play a central role in determining meat shelf life, sensory quality, and safety, and both MAP and VP exert substantial influence on the succession, activity, and metabolic behavior of spoilage and pathogenic microorganisms. The microbiological trajectory of meat during storage is shaped by O_2 availability, CO_2 concentration, temperature, pH changes, water activity, and the endogenous biochemical environment that evolves postmortem. MAP and VP modulate these factors in distinct ways, suppressing or delaying microbial growth through environmental manipulation rather than chemical preservatives. Table 22.2 presents an overview of the microbiological responses of meat to MAP and VP systems and highlights gas compositions, targeted spoilage microorganisms, storage conditions, microbial outcomes, and inhibition mechanisms contributing to shelf-life extension and microbial quality control.

CO_2 is the principal antimicrobial agent in MAP systems. Higher CO_2 concentrations inhibit aerobic spoilage organisms by reducing intracellular pH and interfering with enzymatic activity, thereby slowing bacterial metabolism and multiplication. Kandeepan and Tahseen (2022) explained that CO_2 dissolves into muscle tissues and bacterial cytoplasm, creating an inhibitory environment that extends shelf life by suppressing organisms such as *Pseudomonas* spp. and other psychrotrophic aerobes. This phenomenon is especially relevant for chill-stored meat, where psychrotrophic aerobic bacteria dominate spoilage pathways under aerobic conditions. CO_2-rich MAP mixtures therefore shift the microbial ecology toward slower-growing species, delaying surface slime formation, discoloration, and off-odor development. Experimental observations reinforce this antimicrobial performance. Ząbek *et al.* (2021) showed that lamb packaged in MAP containing 20% CO_2 exhibited significantly lower aerobic plate counts throughout 30 days of storage at 4 °C compared with VP samples. The inhibitory effect of CO_2 was particularly evident during the mid-to-late stages of storage, when microbial growth typically accelerates. Likewise, a study by Maqsood, Al Haddad and Mudgil (2016) on camel meat reported slower bacterial proliferation under VP and MAP conditions than under aerobic packaging, demonstrating that O_2 removal or reduction is an effective strategy for controlling early-stage spoilage organisms. These findings underline the importance of atmosphere composition in shaping meat's microbiological stability during refrigerated storage.

VP exerts its antimicrobial effects primarily through O_2 removal rather than gas substitution. By creating an anaerobic environment, VP inhibits obligate aerobic spoilage organisms such as *Pseudomonas* spp., which are dominant contributors to off-odors and slime formation in aerobically stored meat. Narasimha Rao and Sachindra (2002) highlighted that VP shifts the microbial community toward facultative anaerobes, including lactic acid bacteria (LAB), which grow more slowly and produce milder spoilage characteristics compared to aerobic organisms. LAB-dominated spoilage typically results in sour notes rather than putrid odors and is often considered less objectionable from a sensory perspective. Several studies demonstrate this microbial succession. Ząbek *et al.* (2021) observed that LAB increasingly dominated the microbial profile of VP lamb during extended storage, correlating with reduced surface discoloration and slower onset of rancid aromas relative to MAP samples with higher O_2 permeability.

22.2.2 Active and Intelligent Packaging

Recently, the demand for food-packaging materials has risen sharply, with particular interest in multifunctional materials that are edible, biodegradable, and exhibit excellent mechanical strength and barrier performance. Such properties are vital in the food industry, as they enhance shelf life by minimizing oxidation–reduction processes and reducing microbial interactions (Mercanti *et al.*, 2024). Active packaging systems utilize antimicrobials (such as chitosan, essential oils, and polyphenols), oxygen scavengers (including iron-based and enzymatic types), and moisture absorbers to modify the internal environment of the package (Table 22.3). These systems inhibit microbial growth and oxidative deterioration, thereby enhancing the shelf life of meat during refrigeration. Intelligent packaging employs pH-responsive colorimetric markers, such as bromothymol blue, phenol red, and anthocyanins, which undergo irreversible color changes indicating the transition from fresh to spoiled conditions. These markers correspond to microbial proliferation, volatile amine production, and sensory rejection thresholds.

TABLE 22.2

Microbiological Responses of Meat to MAP and VP Systems

Packaging System	Food Type	Used Gases and Concentration (%)	Spoilage Agents Targeted (Microorganisms)	Time (Days) and Temperature (°C)	Microbiological Outcomes	Mode of Action	Reference
MAP (0–80% O_2) after vacuum aging	Lamb loins and topside	0, 20, 40, 60, 80 O_2	General spoilage flora (counts below threshold)	Display 2–10 days	All O_2 levels kept bacterial counts below spoilage threshold Reducing O_2 to 40% did not worsen microbial status	CO_2 from muscle metabolism + partial O_2 reduction limits aerobic growth	Corlett *et al.*, 2024
MAP (20–80% O_2)	Beef steaks	20, 50, 80 O_2 (balance not specified)	General spoilage flora (TVC, TVB-N indicators)	Superchill −1 °C (≤121 days) + 0–10 days display	Regardless of O_2 level, microbial shelf life ≈3 days after display High O_2 did not improve microbial stability	Cold superchill limits microbial growth O_2 mainly affects oxidation, not microbial suppression	Yang *et al.*, 2024
MAP (40 O_2/60 CO_2 versus 80 O_2/20 CO_2)	Pork longissimus	40/60 80/20	TVC, general spoilage flora	14 days 4 °C	M40 (higher CO_2) → Lower TVC, extended shelf-life by ~3 days versus M80	High CO_2 inhibits aerobic bacteria O_2 supports oxidative stress that accelerates spoilage	Wang *et al.*, 2025
MAP (40–80% CO_2 variants)	Pork patties	80/20 40/20/40 40/40/20 40/60	TVC, TVB-N	16 days 4 °C	Increasing CO_2 from 20→40→60% suppressed microbial growth 40% CO_2 optimal (≥60% increased oxidation)	CO_2 acidifies environment and reduces aerobic metabolism; N_2 stabilizes package headspace	Liang *et al.*, 2024
MAP (70, 50, 30% O_2 combinations)	Beef steaks	70/30 50/30/20 30/30/40 (O_2/CO_2/N_2)	*Serratia*, *Brochothrix*, general aerobic flora	20 days; chilled	Microbial community similar across MAP variants End-stage dominated by *Serratia* and *Brochothrix* regardless of O_2 level	CO_2 partially suppresses aerobes; O_2 variations mainly affect oxidation/color rather than bacterial growth	Feng *et al.*, 2025
MAP (CO_2-MAP, O_2-MAP, CO-MAP) and vacuum	Goat meat	30 CO_2/70 N_2 70 O_2/30 CO_2 0.4 CO/30 CO_2/69.6 N_2 VP (no gas)	APC, *Pseudomonas*, *Shewanella*, *Serratia*, *Lactococcus*	Up to 28 days Chilled	VP → Highest APC O_2-MAP → Oxidized and high spoilage CO_2-MAP suppressed spoilage moderately CO-MAP → Lowest APC, best inhibition of spoilage bacteria	High CO_2 suppresses aerobic spoilage flora; CO binds myoglobin, stabilizes color and indirectly reduces oxidation-related microbial proliferation	Zhang *et al.*, 2025

MAP (Hi-O_2 versus high CO_2)	Marinated pork chops	70 O_2/20 CO_2/10 N_2 80 CO_2/20 N_2	Psychrotrophs, general spoilage flora	14 days at 4 °C; 56 days at −2 °C	High CO_2 significantly reduced bacterial counts Superchill (−2 °C) greatly extended microbial stability versus 4 °C	High CO_2 lowers pH and increases dissolved carbonic acid → Suppressing microbial metabolism	Shi *et al.*, 2025
MAP (Hi-O_2 with 20–40% CO_2)	Goat meat	M20, M30, M40 (20–40 CO_2 + High O_2)	TVC, TVB-N-related spoilage flora	12 days 4 °C	Increasing CO_2 → Reduced TVC M40 achieved strongest inhibition Color decreased at high CO_2	CO_2 reduces water activity and cell membrane integrity; metabolic shift toward carbohydrate fermentation	Sai-Ut *et al.*, 2025
MAP + EMF and vacuum	Pork	MAP (gas not specified), EMF, EMF-MAP	TVC, spoilage flora	14 days 4 °C	EMF-MAP showed lowest TVC and inhibited microbial growth more than MAP alone	EMF disrupts cell membranes and metabolic pathways; combined with MAP strengthens inhibition	Chen *et al.*, 2025
MAP and vacuum (VP, VPS)	Pork ham slices	80/20, 70/30, 60/40, 50/50 (O_2/CO_2) VPS/VP (no gas)	Psychrotrophs, LAB, general spoilage bacteria	28 days; 0–4 °C	VP/VPS → higher psychrotrophs and LAB → Shorter microbial shelf life MAP60/40 best microbial performance	High CO_2 suppresses aerobes; O_2 too high (80%) promotes oxidation and indirect spoilage	Chmiel *et al.*, 2025
MAP with colorimetric indicators	Beef steaks	Not specified	Microbial spoilage (TVC linked to pH change)	7 days; 4 °C and 20 °C	Large ΔE color change (>12) corresponded to microbial spoilage levels → Indicator accurately reflected microbial growth	Indicator detects volatile acids and pH decrease produced by microbial metabolism	Bhadury *et al.*, 2024
Vacuum	Semifinished pork	VP (PA/PE bags)	Mesophilic aerobic bacteria	8 days; 4 ±2 °C	VP had lower microbial counts and remained within sanitary limits for 8 days	O_2 exclusion reduces aerobic spoilage Film barrier slows contamination	Nikulina *et al.*, 2021
Vacuum	Ground mutton + spices	VP with curcumin and black pepper	Spoilage bacteria and pathogens (unspecified)	21 days; 4 °C	Blend of curcumin + Black pepper → Strong reduction of spoilage and pathogens Product acceptable for 21 days versus 7 days control	Curcumin + piperine destabilize cell membranes; vacuum slows aerobic spoilage	Elghareeb *et al.*, 2025

(Continued)

TABLE 22.2 ***(Continued)***

Microbiological Responses of Meat to MAP and VP Systems

Packaging System	Food Type	Used Gases and Concentration (%)	Spoilage Agents Targeted (Microorganisms)	Time (Days) and Temperature (°C)	Microbiological Outcomes	Mode of Action	Reference
Vacuum (VP and VPAM)	Beef striploins	VP versus VPAM	*Pseudomonas*, Enterobacteriaceae, LAB	120 days refrigeration or 28 + 92 days chilled→frozen	VPAM had higher spoilage Gram-negatives LAB dominated VP No visible deterioration despite microbial changes	Low-O_2 favors LAB; antimicrobial surface did not significantly suppress Gram-negatives	Rovira *et al.*, 2023
Vacuum and aerial with EVOO	Chicken breast	No gases (AP versus VP)	TVC, general spoilage flora	15 days Refrigerated	EVOO + VP → Lowest TVC EVOO alone inhibited microbes moderately under AP	Phenolics in EVOO disrupt cell membranes; vacuum reduces O_2 needed for aerobic spoilage	Hashem *et al.*, 2023
Vacuum and VAP (TiO_2 antimicrobial)	Pork	VP VAP (TiO_2) AP	TVC and spoilage-related biochemical indices	12 days Chilled	VAP had lowest TVC, outperforming VP and AP	TiO_2 generates ROS disrupting bacterial membranes; vacuum removes O_2 to prevent aerobes	Chai *et al.*, 2024
Vacuum and VPAM	Beef	Vacuum; vacuum with antimicrobial	*Pseudomonas*, Enterobacteriaceae, LAB	120 days (chilled) or 28 + 92 days (chilled→frozen)	VPAM had higher *Pseudomonas* and Enterobacteriaceae LAB-dominated VP Freezing stabilized flora	Vacuum favors LAB; antimicrobials did not fully suppress Gram-negatives; low-O_2 limits aerobes	Luzardo *et al.*, 2024

Abbreviations: AP, aerobic packaging; APC, aerobic plate count; CO, carbon monoxide; CO_2, carbon dioxide; ΔE, total color difference; EO(s), essential oil(s); EVOO, extra virgin olive oil; LAB, lactic acid bacteria; MAB, mesophilic aerobic bacteria; MAP, modified atmosphere packaging; N_2, nitrogen; O_2, oxygen; TVB-N, total volatile basic nitrogen; TVC, total viable count; VAP, vacuum antibacterial packaging; VP, vacuum packaging; VPAM, vacuum packaging with antimicrobial material; VPS/VSP, vacuum skin packaging.

TABLE 22.3

Performance of Packaging Systems for Meat Shelf-Life Extension at Chilled Storage

Packaging Type	Packaging System	Meat Type	Storage Temperature (°C)	Shelf Life (Days)	Log CFU/g Reduction	pH Range	TVB-N (mg/100 g)	Primary Mechanism	Reference
Conventional	Aerobic control	Beef tenderloin	4 ± 1	6	*TPC*: 6.49 (day 6) → 8.30 (day 12) log CFU/g	5.88 → 8.93	11.21 (day 6) → 32.22 (day 12)	Uncontrolled psychrotrophic bacterial growth	Dirpan, Djalal and Ainani, 2022
	Aerobic control	Fresh beef	5	~6	TVC reduction minimal TVC reaches spoilage	5.7	>20	Psychrotrophic and mesophilic bacterial dominance	Komodromos *et al.*, 2024
Active	Garlic extract active paper (15% w/w)	Beef tenderloin	4 ± 1	12	TPC 6.35 log CFU/g (day 12) Reduction versus control: ~2.0 logs	6.08 (day 12)	22.32 (day 12)	Allicin antimicrobial; inhibits RNA/DNA/protein synthesis	Dirpan, Djalal and Ainani, 2022
	Garlic extract active paper (20% w/w)	Beef tenderloin	4 ± 1	12	TPC 6.09 log CFU/g (day 12) *Reduction versus control*: ~2.2 logs	5.83 (day 12)	21.66 (day 12)	Allicin antimicrobial; higher concentration slightly more effective	Dirpan, Djalal and Ainani, 2022
	Chitosan coating (0.1% w/w)	Fresh beef	5	10	*TVC reduction*: 4.09 log CFU/g (day 4) Maintains <7 log through day 10	5.45 (day 4, 10)	<20 (day 4, 10)	Electrostatic interaction with bacterial cell walls; antioxidant activity	Komodromos *et al.*, 2024
	Chitosan + AgIon absorbent pad (0.1% chitosan)	Fresh beef	5	10	TVC reduction: 3.53 log CFU/g (day 4) Maintains <7 log through day 10	5.45 (day 4, 10)	<20 (day 4, 10)	Chitosan antimicrobial dominates AgIon shows minimal activity on beef	Komodromos *et al.*, 2024
	Gelatin-chitosan-glycerol + Chlorogenic acid	Fresh beef	4	12	TVC 6.0 log CFU/g (day 12) versus control 6–7 logs at day 12 Shelf-life extension + Three to six days	5.8–6.2 (maintained)	Delayed increase versus control	Chlorogenic acid polyphenol + Chitosan synergy Antioxidant effect	Zou *et al.*, 2022

(Continued)

TABLE 22.3 ***(Continued)***

Performance of Packaging Systems for Meat Shelf-Life Extension at Chilled Storage

Packaging Type	Packaging System	Meat Type	Storage Temperature (°C)	Shelf Life (Days)	Log CFU/g Reduction	pH Range	TVB-N (mg/100 g)	Primary Mechanism	Reference
	Gelatin-chitosan-glycerol + Gallic acid	Fresh beef	4	12	TVC 6.0 log CFU/g (day 12) with lowest TBARS (0.76 mg MDA/kg) Shelf-life extension + Three to six days	5.8–6.2 (maintained)	Delayed increase versus control	Gallic acid antimicrobial + Antioxidant Superior to other polyphenols tested	Zou *et al.*, 2022
	Gelatin-chitosan-glycerol + Resveratrol	Fresh beef	4	12	TVC reduction observed Less effective than CA/GA but still improved Shelf-life extension + Three to six days	6.25 (day 12, higher than CA/GA)	Lower than control	Resveratrol antioxidant polyphenol Least effective of three tested	Zou *et al.*, 2022
	Chitosan + Gallic acid coating (2% chitosan)	Jeju black cattle beef	4	21	Spoilage bacteria count reduced Maintains <7 log CFU/g through day 21	5.9–6.2 (maintained throughout)	<20 through day 21	Chitosan + Gallic acid covalent interactions; antioxidant and antimicrobial dual function	de Lima *et al.*, 2024
	Chitosan + Rosemary extract (4%)	Fresh beef	4	14–18	Mesophilic and psychrotrophic bacteria: decreased *Staphylococcus*: decreased	Maintained low	<20 (extended)	Rosemary polyphenol volatile compounds + chitosan film matrix	de Lima *et al.*, 2024
	Chitosan + Rosemary extract (8%)	Fresh beef	4	14–18	Mesophilic and psychrotrophic bacteria: decreased more than 4%	Maintained low	<20 (extended)	Enhanced antimicrobial activity at higher rosemary concentration	de Lima *et al.*, 2024
	Chitosan + Nanoencapsulated *Satureja montana* EO (1% CNPs)	Fresh beef	4	18–20	*TVC reduction*: 2.4 log CFU/g versus control *Pseudomonas reduction*: 3 log CFU/g versus control	Maintained low	Extended preservation	*Satureja montana* volatile compounds in nanoparticles + Chitosan synergy Improved sensory profile	Đorđević *et al.*, 2022

	Whey protein + *Trachyspermum copticum* EO (pickering emulsion)	Fresh beef	4 ± 1	18	*TVC*: 6.8 (control 8.2) *TPC*: 6.7 (control 8.5) *LAB*: 6.5 (control 7.7) log CFU/g	6.3 (control 7.5)	25.1 (control 39.4)	Essential oil in pickering emulsion (whey protein stabilized) provides sustained release and antimicrobial activity	Saghari *et al.*, 2024
Intelligent	Bromothymol blue + Phenol red indicator (pH 5.0)	Beef tenderloin	4 ± 1	Early detection (2–6 hours response)	Nonantimicrobial Monitoring tool only	6.0 (dark yellow) → 6.5–7.0 (reddish-yellow) → >7.5 (faded red)	Correlates with TVB-N elevation	pH-responsive synthetic indicator dyes Linear correlation with TPC, pH, TVB-N	Dirpan, Djalal and Ainani, 2022
Active + intelligent	Garlic extract (15%) + BTB+PR indicator	Beef tenderloin	4 ± 1	12	TPC 6.35 log CFU/g (day 12) Indicator color changes parallel all spoilage metrics	6.08, color change tracks pH	22.32 (day 12), color reflects elevation	Active antimicrobial (garlic) + Intelligent monitoring (indicator) integrated system; six-day extension versus control	Dirpan, Djalal and Ainani, 2022

These complementary methods effectively address microbiological, oxidative, and hydrolytic deterioration processes, providing superior preservation control and nondestructive quality verification compared to passive MAP.

22.2.2.1 Oxygen Scavenging and Antimicrobial Systems

Antimicrobial packaging systems are a significant advancement in meat preservation, employing various biochemical mechanisms to target spoilage and pathogenic microorganisms. Essential oils, rich in volatile phenolic compounds, are intensively studied as natural antimicrobials (Bibow and Oleszek, 2024). Oregano and thyme essential oils contain 30–90% carvacrol and thymol, depending on the chemotype (Flouchi *et al*., 2024). These chemicals cause damage to bacterial cell membranes. These volatile phenolics reduce *Pseudomonas* spp., and Enterobacteriaceae by 1.2–4.8 log CFU/g in packing formulations at 1–2% concentrations, with improved efficacy at higher temperatures (Posgay *et al*., 2022).

Chitosan, a biopolymer derived from crustacean chitin, serves as an alternative antimicrobial agent influenced by its molecular weight and degree of deacetylation (Chicea and Nicolae-Maranciuc, 2024). A high molecular weight (>50 kDa) and high deacetylation (>80%) of chitosan enhances electrostatic interactions with bacterial cell walls, resulting in 1–2 log reductions in aerobic mesophilic bacteria and up to 87% biofilm suppression (Gomes *et al*., 2021). Protein-derived antimicrobials such as lactoferrin and its peptides (lactoferricin and lactoferrampin) sequester iron and interact with membranes (Gruden and Poklar Ulrih, 2021). Lactoferrin demonstrates bacteriostatic activity through iron chelation and possesses bactericidal properties; lactoferricin has shown effectiveness against *Listeria monocytogenes* in packaged ham, particularly against Gram-positive pathogens (Gruden and Poklar Ulrih, 2021). Through free radical formation and cell membrane disruption, polyphenolic substances such as catechins from green tea, gallic acid, and anthocyanins from fruit waste are antibacterial (Li, Sun and Weng, 2024). Catechin concentrations above 0.15 mg/mL inhibit *Staphylococcus aureus* with approximately 80% DPPH radical quenching capacity, avoiding microbial deterioration and lipid oxidation (Westlake *et al*., 2023).

Oxygen-scavenging methods target aerobic respiration pathways that support spoilage organisms and oxidative degradation, complementing antimicrobials. Commercial iron-based oxygen scavengers use moisture-activated ferrous iron oxidation chemistry to reduce atmospheric oxygen from 20.9% to 0.1% in 24–48 hours (Cichello, 2015). These methods suppress aerobic psychrotrophic bacteria, mainly *Pseudomonas* spp., which cause refrigerator spoiling. Iron-based scavengers in chilled beef storage extend shelf life from 6–8 days under conventional MAP to 21–28 days while preserving anaerobic conditions that restrict pathogen growth (Cichello, 2015). Moisture dependence limits systems to activation at 10–15% relative humidity, requiring proper packaging design and cold-chain integrity (Cichello, 2015). Enzymatic oxygen-scavenging systems like laccase and glucose oxidase remove metal residues and produce only water from cofactor oxidation, making them environmentally beneficial. While renewable and biocompatible, enzymatic methods remove oxygen slower and have cost obstacles that limit commercial application (Winestrand, Järnström and Jönsson, 2021). Recently developed bio-based oxygen scavengers use gallic acid-sodium carbonate systems, plant-derived oils encapsulated in silica nanoparticles, and lignin derivative coatings that remove oxygen sustainably (Pan *et al*., 2020).

Antimicrobial efficacy depends on release mechanisms, where uncontrolled release degrades sensory properties and insufficient release fails to meet preservation goals (Lv *et al*., 2025). The most common mechanism is direct surface migration via concentration gradient diffusion. However, careful design is needed to avoid volatile compound loss (Bibow and Oleszek, 2024). Alginate and chitosan microcapsules with essential oils or catechin release 10–30% within 4–8 hours and continue for 10–14 days, improving control (Lv *et al*., 2025). Electrospun nanofiber matrices contain antimicrobial chemicals in polymeric nanofibers (100–500 nm) with high surface-area-to-volume ratios that release for three to seven days, optimized for meat preservation (Lv *et al*., 2025). Vanillin-mediated chitosan cross-linking with green tea polyphenols creates covalent bonds that decrease migration and preserve bioactivity over 400 hours (16+ days) of sustained suppression (Westlake *et al*., 2023). Over immediate effect and persistent suppression over 10–14 days, release timelines should exceed 48 hours (Dirpan, Djalal and Ainani, 2022; Lv *et al*., 2025).

Performance metrics standardize antimicrobial and oxygen-scavenging system evaluation (Dirpan, Djalal and Ainani, 2022; Lv *et al.*, 2025). Log-reduction quantification, expressed in CFU/g, is the main efficacy parameter used to determine treatment's effect, with aims of 1.5–3.0 log reductions for total aerobic mesophilic bacteria and 2–4 log reductions for *Pseudomonas* spp. (Posgay *et al.*, 2022). Depending on concentration and target organism, essential oil systems reduce by 2–3 logs, chitosan films by 1–2 logs, lactoferrin-based systems by 1–2 logs, and polyphenol-rich extracts by 1–3 logs (Westlake *et al.*, 2023). The extension of shelf life at 4 °C until microbiological (7 log CFU/g) or chemical spoilage thresholds are reached is the most relevant metric (Cichello, 2015). Beef can be preserved for 6–8 days, 10–12 days with MAP (70% CO_2/30% N_2), 14–21 days with combined active systems, and 21–28 days with integrated systems using oxygen scavengers, antimicrobial peptides, and moisture control (Trindade *et al.*, 2013). Depletion efficiency targets are less than 2% residual oxygen by day 3 and 0.1% by day 7. Iron-based systems attain residual oxygen levels of 0.1–0.5%, while enzymatic systems reach 1–3% (Cichello, 2015). Temperature sensitivity requires verification since antibacterial activity increases 1.5–2 times with each 10 °C rise, and shelf life extension at 10 °C drops to 50–70% of values at 4 °C (Posgay *et al.*, 2022). The quantified metrics facilitate evidence-based selection of packaging designs for meat preservation under various supply chain conditions (Dirpan, Djalal and Ainani, 2022; Lv *et al.*, 2025).

22.2.2.2 Colorimetric Freshness Indicators

Colorimetric freshness indicators serve as nondestructive quality monitoring systems that visually indicate meat spoilage through color changes. These changes are caused by volatile organic compounds produced during microbial metabolism (Prasetya *et al.*, 2025). Bacteria generate spoilage-related volatile amines, including ammonia, dimethylamine, and trimethylamine, which are collectively quantified as total volatile basic nitrogen (TVB-N) (Oduse *et al.*, 2025). Amines raise the headspace pH of meat from neutral (6.0–6.5 in fresh meat) to basic (7.0–8.5 in damaged meat), providing a chemical signal observable by pH-responsive dyes (Ahmed, Bose and Roy, 2024; Prasetya *et al.*, 2025). At different pH levels, anthocyanins and synthetic dyes change hue. For example, red cabbage anthocyanins change color from purple to blue to green as pH rises, especially when TVB-N levels exceed 15–25 mg/100g, the beef spoiling threshold (Kwak and Min, 2024). Bromothymol blue and phenol red indicator combinations turn dark yellow in fresh meat (pH 6.0), reddish-yellow during marginal freshness (pH 6.5–7.0), and red at spoilage (pH > 7.5), allowing visual safety assessment without laboratory analysis (Dirpan, Djalal and Ainani, 2022).

Anthocyanins from fruit and vegetable by-products like red cabbage, black rice, purple basil, and plums are favored by consumers for their perceived safety, sustainability, and regulatory acceptance, despite variable response times (Adımcılar, Torlak and Erim, 2025; Prasetya *et al.*, 2025). Red cabbage anthocyanins change color by 20.5% in response to indicators and are highly selective for ammonia molecules. In 10–24 hours, volatile amine buildup causes color development (Karimi Alavijeh, Heli and Ajji, 2024; Shahi *et al.*, 2025). Synthetic indicators like bromothymol blue, bromocresol green, and phenol red have rapid response kinetics (2–6 hours) and improved pH specificity (6.0–7.6, 6.8–8.4), enabling earlier spoilage detection (Hidayat *et al.*, 2019; Oduse *et al.*, 2025). Compared to bromocresol purple, phenol red distinguished three freshness phases (fresh, medium fresh, and spoiled) best in pork and fish. Bromocresol green was also more sensitive to pork-rotting volatiles (Oduse *et al.*, 2025). Copigmented with gelatin and polyphenols, natural markers retain 97% color after 30 days of controlled humidity storage, unlike synthetic dyes, which deteriorate under high humidity (Gao *et al.*, 2022; Kwak and Min, 2024). Natural indicators are preferred by 75–82% of consumers due to their perceived health and environmental benefits, despite synthetic indicators' technical advantages (Singh, Kim and Lee, 2022; Zhang *et al.*, 2025).

Real-time colorimetric indicators identify spoilage 24–48 hours earlier than conventional culture-dependent methods or chemical analyses (Karimi Alavijeh, Heli and Ajji, 2024; Waimin *et al.*, 2022; Zhang *et al.*, 2025). Traditional detection approaches need 24–72 hours of laboratory culture or destructive testing that impairs package marketability. In contrast, colorimetric indicators provide rapid visual feedback while retaining product integrity (Oduse *et al.*, 2025; Waimin *et al.*, 2022). This nondestructive examination helps customers make safe choices at the moment of purchase or during home storage,

decreasing uncertainty and perhaps extending safe consumption periods by detecting abuse early (Waimin *et al*., 2022; Xu *et al*., 2025). The linear correlation between indicator color change and degradation criteria such as microbial counts, pH changes, and TVB-N shows that progressive color shifts parallel spoilage (Ahmed, Bose and Roy, 2024; Dirpan, Djalal and Ainani, 2022). Detecting temperature abuse early is important since indicators react faster and warn of deterioration before organoleptic signs appear (Oduse *et al*., 2025; Shahi *et al*., 2025). Exterior indicator films reduce oxygen ingress, cross-contamination hazards, and pathogen exposure by preventing package opening for freshness assessment (Adımcılar, Torlak and Erim, 2025; Dirpan *et al*., 2019).

Consumer benefits include heightened purchase confidence, diminished food safety concerns, and improved satisfaction (Liu *et al*., 2022; Zhang *et al*., 2025). Researchers found that 75–82% of customers prefer visual freshness labels, with color change indicators being more credible than expiration dates (Liu *et al*., 2022; Zainal Arifin *et al*., 2023; Zhang *et al*., 2025). Retail adoption streamlines shelf life management, reduces returns, and collects data that links indicator readings to spoiling parameters for inventory optimization (Dirpan, Djalal and Ainani, 2022; Dirpan and Hidayat, 2023). Commercial trials indicated a marked enhancement in the accuracy of distinguishing safe from unsafe products, thereby increasing staff efficiency (Dirpan, Djalal and Ainani, 2022; Hidayat *et al*., 2019). As consumers trust color signals, retailers have seen fewer quality complaints and higher repeat purchase rates (Dirpan and Hidayat, 2023; Oduse *et al*., 2025). Barcode scanning allows temperature–time tracking and freshness assessments, creating supply chain–wide quality profiles (Dirpan and Hidayat, 2023; Zhang *et al*., 2025).

Colorimetric indicators decrease retail meat waste by 12–15% by providing precise freshness communication (Karwowska, Łaba and Szczepański, 2021; Wikström *et al*., 2019; Wongphan *et al*., 2024). Due to cautious expiration dates and freshness uncertainty, retail meat loses 10–20% of its inventory from good products (Karwowska, Łaba and Szczepański, 2021; Wikström *et al*., 2019; Wongphan *et al*., 2024). Color indicators serve to prevent the disposal of products that retailers are unable to evaluate without unsealing the packaging (Waimin *et al*., 2022). A 10% reduction in packaging waste can offset higher material costs through disposal and recovered value savings (Cruz and Varzakas, 2023; Wikström *et al*., 2019). The 12–15% reduction in false-positive discards implies improved accuracy in recognizing legitimately spoiled products (Karwowska, Łaba and Szczepański, 2021; Wongphan *et al*., 2024). Indicator information helps households make informed decisions, reducing over-discard (Zhang *et al*., 2025). Minimizing retail meat waste reduces replacement order emissions, refrigeration energy use, and disposal burden (Karwowska, Łaba and Szczepański, 2021; Wongphan *et al*., 2024).

22.2.2.3 Moisture Regulation and Gas Management

Moisture absorption systems are essential in active meat packaging, as the accumulation of exudate forms a nutrient-rich substrate that promotes microbial growth and sensory decline (Noori *et al*., 2025; Tran *et al*., 2024). Chitosan-based films absorb moisture well, swelling 200–500%. These films absorb moisture from fresh meat and ensure product contact to boost antibacterial effects (de Lima *et al*., 2024; Noori *et al*., 2025; Tran *et al*., 2024). Natural moisture absorbers such as silica-based aerogels, cellulose derivatives, and protein-based materials function via capillary action and hydrogen bonding. Hydrophilic silica aerogel enhances pore volume by 3.92–5.60 times and specific surface area by 2.21–2.34 times relative to unmodified films (Bhowmik, Agyei and Ali, 2024; Rincón *et al*., 2023). The physiological requirement for water links water activity (aw) to bacterial growth. Microorganisms need water for metabolic activity and osmotic balance; hence, reducing surface moisture from 95% to 65–75% relative humidity (RH) reduces bacterial growth rates by 30–50% (Koutsoumanis *et al*., 2023; McSharry *et al*., 2021). Maintaining humidity below 75% RH reduces *Pseudomonas*, *Lactobacillus*, and *Enterococcus* populations—key spoilage bacteria in refrigerated meat—while maintaining humidity above 90% RH increases bacterial development (Koutsoumanis *et al*., 2023; Qiu *et al*., 2022).

The gas composition of MAP affects aerobic and anaerobic spoilage community growth. Research indicates that CO_2 concentration inhibits psychrotrophic bacteria, while N_2 functions as an inert diluent (Kolbeck *et al*., 2020). Beef packaging with 30–40% CO_2 and 60–70% N_2 efficiently repels obligatory aerobes, such as *Pseudomonas* spp., while maintaining sub-anoxic conditions to prevent anaerobic pathogen growth (Zhang *et al*., 2016). CO_2 inhibits aerobic growth by reducing intracellular pH, blocking

enzymatic pathways, and competing with oxygen intake (Kolbeck *et al*., 2020). Over 70% CO_2 levels can cause "souring" by accumulating carbonic acid, which promotes CO_2-tolerant LAB development during storage. This process can degrade flavor even with low microbial numbers (Babic Milijasevic *et al*., 2023; Kolbeck *et al*., 2020). Packaging gas composition and storage temperature affect shelf life, with aerobic psychrotrophic and LAB indicating deterioration (Babic Milijasevic *et al*., 2023; McSharry *et al*., 2021). Low-oxygen MAP conditions alter spoilage microbial dominance from *Pseudomonas* to anaerobic-tolerant *Brochothrix* and *Carnobacterium*. Despite producing separate spoilage metabolites, these genera nonetheless exhibit restricted growth at high CO_2 levels (Kolbeck *et al*., 2020; Shen *et al*., 2025).

The complementary techniques of moisture control and oxygen scavenging extend shelf life more than either technology alone (Noori *et al*., 2025; Tran *et al*., 2024). Moisture absorption prevents exudate-driven bacterial substrate buildup, the main growth driver at 4 °C. *Pseudomonas* spp., the main psychrotrophic spoilage bacteria, respires less aerobically with oxygen reduction (Shahbazi and Shavisi, 2018). Hydrophilic chitosan films containing oxygen-scavenging iron powder absorb exudate via swelling and reduce residual oxygen from 20.9% to 0.1% within 24–48 hours (Souza *et al*., 2020). Minced beef packaged under ordinary climatic conditions spoils at 4 °C in 6–8 days at 7 log CFU/g. However, moisture absorption and oxygen-scavenging devices can keep levels below 5 log CFU/g for 12–14 days, extending shelf life by 50–75% (Roy, Priyadarshi and Rhim, 2021; Suvarna *et al*., 2022). While extension magnitude is stable in beef, pork, and poultry, absolute values vary according to microbial load, fat content, and packaging design (Muñoz-Tebar *et al*., 2023).

Optimizing packaging necessitates a strategic approach to material design that balances multiple objectives, including moisture absorption capacity, gas barrier properties, mechanical integrity, and cost-effectiveness (Raveena and Kumari, 2024). Micro-perforated film architecture balances restrictions by allowing controlled gas exchange, preventing CO_2 accumulation, and maintaining oxygen barriers. Perforation density is designed to leave 1–5 mL of residual oxygen per package after 48–72 hours (Komodromos *et al*., 2024; Liu *et al*., 2022). After quick absorption in the first 24 hours, the two-stage moisture management system maintains balance from days 2 to 14. Dual-layer designs absorb bursts with highly absorbent chitosan/silica composite core layers and semipermeable outer layers for hygroscopic balance (Komodromos *et al*., 2024; Souza *et al*., 2018). Humidity-buffering polymers like modified poly(acrylic acid), carboxymethyl cellulose, and cross-linked starch polymers maintain RH values between 65% and 75% without desiccation (Matadamas-Ortiz *et al*., 2022; Wu *et al*., 2022). Adding mesoporous silica, chitosan nanoparticles, or cellulose nanocrystals to nanocomposite systems increases surface area, absorption capacity, mechanical properties, and gas-barrier characteristics by three- to fivefold (de Lima *et al*., 2024; Uhlig *et al*., 2024).

Shelf life comparisons measure moisture–gas management efficacy across meat types (de Lima *et al*., 2024). Aerobic minced beef spoils in 6–8 days at 4 °C, but VP extends it to 8–10 days and modified environment packaging (30% CO_2/70% N_2) to 10–12 days (DeWitt and Oliveira, 2016; Nayma *et al*., 2020). Active packaging with moisture-absorbing chitosan films and oxygen-scavenging iron powder extends shelf life by 12–14 days, a 50% increase over VP and 75–100% over aerobic control (DeWitt and Oliveira, 2016; Roy, Priyadarshi and Rhim, 2021). Pork loin stored in 25–50% CO_2 MAP maintains quality (pH < 6.5, TVB-N < 20 mg/100g) for 15 days at 2 °C, whereas moisture-controlled composites can last beyond 18 days (Zambon *et al*., 2022). Chicken leg meat benefits from this technology, where aerobic packaging provides a shelf life of 6 days, MAP extends it to 15 days, and integrated moisture-plus-oxygen systems achieve 18–21 days by inhibiting both *Pseudomonas* and LAB (Bremenkamp and Sousa Gallagher, 2025; Zambon *et al*., 2022). Ready-to-cook fish curry with MAP (75% CO_2/25% N_2) increases shelf life to 20 days at 4 °C while maintaining TVB-N and pH levels. Control packing spoils by days 6–8, proving the technology's applicability to other protein substrates (Clodoveo *et al*., 2021; Cui *et al*., 2024).

22.2.2.4 Synergistic Integration

Active and intelligent packaging features have advanced meat preservation from single-mechanism techniques to full protection systems (Dirpan, Djalal and Ainani, 2022; Zhang *et al*., 2025). Combined oxygen-scavenging, antibacterial systems, and freshness indicators have synergistic effects that exceed their individual contributions (Xie *et al*., 2024; Zainal Arifin *et al*., 2023). This complete strategy addresses

beef spoilage's complex biochemical, chemical, and microbiological characteristics (Dirpan, Djalal and Ainani, 2022). Synergistic integration creates a closed-loop system with real-time monitoring and active preservation procedures. Active components preserve product quality, while intelligent indicators give consumers and retailers objective, visible product status information (Dirpan, Djalal and Ainani, 2022; Zhang *et al.*, 2025; Zhu *et al.*, 2023). This dual-function technique reduced supply chain food waste by improving protective efficacy and consumer confidence through clear freshness communication (Shehzadi *et al.*, 2025; Zhu *et al.*, 2023).

Synergistic systems require precise material structures that maintain functional independence and improve performance interactions (Acharyya, Sarma and Kashyap, 2024). Multilayer film designs contain oxygen scavengers and antimicrobials in polymer layers and indicator systems as sensing elements or throughout complementary layers (Jacob Rani and Venkatachalam, 2024; Zhu *et al.*, 2023). Advanced fabrication methods like electrospinning and layer-by-layer assembly allow precise control over component distribution and release kinetics, ensuring optimal functionality, while pH-sensitive indicators remain stable until spoilage-related chemical changes (Acharyya, Sarma and Kashyap, 2024; Yildiz *et al.*, 2025). Chitosan, carrageenan, and cellulose derivatives are ideal base materials because they form films, are biodegradable, and are compatible with bioactive substances (Jacob Rani and Venkatachalam, 2024; Sinha, 2025). Functional component interactions depend on polymer matrix choice. Hydrophilic matrices support anthocyanin-based pH indicators and are compatible with essential oils and iron-based oxygen scavengers (Sinha, 2025; Zhu *et al.*, 2023). Silver, zinc oxide, or carbon-based nanocomposite methods improve mechanical properties, barrier performance, pH responsiveness, and antimicrobial effectiveness in biopolymer matrices (Jacob Rani and Venkatachalam, 2024; Santhosh *et al.*, 2025). Recent research shows that garlic extract antimicrobials and bromothymol blue/phenol red indicators boost beef shelf life from 6 days to 12 days at 4 °C and provide a color-coded freshness-monitoring system (dark yellow = fresh, reddish-yellow = consume soon, red = spoiled) (Dirpan, Djalal and Ainani, 2022).

Commercial implementation faces major hurdles that limit widespread acceptance, notwithstanding benefits (Shehzadi *et al.*, 2025; Zhu *et al.*, 2023). Current applications are in research-oriented operations and high-end markets where consumers are prepared to pay more for packaging (Lv *et al.*, 2025; Shehzadi *et al.*, 2025). Prominent poultry and fresh meat processors have initiated pilot programs, specifically targeting ready-to-eat and premium fresh meat categories (Shehzadi *et al.*, 2025). As synergistic systems require 15–25% more material than standard modified environment packaging, manufacturing costs impede large-scale commercialization (Santhosh *et al.*, 2025). Indicator system integration requires additional procedures, modern printing technologies, and strict quality control (Zhu *et al.*, 2023). As different countries approve food contact materials differently, notably natural antibacterial agents and synthetic colorants, regulatory approval paths are difficult (Santhosh *et al.*, 2025). Companies emphasize compounds that are FDA Generally Recognized as Safe (GRAS) and EFSA-approved, thereby limiting the availability of potentially effective bioactive agents (Santhosh *et al.*, 2025).

Unresolved technical issues limit implementation. Many limits arise from indicator compound stability. pH-sensitive dyes may deteriorate, move, or interact with packaging, reducing their spoiling detection ability (Zhu *et al.*, 2023). To optimize simultaneous execution of several roles, antimicrobial release rates must prevent excessive initial release while maintaining shelf life activity and indicator responsiveness (Shehzadi *et al.*, 2025). To achieve uniform nanoparticle, extract, and dye distribution in a polymer matrix, manufacturing consistency is required, but at large-scale production, it is difficult (Jacob Rani and Venkatachalam, 2024; Santhosh *et al.*, 2025). Packaging barriers must be calibrated to exclude external oxygen while allowing regulated oxygen scavenging, limiting design (Santhosh *et al.*, 2025). In the absence of regulatory incentives, incremental costs may not justify adoption for lower-value items (Shehzadi *et al.*, 2025). For sustainability improvements over conventional packaging, life cycle evaluations are needed to address end-of-life issues such as recyclability and biodegradability (Shehzadi *et al.*, 2025; Sinha, 2025).

Synergistic systems possess considerable sustainability potential when designed with suitable materials and effective end-of-life management (Jacob Rani and Venkatachalam, 2024; Sinha, 2025). The main sustainability benefits are longer shelf life and better quality assurance, which reduce food waste, which is important as almost one-third of global food production is wasted (Shehzadi *et al.*, 2025; Zhu *et al.*, 2023). Recent research uses food waste and by-products to make active chemicals and biopolymers, demonstrating circular sustainability (Sinha, 2025; Zainal Arifin *et al.*, 2023). Fully biodegradable polylactic

acid, chitosan, or carrageenan formulations with biocompatible nanofillers work well and handle end-of-life issues (Jacob Rani and Venkatachalam, 2024; Sinha, 2025). Manufacturing process simplification, validation protocol standardization, and international regulatory harmonization must be future goals (Santhosh *et al.*, 2025; Shehzadi *et al.*, 2025). The integration of RFID with synergistic active-intelligent films signifies a logical progression, facilitating comprehensive supply chain transparency while upholding safety and quality standards (Zhu *et al.*, 2023).

22.2.3 Digital Innovation and Smart Tracking

Traditional tracking systems often fail to provide the necessary reliable and transparent information, as well as the incompatibility between the systems that will serve the different stakeholders. This leads to an inability to intervene in a timely manner to prevent cases of spoilage or fraud across the supply chain (Vasileiou *et al.*, 2025). Therefore, there is a current global trend to overcome the shortcomings of traditional tracking systems by using new technologies that can provide an integrated, transparent, and secure system for monitoring, tracking, and managing the flow of information in the meat supply chain, which is a pressing requirement at the present time (Caccialanza, Cerrato and Galli, 2023).

22.2.3.1 Smart Indicators and the IoT

Recently, the application of smart indicators and biosensors has received extensive consideration as a technology that can help in monitoring and tracking changes in food across the entire food supply chain. Biosensors, when integrated with food-packaging materials, can provide a novel way for providing immediate and direct feedback on the status of food products, identifying various foodborne pathogens (Sobhan *et al.*, 2019), toxins, food chemical contaminants (Heredia and García, 2018), food enzymes, and spoilage indicators (Youssef *et al.*, 2023). IoT is considered one of the novel technologies of digitalization that refers to the physical layer of data collection that encompasses various sensing technologies and is connected to IoT infrastructure. The global focus on digitalization has made the IoT one of the most dynamic and evolving topics in recent years, with further developments expected in the near future (Sobhan *et al.*, 2025). Reports indicate that the global IoT market was valued at US$18.5 billion in 2022, and with an annual growth rate of 5.3%, this market is expected to reach US$27.7 billion by 2030 (Duguma and Bai, 2024).

The reliance on biosensors for monitoring and tracking the quality and safety of food products has increased in recent years, as evidenced by the remarkable growth in the electrochemical biosensors market, which achieved an annual growth rate of 6.7% in 2023 compared to 3% in 2015 (Marimuthu *et al.*, 2023). Biosensors can be used across different stages of the meat production and supply chain, as shown in Table 22.4. On livestock farms, biosensors can be used for animal care and real-time health monitoring, such as the use of acoustic, thermal, and physiological sensors (Pau *et al.*, 2018). Additionally, sensors integrated into manufacturing, packaging, and logistics infrastructure can play a crucial role in capturing and recording numerous vital indicators that can offer detailed information about meat quality and safety (Sobhan *et al.*, 2025).

The application of biosensors in livestock production farms may constitute the first line of defense against many foodborne diseases, as well as for predicting the animal's condition before slaughter, thus providing high-quality carcasses (Nastasijević and Moračanin, 2021). Several types of biosensors have been designed to monitor the metabolic conditions of animals and their related disorders and diseases. For example, cortisol and chromogranin A biosensors are utilized to detect stress levels in animals (Zhou *et al.*, 2020), and tattoo-based biosensors are utilized to monitor the metabolites in interstitial fluid, such as pH and glucose (Yetisen *et al.*, 2019). Biosensors designed to assess infection markers help control the spread of infection within the herd through rapid prediction, especially in cases of epidemic outbreaks. Biosensors designed to detect the levels of specific acute-phase proteins (such as C-reactive protein or haptoglobin) and cytokines (such as TNF-alpha and IL-6) can serve as indicators of an animal's infection, inflammation, injury, and the immune response (Islam and Masson, 2025). One of these applications, the biosensors that measure haptoglobin (Hp), as one of the acute-phase proteins, can be utilized to provide real-time information about mastitis in milking cows (Nirala *et al.*, 2019) and inflammation related to infection in beef and dairy herds (Weng, Ahmed and Neethirajan, 2018). Furthermore, biosensors that

TABLE 22.4

Changes Detected by Biosensors along the Meat Supply Chain

Targeted Changes	Target Indicators	Relevance to Meat Quality and Safety	Measurement Device	Reference
Physical or environmental	Temperature and humidity	Meat shelf life, microbial growth, detects cold-chain breaches	TTI labels, RFID loggers, smart sensors	Zhou *et al.*, 2025
Chemical	Total volatile basic nitrogen (TVB-N) or biogenic amines	By-products of protein degradation, key indicator of advanced spoilage	Electrochemical sensors, colorimetric indicators	Xu *et al.*, 2023
Packaging atmosphere	Carbon dioxide (CO_2), oxygen (O_2), ammonia (NH_3), and ethylene (C_2H_4)	An indicator on degradation and spoilage	Oxygen scavengers and indicators, gas sensors	Guruprasath *et al.*, 2024
Biological spoilage	Foodborne bacterial antigens Volatile organic compounds (VOCs), pH	Changes in meat quality and safety standards. VOCs signal microbial activity and spoilage. pH decrease indicates lactic acid buildup	Pathogen sensors, immunosensors, electronic noses, pH-sensitive sensors	Kumar *et al.*, 2024

aim to detect volatile organic compound (VOC) levels in animals' blood, breath, and urine can provide a time manner monitoring metabolic disorder and pathogens infection. These biosensors have been successfully applied to monitor bovine respiratory diseases (Cova *et al.*, 2022), bovine tuberculosis (Zahran *et al.*, 2023), brucellosis (Ahangari, Mahmoodi and Mohammadzadeh, 2022), Johne's disease (Asopa and Joshi, 2023), and ketoacidosis (Miezah, 2025; Yokus et al., 2020). Biosensors play a crucial role in tracking the condition of carcasses after slaughter and contamination that may occur during various processing and manufacturing operations. By detecting specific biochemical indicators after slaughter, a rapid monitoring technique can be used to track the animal's health status and whether it was injured or sick before slaughter. These indicators include some stress hormone biosensors, such as cortisol, and CgA, and acute-phase protein biosensors, such as pig major acute proteins and haptoglobin (Nastasijevic *et al.*, 2022).

Various types of biosensors have been successfully applied in the rapid detection and tracking of changes that may occur in meat along the supply chain to the consumer to verify product safety and security. By integrating biosensors into food packaging, a basis has been formed for an instant food quality monitoring system due to its ability to identify specific sensitive targets, including foodborne pathogens, chemical contamination, biomarkers of food spoilage, freshness levels, temperature, humidity, and other indicators closely related to food quality and safety (Sobhan *et al.*, 2021). Foodborne pathogens are among the most dangerous contaminants that can have serious consequences for human health. The contamination by these pathogens can occur at multiple points of the meat production chain, from the farm through slaughter, processing, packaging, and distribution. By applying biosensors, immediate details about the status of the product can be monitored in real time, such as contamination with pathogens or chemicals, changes in the proper storage temperature, changes in meat pH, and changes in meat color. This method provides real-time monitoring that enables product and safety through immediate response and intervention to prevent unsafe products from reaching consumers (Subjakova *et al.*, 2021). Such biosensors, with different conversion principles, have been increasingly used recently to detect many foodborne pathogens and contaminants. The sensors that are classified as electrochemical sensors utilize biological recognition elements, including antibodies, enzymes, and nucleic acids, to detect pathogens. These recognition elements work with electrochemical converters, such as carbon nanotubes, graphene, and conductive polymers, to bind to foodborne pathogen cells, producing an electrochemical signal that indicates microbial load and contamination levels (Sachdeva, Nath and Jain, 2024). Immunosensors are a type of biosensor that can be effectively applied to food packaging to enable early detection of contamination, which includes different types, such as Surface Plasmon Resonance (SPR) biosensors, ELISA biosensors, magnetic immunosensors, and optical immunosensors (Meira *et al.*, 2025; Xue *et al.*, 2018). The electrochemical signal of immunosensors is a result of the interaction between antibodies

and specific pathogen antigens (Polli *et al*., 2025). Bacteriophages used as bioreceptors in phagosensor biosensors succeeded in detecting food contaminated with pathogenic bacteria (Aliakbar Ahovan *et al*., 2020). Optical biosensors, such as aptasensors and antibody-based nano-biosensors, are another group of biosensors that rely on optical changes and can detect pathogenic *E. coli* bacteria in food with a high degree of sensitivity (Fang *et al*., 2021; Pebdeni *et al*., 2022). With continued development in this sector to achieve more accurate and faster detection, CRISPR/Cas sensors have recently been developed, which are considered an effective development for detecting many pathogens in the meat production and supply chain. CRISPR/Cas technology is a new biological tool that relies on a variety of nucleic acid detection (RNA and DNA) techniques, enabling it to be used as a tool for detecting pathogens in the meat supply chain with high flexibility, sensitivity, and accuracy (Xie, Yue and Yang, 2024).

pH, temperature, and gas sensors may provide a necessary tool for monitoring meat freshness during storage and distribution. By integrating pH biosensors with fish, meat, and poultry packaging, a real-time monitoring of product safety is provided by monitoring changes in pH levels of packaged products (Youssef *et al*., 2023). Time–temperature indicators (TTI) are one of the most important applications of temperature sensors, as they can monitor the product's temperature and alert supply chain managers directly when it changes from the appropriate level, thus maintaining product quality and preventing spoilage (To *et al*., 2023). Some gases are often emitted as a result of food spoilage, such as carbon dioxide (CO_2), oxygen (O_2), ammonia (NH_3), and ethylene (C_2H_4); therefore, some types of sensors, gas sensors, have been developed to monitor and detect these types of gases as an indicator of food spoilage (Yang *et al*., 2019). These sensors can provide real-time data about gas concentration in food packaging along the food supply chain, ensuring real-time monitoring and control of food quality and safety (Zare-Shehneh, Mollarasouli and Ghaedi, 2023).

The integration of biosensors and the IoT in food-packaging systems can make real-time monitoring and tracking faster by sharing the data with different stakeholders to identify early signs of food spoilage. This integration can develop tracking and mentoring systems by providing and sharing real-time information about products between different stakeholders throughout the manufacturing, storage, and food supply chain, positively impacting decision-making and enabling rapid intervention when needed. Under this tracking system, the fraud and deception in food products can be mitigated by improving and digitizing the tracking process (Verma *et al*., 2022), as illustrated in Figure 22.1.

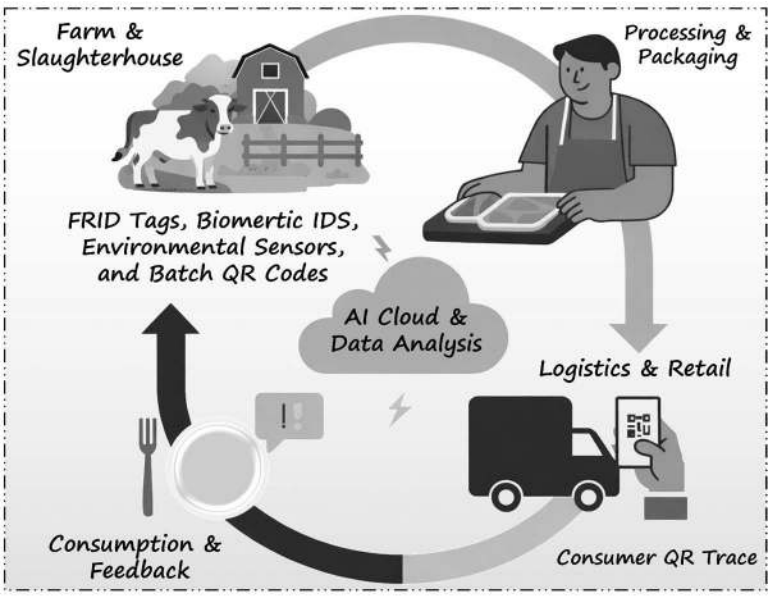

FIGURE 22.1 The integration of different novel technologies that ensure the creation of a secure, digital, and intelligent tracking system for meat and meat products along the supply chain.

IoT represents a significant step toward automating food quality monitoring and tracking. IoT is a system that connects computers, mechanical devices, and digital machines for communication and data exchange. Integrating it into food packaging is a pivotal step toward building smart technologies for data exchange and monitoring food quality throughout its various stages of production and handling (Li, Zheng and Tian, 2025). The application of IoT can facilitate real-time monitoring of critical changes affecting the product. IoT-enabled devices, such as temperature and humidity trackers and radio frequency identification (RFID) chips, can provide important data regarding temperature, humidity, water activity, and microbial counts of foods during storage, which may provide advanced technology for monitoring animals on farms and monitoring products in warehouses (Idrissi, Lachgar and Hrimech, 2024). Furthermore, IoT-enabled packaging, such as near-field communication (NFC) tags and QR codes, can provide an effective way to achieve real-time tracking of food throughout the supply chain (Maritano *et al.*, 2024). Through providing real-time data available for all stockholders, IoT plays a crucial role in helping producers, retailers, and consumers make informed decisions based on accurate information about the product. This approach can be beneficial in some critical cases, such as quickly identifying sources of contamination and providing all information needed for product recall, which reduces the risk of food contamination and economic losses (Dadhaneeya, Nema and Arora, 2023). By sharing the data related to the status of food at different points in the supply chain, IoT can provide food safety authorities with the necessary information that can help in making timely decisions (Sobhan *et al.*, 2025). Due to the highly perishable nature of meat, its preparation, transportation, and storage may require strict conditions to minimize spoilage and contamination. This highlights the role of the IoT in monitoring meat and its products during transport and distribution to reduce food product loss throughout the supply chain (Popa *et al.*, 2019). Biosensors that support IoT technology in meat packaging provide an automated system to monitor several indicators related to product quality and safety, such as temperature, humidity, and pH during food transport. They can track these parameters and send alerts if conditions deviate from the specified standards (Witjaksono *et al.*, 2018).

22.2.3.2 Blockchain Technology

As the world strives to digitize all services, including logistics and food safety systems, to combat corruption, fraud, and illicit activities that food products may encounter throughout the supply chain, database fraud is perhaps one of the most critical areas to control (Li, Zheng and Tian, 2025). Since its initial implementation in 2009 with the launch of the cryptocurrency Bitcoin, blockchain technology has been considered a revolutionary method for trading, storing, and encrypting data. Blockchain has been applied across numerous sectors, bringing about radical transformations (Bouzembrak *et al.*, 2019). Blockchain technology provides a more secure data storage system, wherein data is stored in linked blocks, with each block containing a list of transactions, a time stamp, and a unique cryptographic hash code that ensures its authenticity and immutability (Apeh and Nwulu, 2025). Blockchain technology provides reliable data on food products, as this technology is designed so that the data within it is resistant to change, thus enabling stakeholders to obtain product data reliably, which is reflected in the development of efficient and immediate traceability across the supply chain. This technology can boost consumer confidence in the meat production sector, by providing a secure and tamper-proof data transfer and storage system that contains product details such as origin, storage conditions, and transportation (Melendez, Smith and Bergey, 2025).

The tracking system based on these different layers of novel technology can be integrated together to provide a smart, safe, and effective tracking system, as presented in Figure 22.2. While biosensors are collecting changes in different parameters, IoT will work on collecting and sharing this information with different stockholders, and the blockchain will be used to control and secure these records. This integration aims to provide accurate and reliable details about the journey of the meat product from farm to table and ensure that all stakeholders have access to this information at any time (Sobhan *et al.*, 2025). The application of such technologies is likely to provide a high level of transparency and data integrity, which will be reflected in improved food safety protocols through the rapid identification of contamination sources and timely intervention (Gadge *et al.*, 2024), deterring fraudulent activities, and ultimately increasing consumer confidence in the food system (Rebezov *et al.*, 2024).

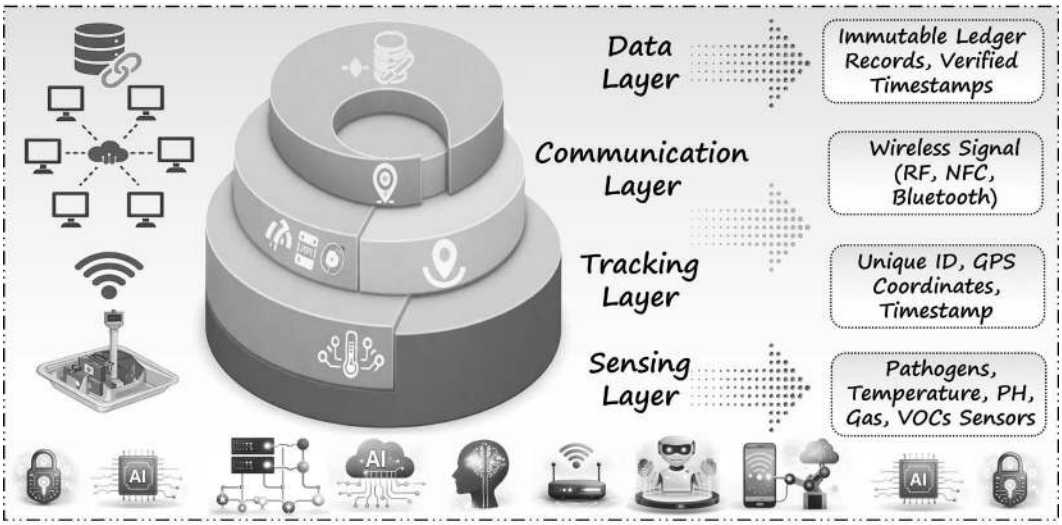

FIGURE 22.2 Multilayer structure model of tracking system based on biosensors, IoT, and blockchain.

22.3 Conclusion and Future Perspectives

Innovative meat packaging technologies are playing a pivotal role in reshaping the modern meat industry by addressing critical challenges related to freshness, safety, and sustainability. As discussed in this chapter, the transition from conventional packaging to advanced solutions, such as active and intelligent packaging, MAP, and biodegradable materials, has significantly improved the ability to preserve meat quality while ensuring microbial safety. These technologies not only slow spoilage processes and maintain sensory attributes but also enhance consumer confidence through improved transparency and real-time freshness monitoring.

The integration of smart sensors and digital tracking systems represents a major step forward, enabling proactive quality control and more efficient supply chain management. At the same time, the adoption of environment-friendly materials supports global efforts to reduce plastic waste and the overall environmental footprint of food packaging. Together, these innovations contribute to reduced food loss, extended shelf life, and safer meat products.

Looking ahead, continued interdisciplinary research and collaboration between food scientists, material engineers, and industry stakeholders will be essential to optimize performance, scalability, and affordability of these packaging systems. As consumer expectations and regulatory demands continue to evolve, innovative meat packaging will remain a key driver in promoting a safer, more transparent, and sustainable meat supply chain.

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23

Manufacturing Equipment and Engineering Innovations for Meat and Its Products

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23.1 Introduction

Engineering and equipment have long been recognized as pivotal drivers in the modernization of the meat industry. Historically, these innovations focused on productivity and basic food safety, aiming to ensure efficient slaughter, processing, and distribution. However, the scope of technological development has widened considerably in recent decades. Today, the sector faces a convergence of global challenges—sustainability, safety, efficiency, and rapidly shifting consumer demands—that compel a more systemic and forward-looking approach to engineering. Modern innovations are not only mechanistic tools but also strategic levers that reshape the very architecture of meat production, distribution, and governance.

The traditional view of equipment as a means to increase throughput is giving way to a more nuanced understanding: machines and digital systems now serve as the backbone of food integrity, quality assurance, and environmental stewardship. This transformation is particularly visible in the rise of nonthermal technologies, digital integration, and sustainable engineering strategies, which collectively redefine both upstream primary processing and downstream value-chain operations. As such, engineering has become a decisive factor in ensuring that the meat sector is not only profitable but also ethically aligned, resilient to disruption, and environmentally responsible.

One striking example is ultrasound-assisted processing technology, which demonstrates how physical forces can be strategically applied to enhance meat quality at the molecular level. Through acoustic cavitation—the rapid collapse of microscopic bubbles in a liquid medium—ultrasound generates localized extremes of pressure and temperature. These forces trigger protein conformational changes and even partial peptide bond cleavage, improving tenderness, water retention, and other key functional attributes of meat (Hu *et al*., 2015; Wang *et al*., 2022a, 2023; Xu *et al*., 2024). Yet, the effectiveness of ultrasound depends heavily on multiple interacting parameters such as frequency, intensity, and system temperature (Chen *et al*., 2020). This necessity for precision highlights the central role of equipment engineering in balancing mechanistic power with product quality. It also illustrates how meat processing has shifted from being largely empirical to requiring a deep understanding of biophysical mechanisms.

Parallel to advances in processing, intelligent cold chain logistics has emerged as another critical domain where engineering meets sustainability and safety. For small-batch products, transportation and storage costs can be disproportionately high, while large-scale operations rely on highly coordinated warehousing and distribution networks. Failures in infrastructure or management can lead to spoilage, food safety risks, and considerable economic loss (Luo *et al*., 2025). Since different meat products exhibit varied sensitivities to temperature, humidity, and lipid oxidation, cold chain systems must be adaptive and product-specific. Here, engineering solutions such as real-time monitoring, IoT-enabled tracking, and predictive logistics algorithms are being deployed to minimize waste, extend shelf life, and uphold consumer trust. In this way, cold chain innovation exemplifies how equipment now functions as both a technological and an ecological safeguard.

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The integration of artificial intelligence (AI) with nonthermal technologies introduces an even more profound techno-economic and regulatory frontier. AI now acts as the "intelligent brain" of modern meat processing systems, dynamically optimizing conditions in high-pressure processing (HPP) or pulsed electric field (PEF) treatments. By analyzing sensor data in real-time, machine learning (ML) models can adjust parameters to strike an optimal balance between microbial inactivation and sensory preservation. However, this adaptive and data-driven model challenges traditional regulatory frameworks, which are built on validating fixed parameters. The resulting tension underscores the urgent need for performance-based regulatory approaches, such as regulatory sandboxes that allow for controlled testing of novel technologies. This regulatory evolution is critical if the industry is to safely and ethically leverage the full potential of intelligent, adaptive processing.

Digital innovations further reinforce this transformation. The immutable and traceable nature of blockchain systems enables reliable certification of meat origin, processing conditions, and logistical history, significantly enhancing consumer trust and supporting the sustainable development of the industry (Kodan, Parmar and Pathania, 2020). Similarly, IoT technologies, as highlighted by Režek Jambrak (2021), have already demonstrated their capacity to enhance food processing. The next frontier lies in integrating IoT with emerging technologies such as nonthermal processing and 3D printing, paving the way toward a more intelligent, secure, and sustainable digital future. However, for these technologies to achieve their potential, systemic challenges must be addressed: standardizing data formats, ensuring secure device communication, and lowering the hardware and software costs through cloud-based and open-source platforms. Policy interventions—such as subsidies, regulations, and consumer education—will also play a critical role in mainstream adoption (Vern *et al.*, 2025).

Beyond digitalization, resource utilization breakthroughs are emerging that fundamentally alter the raw material base of meat products. Among the most disruptive is cell-based cultured meat, also known as lab-grown or in vitro meat. By applying cell and tissue engineering to culture animal-derived cells in controlled environments, cultured meat mimics the structural and nutritional characteristics of conventional meat (Jahir *et al.*, 2023; Nyika *et al.*, 2021; Treich, 2021). Compared with intensive livestock farming, cultured meat offers clear environmental benefits, including lower greenhouse gas emissions, reduced land use, and decreased water consumption (Boland *et al.*, 2013). The potential also extends to 3D food printing, which can enhance the structural integrity, sensory properties, and personalization of both cultured and traditional meat products (Li *et al.*, 2024; Pan *et al.*, 2024; Tong *et al.*, 2024). Such technologies demonstrate how engineering extends beyond conventional machinery to the frontier of biological design, offering radical solutions for sustainability and personalization.

At the same time, traditional yet foundational processes such as meat curing are being revisited through an engineering lens. Curing—an age-old method for preservation and flavor development—relies on the diffusion of salts, sugars, and spices into muscle tissue (Xiong *et al.*, 2020). While classical methods depend on passive diffusion, advances in mass transfer engineering now allow for more precise control of solute migration, water activity, and tissue interactions (Cárcel *et al.*, 2007; Gou, Comaposada and Arnau, 2003). Revisiting such processes not only bridges the gap between tradition and innovation but also demonstrates the breadth of engineering contributions, from heritage techniques to frontier technologies.

In conclusion, these diverse but interconnected developments illustrate how engineering and equipment are central to the ongoing transformation of the meat sector. The spectrum ranges from molecular modifications induced by ultrasound to system-wide cold chain logistics, from AI-driven optimization of nonthermal processes to blockchain-enabled transparency, and from lab-grown meat production to re-engineered curing methods. Each of these innovations reflects a broader narrative: that the modernization of the meat industry is a systemic project requiring cross-disciplinary collaboration, regulatory adaptation, and consumer engagement.

This chapter seeks to provide a comprehensive and systematic review of the technological advancements currently shaping the meat industry. Specifically, it synthesizes innovations across the full spectrum of meat production, from primary processing (e.g., slaughter, cutting, portioning, and curing) to secondary operations (thermal and nonthermal processing, packaging, and preservation), and through to distribution and market-facing systems (cold chain logistics, traceability, digital integration, and consumer-facing sustainability strategies). By integrating perspectives from engineering design,

digitalization, sustainability science, and regulatory policy, the chapter underscores how technological progress is reshaping the industry into one that is not only safer and more efficient but also more accountable to environmental imperatives and consumer values. The objective is not merely to catalogue equipment innovations, but to illuminate their systemic interactions and long-term implications for the future of global meat production.

23.2 Advanced Primary Processing Equipment

At the most fundamental level, modernization in meat engineering begins with size reduction, a principle that appears deceptively simple yet carries profound implications for both efficiency and product quality. Processes such as chopping, grinding, mincing, or cutting mechanically reduce particle size, thereby increasing surface area and enabling faster, more uniform heat and mass transfer. For example, ground beef provides a larger exposed surface for microbial inactivation during cooking and creates substrates more receptive to curing agents, marinades, or binding additives. Unlike brittle solids, meat exhibits a ductile–fibrous structure, meaning classical comminution models such as Rittinger's, Kick's, or Bond's laws are not applicable (Berk, 2009). Instead, the energy required for size reduction arises predominantly from shearing forces acting along the muscle fibers. This process is better described using the specific cutting energy (SCE) concept, where the total mechanical work (E) depends on the inherent shear stress (τ) of the meat matrix and the total cut surface area (A) produced:

$$E = \tau \times A$$

This relationship highlights that the cutting energy is governed by the structural resistance of muscle fibers rather than particle fracture mechanics. Consequently, the optimization of equipment design—such as blade geometry, grinder plate configuration, and operational speed—is essential to manage energy consumption, enhance uniformity, and preserve the sensory attributes of the final product (Barbut, 2010; Berk, 2009).

From an engineering perspective, size reduction also improves mixing dynamics in multicomponent formulations, enhances the homogeneity of emulsified products such as sausages, and facilitates uniform texture across batches. The mechanical energy imparted during size reduction influences protein denaturation and water-binding capacity, properties which directly impact juiciness, tenderness, and cohesion. For this reason, the design of cutting blades, grinder plates, and rotational speeds must be carefully optimized to minimize oxidative changes and preserve sensory quality (Barbut, 2010).

This principle, though basic, sets the foundation upon which advanced processing methods operate. By controlling particle size and surface exposure, engineers establish the baseline conditions for subsequent applications of novel technologies such as ultrasound, PEF, or HPP. In this sense, size reduction exemplifies how traditional engineering approaches remain essential in preparing raw meat for the next generation of technological interventions (Troeger, 2003).

Building upon size reduction, dimensional reduction represents an emerging paradigm in meat engineering that strategically reshapes meat structures for novel functionalities. Unlike size reduction, which focuses on reducing particle diameter, dimensional reduction manipulates geometry, orientation, and microstructure to create new textural and functional properties.

Zhang *et al*. (2024) describe dimensional reduction as a versatile strategy to tailor meat proteins into nanofibrils, thereby unlocking structural, nutritional, and functional advantages. The process leverages principles of soft matter physics and mesoscopic polymorphism, enabling muscle proteins to be reorganized into nanofibrillar scaffolds. These nanofibrils exhibit unique physicochemical properties—such as improved gelation, water retention, and emulsification—that can be harnessed in product design.

Applications are wide-ranging. Dimensional reduction supports the creation of texture-modified meat products for elderly populations requiring softer, easy-to-chew foods. It also enables the development of liquid protein foods, expanding opportunities in clinical nutrition and personalized diets. Moreover, when integrated with 3D printing technologies, nanofibril-based structures allow for customized shapes, fat-to-lean ratios, and flavor profiles, bridging traditional and alternative meat systems (Zhang *et al*., 2024).

The novelty of this approach lies not only in the fabrication of protein nanofibrils but also in the linkage between structural modification and functional outcomes. By probing structure–property relationships, researchers can design meat matrices that mimic conventional sensory attributes while offering superior nutritional or processing advantages. In this way, dimensional reduction serves as both a scientific and practical innovation, redefining what meat can be in the context of sustainability, personalization, and efficiency.

23.2.1 Stunning and Harvesting Technologies: Innovations for Animal Welfare and Meat Quality

The modernization of meat production systems has increasingly placed emphasis on how animals are handled in the critical stages of preslaughter, stunning, and harvesting, recognizing that welfare, meat quality, and food safety are deeply interlinked. Engineering solutions and welfare-centered practices have together reshaped the landscape of stunning and harvesting, where once the focus was predominantly on productivity, but now broader considerations of sustainability, consumer expectations, and ethical imperatives are unavoidable. Conventional methods such as electrical stunning, carbon dioxide exposure, and captive bolt remain the most widely applied in commercial operations, but the limitations of these approaches in terms of animal welfare, consistency of outcome, and downstream effects on carcass quality are increasingly scrutinized. Some approaches, such as electrical, gas (controlled atmosphere), and mechanical (captive bolt), remain dominant because they can render animals insensible rapidly when correctly applied, yet each presents practical trade-offs for welfare and meat quality that must be managed with engineering controls and training (Ismail *et al.*, 2014; Troeger, 2003). These established technologies were developed to provide rapid unconsciousness and facilitate efficient slaughter, but a closer examination reveals that each method introduces its own physiological stressors, welfare dilemmas, and implications for meat quality parameters. For example, electrical stunning, widely used in poultry and ruminant industries, produces reliable unconsciousness yet risks over- or under-stunning if equipment calibration or operator skill is insufficient, leading to compromised welfare and variability in bleeding efficiency (Barbut, 2010). In practice, this means that stunning must render animals insensible to pain while also enabling smooth exsanguination and stable line operation; the same technical parameters that protect welfare also influence pH decline, bleeding efficiency, color, and the incidence of appearance defects (Fernandez *et al.*, 2010; Troeger, 2003).

23.2.1.1 Methods in Use and Their Implications

Electrical stunning, controlled-atmosphere stunning (CAS, typically CO_2 or mixed gases), and mechanical (captive bolt/percussive) systems remain the dominant commercial options. When properly applied, each can meet welfare goals; however, their process signatures differ in ways that matter for quality and operations. CAS, for example, allows group handling and eliminates the need for individual restraint, which pigs usually find stressful, while modern "backloader" systems move cohorts through the stunning unit automatically—features that help with both welfare and high-speed logistics (Troeger, 2003).

In waterfowl and geese, comparative trials have shown how different methods alter early postmortem physiology and appearance outcomes. In force-fed ducks, head-only electrical and mechanical (captive bolt) stunning were associated with more post-stun convulsions, faster early pH decline, and paler breast meat at 24 hours and 6 days, whereas water-bath electrical stunning yielded the lowest bleeding efficiency. In geese, mechanical stunning recovered the most blood, and CAS gave the lowest humeral fractures albeit more engorged wing veins. These controlled comparisons underline that method choice and parameterization reverberate into both appearance defects and process control (Fernandez *et al.*, 2010).

From a religious and cultural perspective, the *halal* sector has engaged deeply with the reversibility and practicality of stunning. A broad review notes that many jurisdictions and certifiers now accept reversible stunning provided animals are alive at neck cut and verification procedures are in place. Debates persist around blood loss and pain perception, but studies reported no significant differences in total blood loss by 90 seconds across non-stun and electric head-only approaches. Technical pitfalls,

such as mis-applied currents, poor training, and equipment deficits, can compromise welfare, which then reinforcing why standardized procedures and operator competence are central to *halal*-compliant practice (Riaz *et al*., 2021).

23.2.1.2 Preslaughter Handling and the Welfare–Quality Continuum

Welfare and quality outcomes are inseparable from how animals are moved, mixed, laired, and queued before stunning. Guidance emphasizes gentle driving, short, well-lit races, group penning without mixing unfamiliar animals, and the availability of water and sprinkling—conditions that limit stress responses associated with PSE, blood splash, or dark-cutting beef. Importantly, training and certification for staff are encoded in European practice, aligning labor competence with welfare protection and quality assurance (Troeger, 2003).

Studies in Ethiopia demonstrate how poor preslaughter management directly translates into quality downgrades. Cattle trekked long distances without feed and water displayed extreme fatigue, with 47% of carcasses classed as dark, firm, and dry (DFD) and higher microbial contamination (Bekuma and Tadesse, 2024). In goats, electrical stunning combined with poor bleeding efficiency has been associated with higher residual blood content and microbial counts in several muscles (Al-Amri *et al*., 2022). Similarly, Suliman *et al*. (2024) found that improper handling practices, such as ear or hind-leg pulling, led to increased microbial loads and reduced tenderness, highlighting the clear link between welfare breaches and meat quality losses.

Scoping reviews reinforce these findings at a broader level. Sullivan *et al*. (2022) reported that transport, lairage, and handling were the most frequently cited preslaughter factors influencing beef quality, with effects consistently observed on ultimate pH, bruising, and carcass downgrading. This pattern confirms that preslaughter stressors are systemic and not confined to specific regions.

23.2.1.3 Digital Oversight and "Harvesting 4.0"

Digital monitoring systems now play an essential role in ensuring compliance with welfare regulations and consistency of process. Real-time video surveillance, automated detection of improper stuns, and data-driven auditing platforms enable processors to demonstrate adherence to legal frameworks and respond to increasing consumer expectations of transparency. Blockchain-enabled certification, for example, provides immutable records of welfare compliance, slaughter conditions, and cold chain management, thereby building consumer trust and aligning production with sustainable development goals. At the same time, IoT-based smart sensors integrated into stunning and harvesting equipment allow continuous monitoring of voltage, current, exposure duration, and animal response metrics, ensuring precise application of technologies while generating data to guide continuous improvement. The integration of digital systems into animal processing aligns with the broader Industry 4.0 transformation of the food industry, where real-time data analytics, predictive maintenance, and algorithmic decision-making are reshaping not only efficiency but also ethical and safety standards (Jambrak *et al*., 2021).

Primary processing is also being reshaped by digital tools. Blockchain, AI, and IoT are increasingly used to deliver end-to-end traceability, monitor animal conditions, and record welfare practices (Rebezov *et al*., 2024). By capturing stunning parameters, lairage conditions, and cold chain data, processors create verifiable, immutable records that align with regulatory frameworks. AI-driven anomaly detection and predictive analytics further strengthen process control. Consumer studies demonstrate the importance of these digital innovations. Ethical consumption research shows that consumers associate humane processing and digital monitoring with ethical and hedonic benefits, and are willing to pay more for products carrying assurances of welfare compliance (Jose *et al*., 2025).

Collectively, the integration of engineering solutions, welfare science, and digital oversight has shifted stunning and harvesting from what was once regarded as a throughput bottleneck into a central welfare–quality lever in modern meat production. Well-designed lairage facilities and careful preslaughter handling reduce animal stress, leading to more predictable pH decline, lower incidences of DFD meat, and reduced microbial load (Bekuma and Tadesse, 2024; Sullivan *et al*., 2022). Controlled stunning techniques provide further gains: controlled atmosphere stunning (CAS) eliminates the need for individual

restraint and has proven particularly advantageous in pigs, where group handling reduces struggling and associated injuries (Troeger, 2003). At the same time, comparative studies in waterfowl reveal that stunning methods are not without trade-offs, with specific techniques influencing bleeding efficiency, fracture rates, and appearance quality (Fernandez *et al.*, 2010).

Beyond these technical outcomes, *halal*-compliant reversible stunning has become increasingly codified, balancing religious requirements with welfare standards and industry practicality (Ismail *et al.*, 2014). This codification reflects a broader global shift in recognizing that welfare and quality are not mutually exclusive but rather complementary when systems are carefully calibrated.

Finally, the rise of digital monitoring and blockchain-based certification systems has tied welfare practices directly to consumer trust. Studies show that consumers are more willing to purchase—and even pay premiums for—meat products carrying assurances of humane treatment and transparent monitoring (Jose *et al.*, 2025). Such digital tools make welfare visible to the consumer while also offering processors verifiable evidence of compliance. These developments underscore that humane practices are not merely ethical imperatives but also strategic levers of quality, safety, and market differentiation (Al-Amri *et al.*, 2022; Suliman *et al.*, 2024).

23.2.2 Carcass Processing: Automated Dehiding, Defeathering, and Evisceration Systems

23.2.2.1 Carcass Processing Systems

Carcass processing is where safety-critical and yield-critical decisions concentrate. Line speeds in poultry have risen dramatically over the past decades—new plants designed for ~12,000 broilers/hour—powered by improvements in computer vision, online weighing/tracking, and the tight integration of unit operations from stunning through cut-up (Barbut, 2010). The logic of high-speed in-line processing is that identification, grading, routing, and trimming decisions are made on the fly, with machine-vision grading and automated rejection enabling stable throughput and higher uniformity (Barbut, 2010).

Carcass processing represents the stage where both safety-critical and yield-critical decisions converge, making it one of the most demanding parts of the meat production chain. In poultry, line speeds have risen dramatically over recent decades, with some modern plants now operating at approximately 12,000 broilers per hour. This escalation in speed has only been possible because of simultaneous advances in engineering and digital technologies (Barbut, 2010). Importantly, these developments have been supported by modern automation principles for slaughterhouses, which emphasize integrated process flow, ergonomic equipment, and hygienic automation to reduce human error and contamination risks (Purnell and Loeffen, 2006).

At such high throughput, the traditional reliance on manual inspection and decision-making would be unsustainable. Instead, plants increasingly depend on computer vision systems and online weighing/tracking technologies, which allow every carcass to be assessed in real time. These systems do more than accelerate the process; they provide objective data that reduces human variability, ensuring consistency in quality grading and food safety monitoring (Barbut, 2010).

The broader logic of high-speed in-line processing is that identification, grading, routing, and trimming decisions must occur "on the fly". This is made possible by integrating machine-vision grading with automated rejection and routing mechanisms, which allow carcasses that fail to meet safety or quality thresholds to be removed instantly. Such integration stabilizes throughput, minimizes slowdowns, and produces a more uniform product flow, which benefits both yield optimization and consumer-facing consistency (Barbut, 2010). In this way, carcass processing illustrates the larger shift in meat engineering: rather than treating safety and efficiency as separate goals, automation and digital monitoring create a system where high speed and high standards reinforce one another.

23.2.2.2 Automation in Carcass Handling

The removal of hides in cattle and sheep is one of the earliest and most critical stages of carcass processing, as it carries a high risk of microbial contamination. Manual dehiding, while adaptable, often results

in inconsistencies that can compromise product safety. Contact between hide and underlying muscle is particularly problematic, as it facilitates the transfer of pathogens from the animal's exterior surface to sterile tissue. Automated dehiding systems were developed to address these challenges by standardizing removal techniques. They apply controlled force and cutting trajectories, reducing both carcass damage and contamination risks. For ruminants, dehiding is a primary contamination hazard. Engineering solutions that standardize force and trajectory reduce variability and lower contamination risk, similar to how vision-guided poultry processing improved quality outcomes (Troeger, 2003).

In similar vein, defeathering in poultry underpins throughput and quality. Barbut (2010) notes that efficient, well-maintained pluckers minimize contamination and appearance defects, while integrated scalding, chilling, and vision-guided trimming increase yield. Defeathering is more than a mechanical step; it is a hygienic control point. Poorly designed or poorly maintained equipment can facilitate microbial contamination through inadequate removal of feathers and skin residues. Automated systems improve hygienic outcomes by ensuring more consistent carcass handling, reducing direct human–carcass contact, and operating within controlled parameters that can be integrated into broader quality management systems. Evidence from recent engineering trials supports this: locally developed poultry defeathering machines achieved high efficiency across bird sizes, with lower energy use and less contamination compared to traditional systems, showing how context-specific automation can improve both hygiene and sustainability (Adetola, 2025).

Moving further along the line, evisceration represents the most critical food safety hazard in carcass processing. The gastrointestinal tract harbors pathogenic microorganisms such as *Salmonella* and pathogenic *Escherichia coli*, which can contaminate carcasses if viscera are punctured or ruptured during removal. Manual evisceration, especially at high line speeds, is prone to such accidents. Automation and robotics have therefore become central to improving consistency and reducing contamination risks. Evisceration is the most acute food safety hazard, as gut rupture can spread pathogens. Fernandez *et al.* (2010) showed how handling methods influence carcass presentation, with CAS reducing fractures and facilitating cleaner evisceration. Chen and Wan (2019) reported on robotic evisceration technologies using image processing and visceral contour recognition. These systems guide robotic instruments with high precision, minimizing the likelihood of gut rupture and ensuring standardized cuts. Unlike human operators, robots do not fatigue or vary in performance, enabling uniform outcomes at industrial speeds. Although high initial costs and technical maintenance requirements remain barriers, the long-term benefits in food safety, product yield, and labor efficiency make robotic evisceration a transformative innovation. Moreover, CFD simulations confirm that ventilation and mechanical barriers can drastically reduce airborne contamination during evisceration, preventing cross-contamination that traditional manual approaches struggle to control (Lichtner, Cetin and Kriegel, 2024).

Taken together, across dehiding, defeathering, and evisceration, automation delivers multiple benefits: improved product consistency, reduced microbial contamination, higher yields, and alleviation of labor shortages. The slaughterhouse has long struggled with recruitment and retention, as work is physically demanding, hazardous, and socially stigmatized. Automation reduces dependence on manual labor, reallocating workers to supervisory, maintenance, and quality assurance roles. However, this shift also raises questions about workforce displacement and the need for reskilling. Skilled technicians capable of programming and maintaining robotic systems are increasingly required, underscoring the importance of workforce development alongside technological adoption. Beyond these direct operational gains, robotics such as water-jet cutting and "Robo-Batcher®" portioning systems improve labor efficiency and consistency. They reallocate labor away from repetitive manual tasks, reducing injury risk while delivering more standardized outputs (Barbut, 2010).

23.2.2.3 Hygienic Design and Cross-Contamination Control

Automation must be paired with hygienic facility design. Reviews emphasize that airflow management, cleanable surfaces, and low-retention designs reduce microbial hazards while also lowering water and chemical consumption (Rebezov *et al.*, 2024).

The microbial load of carcasses is particularly sensitive to preslaughter handling and bleeding efficiency. For goats, electrical stunning combined with poor bleeding resulted in significantly higher microbial counts in longissimus muscles (Al-Amri, 2022). Early postmortem interventions in sheep also influenced both tenderness and microbial safety, with interventions such as chilling or electrical stimulation directly modulating microbial colonization (Álvarez *et al.*, 2022).

Automation must be paired with hygienic facility design to achieve meaningful improvements in both safety and efficiency. Reviews have consistently emphasized that features such as directed airflow, cleanable surfaces, and low-retention materials help to prevent microbial hazards while simultaneously reducing water and chemical use during sanitation (Rebezov *et al.*, 2024). This means that the value of automation is not only in speed or precision, but also in how well it integrates into an environment that limits contamination risks from the outset.

Consider, for example, the influence of preslaughter handling and bleeding efficiency on microbial load. Carcasses that are not bled effectively can retain higher residual blood, which provides nutrients for microbial growth. Evidence from goat processing shows that when electrical stunning is combined with inadequate bleeding, microbial counts in the longissimus muscle rise sharply compared with carcasses handled under optimal conditions (Al-Amri *et al.*, 2022). This illustrates that even sophisticated stunning technologies can backfire if not aligned with hygienic design and effective bleeding protocols.

Early postmortem interventions further demonstrate the interplay between technology, quality, and microbiology. In sheep, interventions such as rapid chilling or electrical stimulation not only improved tenderness but also reduced microbial colonization, proving that meat safety and eating quality can be enhanced simultaneously when interventions are carefully chosen (Álvarez *et al.*, 2022). Here, technology is not working in isolation; rather, it forms part of a broader system where each stage, such as stunning, bleeding, chilling, contributes to the final safety and sensory attributes of the meat.

In sum, these examples show that hygienic design and careful post-slaughter interventions form the "silent partner" to automation. Robots and machines may provide precision, but it is the integration of airflow management, effective bleeding, and targeted interventions that ensures carcasses are not only uniform and efficient to process, but also safe, tender, and appealing for consumers (Al-Amri *et al.*, 2022; Álvarez *et al.*, 2022; Rebezov *et al.*, 2024).

23.2.2.4 Integration with Sensors and Imaging Systems

Digitalization has become the backbone of modern carcass inspection, transforming what was once a manual, subjective process into a data-driven ecosystem. Computer vision systems are now integral to high-speed poultry lines, where they enable real-time grading and routing at speeds of up to 12,000 birds per hour (Barbut, 2010). By detecting abnormalities, assigning quality classes, and ensuring uniformity, these systems provide the foundation for precision portioning and downstream automation. Importantly, their use reduces operator fatigue and variability, ensuring that safety and quality assessments are not left solely to human judgement.

Building on this, biosensors expand the reach of digital monitoring directly onto the processing floor. Portable biosensors integrated with Internet of Things (IoT) systems can detect pathogens, residues, or quality markers within minutes, providing a level of responsiveness that traditional laboratory methods cannot achieve. Their true value lies in connectivity: biosensor data can be instantly logged into blockchain-based traceability platforms, creating an immutable record that follows the product throughout the supply chain (Rebezov *et al.*, 2024). In this way, biosensors function not only as safety tools but also as transparency devices, giving regulators, processors, and consumers verifiable evidence of compliance with food safety standards.

AI adds a predictive dimension to this digital ecosystem. Instead of reacting to problems after they arise, AI-assisted process control analyzes streams of data from sensors, cameras, and biosensors to forecast deviations before they occur. By predicting anomalies in microbial load, equipment function, or product quality, processors can intervene in real time, preventing safety risks and minimizing waste. When these predictive models are coupled with blockchain records, they not only improve operational resilience but also enhance consumer trust by providing visible proof that every carcass has passed through a monitored, transparent system (Jose *et al.*, 2025).

Together, these technologies illustrate how regulatory compliance, consumer expectations, and operational efficiency are converging. Food safety frameworks such as HACCP and FSMS increasingly encourage continuous monitoring, while ethical consumption trends show that consumers actively reward companies that demonstrate humane and transparent practices (Jose *et al.*, 2025). Computer vision provides the speed and objectivity, biosensors offer immediacy and traceability, and AI ensures predictive oversight—forming a digital triad that redefines what it means to manage risk and quality in the meat industry.

23.2.2.5 Future Perspectives

Future processing facilities are expected to evolve into fully fledged cyber-physical systems, where robotics, sensors, and blockchain operate in a seamless network. In these environments, stunning methods will continue to become more welfare-sensitive, cutting and portioning will be dynamically optimized by AI, and biosensors will provide continuous, line-side monitoring of microbial safety. These developments signal not only a technological transformation but also a need for governance frameworks capable of validating ML-based processes, which do not rely on fixed parameters but instead adjust dynamically in real time (Rebezov *et al.*, 2024).

At the same time, the literature makes clear that preslaughter conditions will remain critical levers for quality and safety. Scoping reviews and field studies emphasize that transport and lairage practices—such as minimizing the mixing of unfamiliar animals, reducing holding times, and ensuring access to rest and water—directly improve postmortem physiology. These interventions lead to more predictable pH decline, improved tenderness, and lower microbial load, thereby enhancing both consumer acceptability and shelf life (Bekuma and Tadesse, 2024; Sullivan *et al.*, 2022). More recent evidence adds that stressors like rough handling, overcrowding, and delayed slaughter elevate microbial counts and toughen muscle structure, further underlining the strong link between welfare and safety (Suliman *et al.*, 2024). In short, the future of meat processing will be defined by a dual focus: high-tech systems that deliver precision and transparency, and low-tech but equally crucial welfare practices that prevent stress and contamination before slaughter. By combining these dimensions, the industry can move toward a model that is technologically advanced, ethically responsible, and biologically sound.

23.2.2.6 New Robotics in Carcass Handling that Reduce Labor Intensity and Increase Consistency

Robotics is now integral to modern poultry processing. Barbut (2010) describes systems such as "RoboBatcher®", which sorts and packs cuts by weight, and 3D-guided water-jet cutting, which scans and portions with high precision. These reduce repetitive strain injuries, ensure uniform pack weights, and improve traceability. The impact is not only operational but also reputational. By integrating AI, robotics deliver predictable outcomes, reduce human error, and support consumer trust in consistent quality (Jose *et al.*, 2025; Rebezov *et al.*, 2024).

Across stunning, harvesting, and carcass processing, the evidence consistently confirms that welfare, technology, and meat quality are inseparable. Humane preslaughter handling reduces stress, improves tenderness, and lowers microbial risks, as demonstrated in goats, sheep, and cattle under varying handling and bleeding conditions (Al-Amri *et al.*, 2022; Álvarez *et al.*, 2022; Bekuma and Tadesse, 2024; Suliman *et al.*, 2024). At the same time, digital monitoring systems enhance compliance and transparency, providing processors with verifiable records and reinforcing consumer trust in safety and ethical standards (Pinela *et al.*, 2017). Furthermore, robotics and automation relieve labor-intensive bottlenecks, improve consistency, and standardize outcomes at high line speeds, showing how mechanization directly supports both efficiency and quality (Barbut, 2010). All in all, these transformations demonstrate that modern meat processing is no longer defined solely by throughput. Instead, it represents a model where technological precision, ethical responsibility, and sustainability are deeply interconnected, shaping not only how meat is produced but also how it is perceived and valued in contemporary food systems.

23.2.3 Smart Cutting and Portioning Systems: Computer Vision, Robotics, and Water-Jet Cutting for Precision, Yield Optimization, and Labor Reduction

In the story of meat processing, cutting and portioning occupy a curious place. They are at once mundane and extraordinary, routine and revolutionary. To the untrained eye, trimming fat from a poultry breast or portioning pork chops may look like ordinary butchery. Yet, behind the knife strokes lies the essence of industrial food processing: yield, uniformity, hygiene, and, increasingly, consumer trust. The efficiency of these operations determines not only how many products reach the supermarket shelf but also whether those products meet the expectations of both industry and consumers.

Just as a tailor transforms fabric into garments, meat processors transform carcasses into consumer-ready portions. The analogy is apt: both professions require precision, knowledge of material properties, and the ability to match outcomes with consumer demands. Where a tailor once wielded scissors, the modern meat plant now deploys lasers, high-pressure water-jets, and robotic arms—tools of an era that blends biology, engineering, and data science (Figure 23.1).

One of the most striking innovations in this domain is the development of frameworks for executing primal cuts within meat factory cell (MFC) contexts. For example, researchers have shown how a 3D model created from CT scans can be aligned with 3D point clouds acquired from Intel© Realsense™ cameras, refined through Bayesian Coherent Point Drift, and then used to generate cutting trajectories tailored to each animal's skeletal structure. The resulting paths guide a robotic knife, allowing it to execute precise primal cuts that account for anatomical variability. Evaluations against professional butchers demonstrate promising results, even if refinements are still needed (Mason *et al.*, 2024). This kind of work embodies the transition from butchery as a craft to butchery as an engineered process, where data rather than muscle memory guides the cut.

The need for such advances is not merely technological curiosity. The meat industry operates under relentless pressure: increasing consumption, consumer scrutiny over hygiene, and chronic labor shortages. Traditionally, carcass sorting and portioning depended on skilled workers whose judgment, speed, and dexterity were indispensable. Yet these tasks are physically demanding, repetitive, and expose workers to zoonotic risks. With diseases such as avian influenza and swine flu gaining global attention, the logic of separating humans from direct contact with raw poultry becomes undeniable. In this light, automation is more than a cost-saving measure; it is a shield against both microbial contamination and

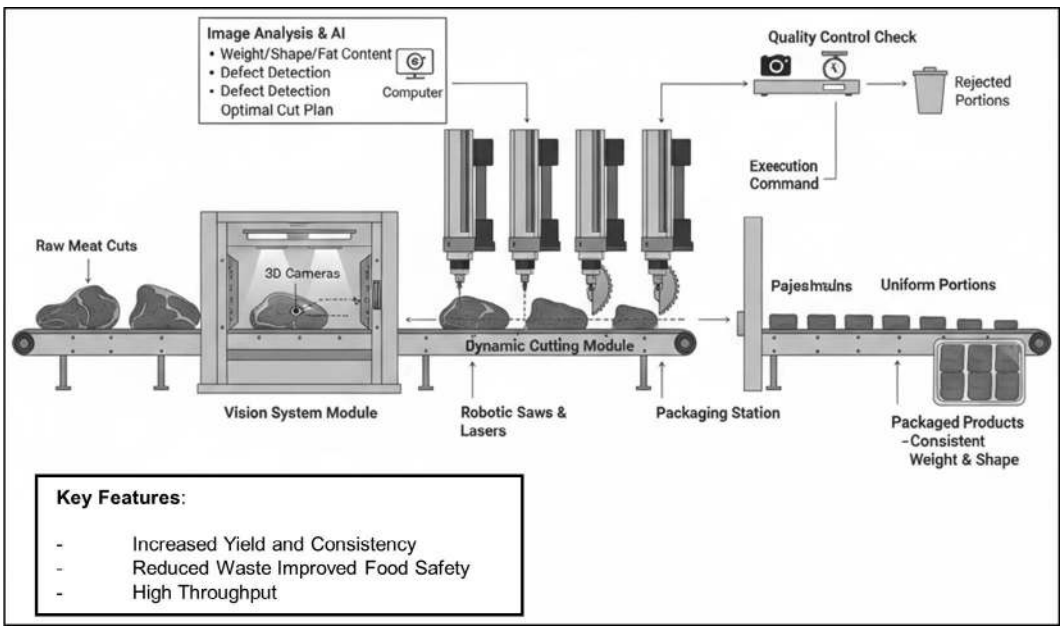

FIGURE 23.1 Smart portioning system with computer vision.

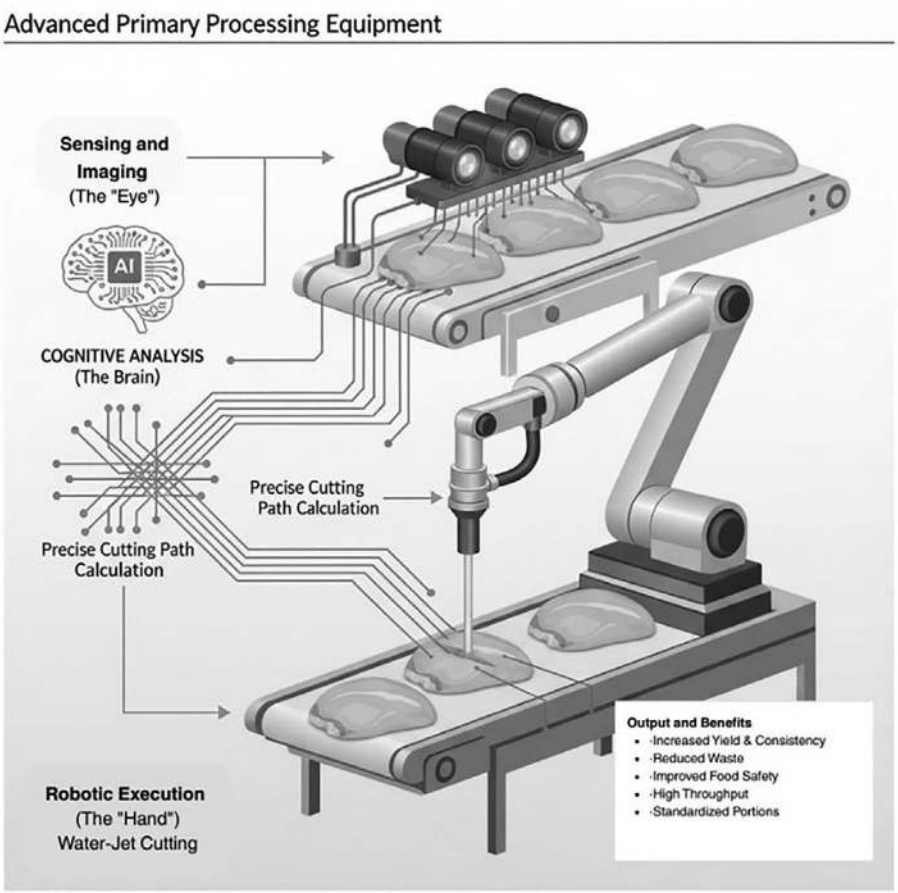

FIGURE 23.2 A smart portioning system with computer vision.

human vulnerability. Intelligent systems that combine image processing with neural networks, capable of recognizing and classifying poultry portions before guiding robotic arms to sort them, demonstrate how automation closes the gap between hygiene imperatives and industrial productivity (Figure 23.2) (Khashman, Aşıksoy and Fikretler, 2009).

23.2.3.1 Smart Cutting and Portioning Systems

The ambition of robotics in meat cutting is not new. Since the 1980s, innovators have dreamed of machines that could match or even surpass the dexterity of butchers. Yet, as one veteran in the field observed, adoption has been slow because technology alone cannot carry the weight of change. Acceptance requires commitment from the industry, financing for procurement, and a willingness to retrain staff whose roles evolve from manual cutting to supervisory and maintenance tasks. Without this cultural readiness, automation risks are seen as an intruder rather than an ally (Khodabandehloo, 2022).

The task is formidable. Unlike cutting rigid materials such as metals or plastics, meat is a deformable medium. Its texture shifts under pressure, its anatomy varies across breeds and individuals, and its value depends on achieving exacting standards of appearance and weight. It is like asking a violinist to play perfectly in tune on an instrument whose strings change tension mid-performance. To succeed, robotics must combine vision, modeling, control systems, and dexterous hardware. Recent research in vision-based approaches to cutting food underscores these challenges while also pointing to breakthroughs. By improving how robots perceive deformable objects, engineers are creating machines that can cut meat with a level of finesse once thought to be the exclusive domain of human hands (Singh *et al.*, 2025b).

From an industry perspective, cutting and portioning are about much more than appearance. They directly shape yield—the proportion of usable product from each carcass—and standardization, which drives retailer and foodservice satisfaction. Over the last decades, processors have increasingly embedded vision systems, in-line weighing, and automated routing into their production lines. These systems not only accelerate throughput but also transform cutting into a data-driven process where every carcass is graded, identified, and routed in real time (Barbut, 2010). The lesson is clear: precision cutting is not a luxury; it is a prerequisite for modern meat processing.

23.2.3.2 Computer Vision and Robotics for Precision Cutting

At the heart of these transformations is computer vision. Where once the human eye judged fat content, thickness, or shape, now 3D cameras and ML algorithms take over. In poultry breast trimming, for example, cameras measure attributes like weight distribution and thickness, feeding this data into software that calculates an optimal trim strategy. The cutting head—whether robotic knife or water-jet—then executes these paths with precision, minimizing waste and maximizing yield (Barbut, 2010).

This technological choreography can be likened to a GPS system for meat cutting. Just as GPS translates raw satellite data into turn-by-turn instructions, computer vision translates pixels into precise cutting paths. The result is not only greater efficiency but also resilience against human fatigue and error. Water-jet cutting exemplifies this promise. Unlike traditional blades, water-jets slice through meat using ultrahigh-pressure streams of water, offering noncontact, cold cutting. This avoids microbial cross-contamination and eliminates the need for constant blade sharpening. Reviews of agricultural applications highlight its versatility, from vegetables and fruits to meats and soils, and call for further development to expand its efficiency and control (Cui *et al.*, 2022). The broader industrial context adds urgency. Meat consumption is projected to increase by 15% over the next decade, placing strain on processing capacity. Yet the sector faces labor shortages and harsh working conditions that deter new entrants. Here, robotics and intelligent systems are positioned as the "knights in shining armour", providing flexible, adaptive, and sustainable solutions under the banner of Industry 4.0. Systematic reviews show how dexterous cutting robots, advanced sensors, and modular MFCs can redefine efficiency, scalability, and profitability. In this narrative, robotization is not merely about substitution but about transformation—a new industrial philosophy of meat cutting (Xu *et al.*, 2023).

23.2.3.3 Water-Jet and Laser-Cutting Systems: Advantages for Yield Optimization and Reducing Waste

Among the suite of technologies, water-jet cutting deserves special attention. Modern systems combine ultrahigh-pressure pumps, diamond orifices, CNC controllers, and fast-acting on/off valves to produce tightly controlled cutting jets. These systems excel at portioning and trimming with tight specifications and are already widely used in fish deboning, poultry trimming, and vegetable processing. Studies show that water-jet cutting not only improves ergonomics for workers but also extends shelf life in products such as lettuce and celery compared with conventional blades (Hashish, 2025).

The image is striking: a jet of water, sharpened to the fineness of a blade, slicing through meat without ever making contact. Integrated with 3D vision, these systems become even more powerful, enabling robots to portion poultry with uncanny precision at industrial speeds (Barbut, 2010). The analogy here might be of a master chef's knife guided not by the hand of a human but by the "eye" of a machine, calibrated for consistency and safety.

23.2.3.4 Benefits for Standardization of Portion Sizes, Linked to Consumer Demand for Convenience and Consistency

Yet, precision cutting is not only an industrial concern; it intersects directly with public health. Portion size has become one of the most hotly debated issues in nutrition science, as oversized servings contribute to obesity and diet-related diseases. Consumers often lack the ability to accurately judge caloric intake, and "portion distortion"—the tendency to perceive larger servings as normal—has emerged as a serious

challenge (Benton, 2015; Cohen and Story, 2014). Automated portioning systems, by contrast, enforce standardization. By ensuring fixed weights and dimensions, these systems reduce giveaway, improve retail presentation, and align with regulatory or health-oriented targets (Barbut, 2010). In this sense, portioning becomes the silent conductor of the orchestra, harmonizing consumer needs, public health imperatives, and industrial efficiency.

Evidence from consumer studies also highlights how portion size norms differ across contexts. While servings at home may be modest, out-of-home portions—particularly sugar-sweetened beverages in restaurants—tend to be significantly larger, perpetuating unhealthy norms (Liu, Allman-Farinelli and Rangan, 2024). Addressing this requires both industrial discipline in standardization and cultural shifts in consumer behavior.

23.2.3.5 Linking AI with Dynamic Portioning: Evidence from Attached Reviews of Industry Innovation

The frontier of smart portioning is being redrawn by AI. Traditional quality assessment methods are slow, costly, and limited. AI-driven models, however, offer predictive precision. For instance, ensemble learning methods such as LightGBM, XGBoost, and random forest have been used to model post-slaughter pork quality dynamics, capturing biochemical processes such as glycolysis, protein denaturation, and myoglobin redox reactions. These models achieved high accuracy, offering scalable alternatives for predicting meat color and pH (Yang *et al.*, 2025). Beyond meat chemistry, AI and IoT enable real-time automation across classification, regression, and image analysis tasks, reducing labor demands while improving safety and consistency (Jeong *et al.*, 2025). They are also reshaping quality evaluation, providing precise insights into attributes such as color, texture, and microbial load. These predictive models act like weather forecasts for meat: anticipating quality risks before they manifest, allowing processors to intervene early (Hwang *et al.*, 2025). Perhaps most transformative is the integration of AI with blockchain and IoT sensing. Together, these tools create dynamic portioning systems where cutting patterns adapt in real time based on product variability, while quality assurance data are logged into immutable records. Such integration builds brand trust, assures regulators, and provides consumers with transparency that was unimaginable in earlier eras (Rebezov *et al.*, 2024).

23.3 Automation and Robotics in Meat Manufacturing

Automation and robotics in meat manufacturing have emerged not merely as a response to labor scarcity, but as a strategic lever to transform efficiency, safety, and quality. From robotic skinning and evisceration to intelligent portioning of livestock, poultry, and seafood, recent advances reveal how sensors, computer vision, and adaptive algorithms are steadily matching—and in some cases surpassing—the dexterity of skilled butchers (Table 23.1) (Lyu *et al.*, 2025). These technologies, once confined to experimental labs, are now walking onto factory floors, reshaping workflows and reducing reliance on physically grueling tasks. Yet, as the idiom goes, "the devil is in the detail": widespread adoption still hinges on bridging the gap between industrial feasibility and cultural acceptance within the sector. If embraced holistically, the shift from muscle to microchip promises not only to lighten the load on human shoulders but also to carve out a more resilient and sustainable future for global meat supply chains.

23.3.1 Robotic Palletizing and Packaging: Enhancing Speed, Hygiene, and Flexibility

Robotic palletizing and packaging systems have emerged as the linchpin of modern agri-food logistics, combining speed with precision in environments where consistency and hygiene are paramount. The case of Dalton Seeds illustrates how automation can transform production bottlenecks into strategic advantages: the integration of robotic palletizers with weigh-bagging lines doubled capacity, streamlined changeovers between seed varieties, and virtually eliminated the ergonomic risks associated with manual handling (Schwier, Lays and Fox, 1999). Beyond throughput gains, these systems embody the principle of "doing more with less"—optimizing space with compact layouts, lowering maintenance demands,

TABLE 23.1

Comparison of Traditional versus Robotic Systems for Deboning and Trimming

Parameter	Traditional (Manual) Deboning and Trimming	Robotic / Automated Systems
Labor requirement	• High dependency on skilled labor • Repetitive strain injuries common	• Significantly reduced labor needs • Operators focus on supervision, not manual cutting
Consistency and precision	• Variable—affected by worker fatigue, experience, and technique	• High repeatability • Precise cuts guided by sensors, AI, or 3D vision
Yield efficiency	• Potential for meat loss due to over- or under-trimming • Inconsistent portioning	• Optimized yield through standardized cutting algorithms and real-time adjustments
Hygiene & safety	• Higher risk of cross-contamination due to human contact • Frequent sanitation cycles required.	• Improved hygiene with minimal human contact • Enclosed, easy-clean designs
Throughput capacity	• Limited by worker speed and shift fatigue • Variable productivity	• High-throughput • Continuous operation with consistent cycle times
Operational costs	• Lower upfront cost but high ongoing labor and training expenses	• High initial investment • Lower long-term operating costs due to automation efficiency
Flexibility	• Highly adaptable to carcass variability and complex cuts	• Increasing flexibility with AI-driven robotics, although some variability still challenging
Data and traceability	• Minimal digital data • Process monitoring relies on human reporting	• Integrated data capture (cut yield, cycle time, deviations) enabling traceability and optimization
Worker safety	• Higher exposure to knives, repetitive tasks, and ergonomic hazards	• Reduced injury risk as robots handle cutting, lifting, and hazardous motions

and embedding digital controls that monitor accuracy in real time. By replacing repetitive, heavy labor with programmable, multi-articulated arms, robotics not only curtail human error but also endow facilities with the agility to adapt to fluctuating demand. In a world where flexibility is as prized as efficiency, robotic packaging becomes more than a technical upgrade; it is a cultural shift in manufacturing, enabling food and agricultural industries to meet consumer expectations for safety and reliability while safeguarding the workforce. Ultimately, what was once a strenuous and error-prone task has become a seamless choreography of speed and reliability—automation making the process run smoothly.

According to a 2025 review in *Frontiers in Robotics and AI*, the meat industry is both one of the biggest beneficiaries and one of the toughest testing grounds for automation. Tasks such as cutting, deboning, and carcass handling are physically demanding and inherently variable, making them difficult to standardize. Yet, robotic systems—from portioning units to palletizers—are now increasingly being integrated into meat plants. The review notes that palletizing and packaging robots are not just "end-of-line conveniences" but essential to maintaining hygiene, minimizing ergonomic risks, and keeping pace with high-speed slaughter and deboning lines. By automating the transfer of boxed, bagged, or portioned meat cuts onto pallets, processors reduce contamination risks and labor injuries while also embedding digital traceability into the supply chain (Shweta *et al.*, 2025).

In short, robotic palletizing in the meat industry is inseparable from the wider move toward Meat Industry 4.0. It is not only about stacking boxes efficiently, but also about ensuring food safety, consistency, and traceability in an environment where biological variability and high-speed throughput leave little room for error (Lyu *et al.*, 2025).

23.3.2 Automated Deboning and Trimming: Robotics for Complex Tasks, Improving Yield and Worker Safety

Robotics in meat processing has moved from promise to practice, particularly in the demanding domains of deboning and trimming, where precision and consistency are paramount. As Joshi *et al.* (2016) observed, pork plants remain at the forefront of this transition, with some facilities operating near-full automation. These advances illustrate how robotics are no longer peripheral but central to addressing labor scarcity, ergonomics, and hygiene in meat manufacturing. What was once the artisanal craft of butchers has become a theater where robotic arms, guided by sensors and computer vision, act as "new hands with unerring precision".

The implications extend beyond efficiency. Studies underscore that mechanically deboned meat, though efficient, carries trade-offs in texture and quality (Barbut, 2015), reminding us that technology cannot bypass the need for vigilance in safety and quality assurance. At the same time, innovations such as HPP, modified atmosphere packaging, and irradiation help safeguard nutritional integrity while extending shelf life (Rebezov *et al.*, 2024). By coupling robotics with these protective technologies, processors can improve yield without compromising safety.

Automation also shifts the calculus of worker safety: instead of laborers enduring repetitive, injury-prone tasks, robotic systems assume the physical burden, while operators supervise and fine-tune processes. In this way, robotics represents both a technological breakthrough and a cultural shift, reframing meat cutting as a discipline that balances innovation with tradition. Ultimately, automated deboning and trimming are not simply about carving efficiency from carcasses—they exemplify how the industry walks a fine line between yield and ethics, precision and flexibility, ensuring that meat on the plate is not only plentiful but predictable.

23.3.3 Challenges and Future Directions: Adapting to Biological Variability and High-Speed Processing Lines

The future of meat processing stands at a crossroads where biological variability meets the unforgiving tempo of high-speed lines. Freezing and thawing technologies, despite decades of innovation, still struggle to reconcile consumer preference for "never frozen" meat with the inevitable biochemical changes wrought by ice crystals and protein denaturation (Zhang *et al.*, 2023). At the same time, automation and AI-driven systems promise a revolution, offering noninvasive, real-time solutions for classification, trimming, and quality prediction—but these gains are tempered by the reality that meat is a living legacy of variability, a "non-standard flexible material" whose shape, size, and elasticity continually test machine precision (FAO, 2025; Jeong *et al.*, 2025). The challenge is compounded by global demand, especially in emerging markets, where rising consumption collides with sustainability constraints, welfare expectations, and mounting competition from plant, fungal, and cell-based alternatives (Bansback, 2014; Benny, Pandi and Upadhyay, 2022; Jůzl *et al.*, 2022). Nonthermal processing technologies such as HPP, cold plasma (CP), and PEFs add powerful tools to the suite of technologies available, extending shelf life, improving tenderness, and enhancing safety—but they, too, raise unresolved questions of scalability, consumer acceptance, and regulatory adaptation (Barbhuiya, Singha and Singh, 2021; Bolumar *et al.*, 2021).

Robotics and modular MFCs are perhaps the most emblematic of the sector's future direction, shifting away from brittle, Ford-style production lines toward resilient, cell-based designs that can "dance with variability rather than stumble over it" (Hinrichsen, Wu and Gregersen, 2022; Mason *et al.*, 2024). Yet even as these technologies mature, they demand cultural change: new investment logics, workforce reskilling, and governance frameworks attuned not just to speed but to precision, safety, and ethics. The road ahead, then, is both promise and paradox. On one side lies the drive for higher throughput and uniformity; on the other side, the stubborn truth of biological complexity and shifting consumer norms. If the industry can teach machines to "see and feel as butchers do", it may finally reconcile efficiency with empathy, volume with value, and automation with authenticity.

23.4 Hygienic Design and Sanitation Engineering

At its core, hygienic design is not merely about stainless steel and smooth surfaces, but about engineering trust into every stage of food and meat processing. Consumer demand for "fresh-like", minimally processed, additive-free foods has raised the stakes: equipment must now guarantee safety without compromising quality or sustainability (Moerman and Kastelein, 2014). International standards such as the EU Machinery Directive 2006/42/EC and harmonized guidelines like EN ISO 14159 and EN 1672-2 codify this imperative, requiring all food-processing machinery to be cleanable, drainable, and resistant to contamination (Petrović, 2014). Yet, practical experience reveals that poor hygienic design—crevices, rough surfaces, dead zones—creates microbial harborage and undermines cleaning regimes, turning equipment into reservoirs of infection rather than barriers (Timperley, Thorpe and Holah, 1992). Research in Norwegian meat facilities further shows that while industry leaders acknowledge hygienic design as central to both safety and environmental sustainability, short-term cost considerations and production pressures still shape decision-making, highlighting the need for stronger regulation and targeted managerial training (Pakdel, Olsen and Bar, 2025). Sanitary design also bridges continents: while the United States speaks of "sanitary design" and Europe of "hygienic design", both converge on the same goal—processes and facilities that reduce risks of microbial, chemical, and physical contamination while streamlining maintenance and downtime (Schmidt and Piotter, 2020). Beyond compliance, hygienic design has a broader economic and ethical logic: though initially more costly, properly engineered systems extend equipment life, reduce recalls, and protect workers and consumers alike. As Bilgili (2006) notes for poultry systems, sanitation failures can cascade into costly outbreaks, while hygienically engineered plants aligned with HACCP principles safeguard not just products but also corporate reputation. Looking ahead, hygienic engineering will need to evolve in tandem with sustainability imperatives, embracing eco-friendly materials, energy-efficient cleaning systems, and multifunctional equipment. In this sense, hygienic design is more than a technical requirement—it is the quiet architecture of trust, ensuring that efficiency, safety, and sustainability sit at the same table.

23.4.1 Principles of Hygienic Equipment Design: Materials (e.g., Stainless Steel Alloys), Surface Finishes, and Cleanability

23.4.1.1 The Role of Hygienic Design in Food Safety and Consumer Trust

Hygienic design is not simply a matter of technical compliance but also the foundation upon which consumer trust in modern food and meat industries rests. As Pakdel, Olsen, and Bar (2025) emphasize, equipment design that minimizes microbial, chemical, and physical contamination is a cornerstone of sustainable operations, reducing water, energy, and chemical use while prolonging product shelf life. Their study further highlights that well-designed surfaces and configurations reduce microbial activity and support waste minimization, making hygienic design a key enabler of both safety and sustainability.

At the same time, Górny (2018) reminds us that hygienic design is inseparable from ongoing practices—sanitation, pest control, chemical monitoring, and workforce training—which together form a "living ecosystem" of hygiene. By framing hygienic design alongside occupational safety standards such as ISO 45001, he shows that safety is both a technical specification and an ethical duty, directly linking equipment integrity to workplace well-being and production quality. This synergy illustrates that hygiene is not a one-off achievement but a culture that must be continuously sustained.

Trust is the intangible currency at stake. Yang *et al.* (2023), studying public trust in water systems, show how lapses in communication or perception can erode confidence even when technical safety is intact. Drawing parallels to food production, their findings reveal that consumer faith in hygienic practices is fragile—built painstakingly over time, yet vulnerable to collapse with a single incident of contamination. De Paula *et al.* (2025) extend this view by stressing the importance of aligning systemic goals with individual behaviors, noting that infrastructure design is only as effective as the human responsibility and accountability that support it.

Gupta *et al.* (2024) provide a vivid analogy from community sanitation in India, where infrastructure alone could not eliminate open defecation without parallel social and cultural shifts. Their findings highlight the critical role of collective responsibility and investment in hygienic behaviors, lessons equally relevant to meat processing facilities. Ultimately, hygienic design emerges not as a passive technical standard but as a moral and professional commitment: every stainless steel weld, drain, or conveyor is part of a broader promise to safeguard public health and maintain consumer confidence.

Therefore, hygienic equipment design is crucial in meat processing facilities, especially since stainless steel is the preferred material due to its durability, corrosion resistance, and low microbial adhesion. Smooth, nonporous surfaces and rounded edges are highlighted as critical for minimizing microbial harborages in meat environment (Chandimali *et al.*, 2025). Moreover, meat processing plants are advised to implement *risk-based zoning*—segregating raw and finished products, using airlocks, and directional workflows. This is particularly important in high-care meat environments (like fresh meat cutting rooms) to avoid cross-contamination (Chandimali *et al.*, 2025).

23.4.1.2 Materials, Finishes, and Cleanability: Foundations of Hygienic Equipment Design

The materials and surface finishes chosen for food processing equipment form the tangible backbone of hygienic design. Detry, Sindic, and Deroanne (2010) underscore how surface characteristics—roughness, chemical composition, and surface energy—govern cleanability, with smoother and chemically stable surfaces resisting microbial adhesion more effectively. Their work further points to the potential of self-cleaning and easy-to-clean materials, showing how innovation at the microlevel translates directly into macro-level gains in safety and efficiency.

Timperley (2012) describes how organizations like the EHEDG (European Hygienic Engineering and Design Group) established systematic test methods for evaluating in-place cleanability of equipment. He stresses that cleanability is not a theoretical concept but a practical benchmark, measurable through independent certification schemes that guide both equipment manufacturers and food processors. The implication is clear: design choices validated by robust standards reduce microbial risk and elevate industry-wide trust.

Silva *et al.* (2016) provide sobering evidence from butcher shops, where *Listeria monocytogenes* was detected in 21.5% of tested surfaces, ranging from knives and grinders to workers' hands. Their findings reveal that even minor lapses in hygienic procedures, particularly where equipment surfaces harbor microbial niches, can lead to serious contamination risks. This case highlights how the interplay between material selection, surface finish, and operator practice determines real-world safety outcomes.

Material science advances reinforce these lessons. Rossi, Leso, and Calovi (2024) examined AISI 304L, one of the types of stainless steel widely used in food equipment, and showed that corrosion phenomena such as pitting and crevice formation are strongly influenced by chloride concentration, temperature, and bacterial presence. By optimizing passivation and surface treatments, they demonstrated that durability and resistance can be significantly enhanced, securing both long-term equipment performance and food safety.

Ihara *et al.* (2025) add an environmental dimension by showing how smoother surfaces created through magnetic abrasive finishing (MAF) reduced milk and protein residues in dairy pipes, cutting cleaning times and energy use. Their results illustrate that the choice of surface finish is not only about microbial control but also about sustainability, reducing the carbon and water footprint of food processing operations.

Apart from that, Waldhans *et al.* (2023) did a comparison observation toward thermoplastics, stainless steels, and nanostructured aluminized surfaces for conveyor belts. They found out that surface topography dictated cleanability, with nanostructured surfaces outperforming rough stainless steel and polymers. These results remind us that not all "stainless" or "polymeric" surfaces are created equal, and that advances in material engineering can redefine the hygiene frontier in food processing.

To sum up, these studies reinforce that material integrity, surface smoothness, and ease of cleaning are not optional extras but the very pillars of hygienic design. By grounding food safety in the molecular stability of stainless steel, the polish of a weld, or the innovation of a nanostructured surface, the industry builds not only safer equipment but also safer trust with consumers.

Last but not least, meat processing requires the strictest adherence to hygienic design principles. Stainless steel equipment with smooth finishes is essential for minimizing microbial risks. Poultry and red meat facilities are often cited as benchmarks for applying hygienic design, though real-world cases like the South Wales *E. coli* outbreak highlight lapses when design and sanitation fail. Innovative approaches—UV-C, neutral electrolyzed water, nanoscale coatings—are being explored in beef, ham, and salmon to control *Listeria* and other pathogens. Finally, zoning and workflow design in meat plants are repeatedly underscored as critical for keeping raw and cooked meat streams separated to protect consumer safety (Chandimali *et al.*, 2025).

23.4.2 Clean-in-Place (CIP) and Sterilize-in-Place (SIP) Systems: Automation of Cleaning Processes to Enhance Food Safety and Operational Efficiency

In the meat industry, where every surface that touches a carcass can become a reservoir for pathogens, the promise of CIP and SIP systems lies in their ability to transform cleaning from a disruptive, manual chore into a seamlessly automated safeguard. CIP, defined as the circulation of cleaning solutions through equipment without disassembly, has long been applied in dairies and brewing, but its value in meat processing is even more pronounced: conveyor belts, deboning machines, pipework, and chilling tanks can all be sanitized consistently without dismantling (Loeffler, 2006). The advantage is not only in speed but in repeatability—each cleaning cycle becomes as predictable as the one before, reducing human exposure to caustic agents and minimizing the ergonomic burdens of manual scrubbing. Mettu and Student (2022) stated that SIP, through the use of in situ steam sterilization, extends this logic to aseptic operations, offering validated sterility barriers that align with the regulatory expectations increasingly demanded of modern meat facilities.

Yet, experience shows that automation does not absolve complexity. Validation remains essential to ensure that CIP and SIP regimes actually achieve microbial inactivation and regulatory compliance (Kiran Deokate, Shrikrishna Baokar and Rajendra Patil, 2025). A stainless steel weld that is poorly finished or a corner of a deboning chute that traps fat residues can undermine even the most sophisticated cleaning cycle. Research in dairy pipelines, where *Bacillus cereus* was found to thrive in stagnation zones like tees and elbows, echoes challenges that are all too familiar in meat plants: complex geometries are the Achilles' heel of sanitation (Moerman, Rizoulières and Majoor, 2013; Silva *et al.*, 2023). Here, pulsed-flow CIP strategies have proven capable of not only enhancing microbial reduction—up to 2.3 log CFU/cm^2 greater in tee branches compared to conventional methods—but also cutting downtime by 20% and reducing water and chemical usage by up to a quarter. For meat machinery, which often operates under high throughput and tight margins, such improvements translate directly into safer products, longer equipment lifespans, and greener, more sustainable operations.

As an upshot, these insights highlight CIP and SIP not as optional add-ons but as integral parts of meat machinery design. Their implementation speaks to a broader cultural and technological shift in meat processing: one where cleaning is no longer reactive but embedded, where hygiene is engineered into the equipment itself, and where sustainability and safety move hand in hand. In the "hidden hours" when lines are silent, automated cleaning systems are the unseen workforce, such as scrubbing pipes, scouring joints, and sterilizing valves, which will be ensuring that when production resumes, every cut of meat is handled within a clean, safe, and compliant environment. In this sense, CIP and SIP embody the invisible scaffolding of consumer trust, reminding us that in meat science, the battle for safety is often won not at the cutting line but in the silent flow of water, chemicals, and steam that prepare it for another day of operation (Figure 23.3).

23.4.3 Biofilm Prevention and Control: Design Strategies and Technologies to Mitigate Microbial Hazards

Biofilms are more than just microbial colonies; they are sophisticated, self-protecting structures that encase bacteria within a matrix of extracellular polymeric substances, making them notoriously resilient to hostile environments and chemical disinfectants. From a public health perspective, they are a double-edged sword—some biofilms can be neutral or even beneficial, but harmful ones compromise

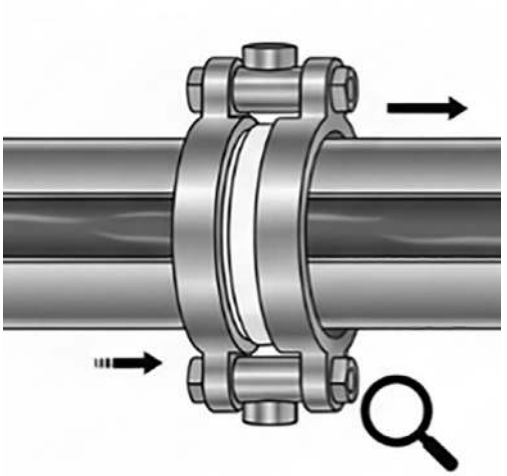

FIGURE 23.3 Comparison of hygienic versus non-hygienic equipment joints.

food safety, trigger diseases in animals and humans, and jeopardize industrial hygiene, calling for robust strategies to disrupt their formations (Yin *et al.*, 2021). Approaches have ranged from altering surface properties to block microbial adhesion, to interfering with bacterial signaling pathways, to applying external forces that literally strip away biofilms—each reflecting the principle that prevention is more effective than cure.

In food production systems, biofilms magnify the challenge of pathogen control, as foodborne microbes protected by these matrices exhibit remarkable resistance to sanitizers and preservation technologies. Physical interventions such as thermal shocks, ultrasonic waves, and electric fields have demonstrated promise in weakening biofilm integrity, while chemical agents—ranging from acidulants to enzymatic cleaners—target the extracellular scaffolding that holds biofilms together (Dawan, Zhang and Ahn, 2025). Surface engineering, through advanced coatings and antimicrobial modifications, represents a parallel frontier, offering equipment that resists microbial colonization from the start.

The science of biofilms also reveals their complexity at the microscopic level: adhesion and persistence depend not only on microbial genetics but also on surface chemistry, pH, and nutrient availability. This means biofilms amplify microbial virulence and make pathogens harder to eradicate with traditional antimicrobials. To address this, novel control methods are emerging, including nutrient manipulation, biosurfactants, and patented surface-modification technologies that aim to deny bacteria the foothold they need to form structured communities (Cortés, Consuegra and Ruben, 2011).

Medical research adds another layer of urgency, as biofilms have been implicated in infections tied to orthopedic devices, catheters, and chronic wounds. Such infections are notoriously resistant to antibiotics, fueling the search for alternative solutions like photodynamic therapy, antimicrobial lock techniques, and bioactive molecules that can break biofilm barriers (Kalkanci and Güzel Tunçcan, 2019). While these studies are healthcare-focused, the underlying lesson applies equally to food and meat plants: once biofilms are established, conventional treatment options lose their edge.

In the broader food industry, biofilms drive spoilage, shorten shelf life, and threaten consumer trust. Their control hinges on understanding how surface roughness, topography, and free energy influence microbial adhesion. Advanced innovations, such as nanotechnology-based detection systems and computational modeling, are beginning to offer predictive and preventive tools that could shift industry practice from reactive cleaning to proactive biofilm management (Anjum Reem *et al.*, 2025).

Similarly, pharmaceutical and food science studies have highlighted that biofilms resist antibiotics, demanding agents with structural versatility. Research has explored peptides, lantibiotics, enzymes, nanoparticles, and biosurfactants as next-generation antibiofilm molecules capable of disrupting these defensive layers without harming the host or product environment (Asma *et al.*, 2022). For meat processors, such agents could form part of the biochemical portfolio of tomorrow's sanitation strategies.

Dairy systems provide a close analogue to meat plants: stainless steel lines, bends, and tees in circulation pipelines become micro-niches for biofilms that daily sanitation cannot fully remove. Studies evaluating CIP enhancements—like high-pressure sprays, pulsed flow, or even robotics—demonstrate that redesigning both equipment geometry and cleaning chemistry can deliver significant improvements in microbial reduction, while cutting water, energy, and chemical use (Chowdhury *et al.*, 2025). This mirrors the sustainability imperative increasingly demanded in meat machinery design.

The battle is ongoing, as biofilms persist even after sanitation cycles. Their life cycle—attachment, maturation, and dispersion—means that any lapse in control allows pathogens to reseed entire facilities. Thus, green biochemical solutions such as essential oils, enzymes, and biosurfactants are being explored as safe and consumer-friendly alternatives to harsh chemical disinfectants (Zhu *et al.*, 2022).

For meat processors, the challenge is not hypothetical. Biofilms readily form on fresh meat, processed products, and on critical surfaces of equipment like slicers, grinders, and conveyors. Once established, they resist removal during routine sanitation, forcing processors to adopt novel hurdles such as ultrasound, CP, bacteriocins, and phage-based interventions to prevent bacterial persistence and contamination (Oliulla *et al.*, 2024).

Industry experience confirms this: visually clean surfaces can still harbor biofilm-embedded bacteria, which daily sanitation routines rarely eliminate completely. Mechanical abrasion, intensified disinfection, or targeted sanitation protocols can reduce microbial loads, but the most effective strategy is proactive identification of critical sites and the deployment of the right cleaners and disinfectants in combination (Jessen and Lammert, 2003). This "multiple-hurdle" approach is now seen as essential in modern meat plants.

Molecular surveys further highlight that meat plant biofilms are not dominated by pathogens alone; background microbiota such as *Pseudomonas* and *Acinetobacter* often form the foundation upon which more dangerous bacteria like *L. monocytogenes* and *Salmonella* attach and thrive. These commensal organisms provide protection and even harbor resistance genes, complicating disinfection. Addressing this layered ecology requires not just pathogen-targeted cleaning, but eco-friendly antibiofilm strategies capable of dismantling the entire microbial community (Alves *et al.*, 2024).

Looking to the future, even cultured meat production faces risks from biofilm contamination in scaffolds, bioreactors, and nutrient media. Studies warn that *Listeria*, *Salmonella*, and *E. coli* could exploit design flaws in scaffolds or reactor walls to establish persistent biofilms, compromising safety and efficiency. Preventive solutions may include biosensor-based detection, AI-driven monitoring, and advanced enzymatic treatments that are able to keep pace with the unique challenges of cellular agriculture (Rahman *et al.*, 2025).

In sum, biofilm prevention and control represent one of the most pressing frontiers in meat processing hygiene. From modifying surface finishes and deploying green antimicrobials, to redesigning cleaning regimes and embracing smart detection technologies, the industry must learn to "think like microbes" in order to outmaneuver them. The message is clear: in meat plants, the battle against biofilms is not won with a single technology or agent, but with a layered strategy that anticipates microbial persistence, targets both pathogens and their protective allies, and integrates hygiene into the very fabric of equipment design. Only then can processors ensure that the promise of safe, high-quality meat products is not compromised by these silent but stubborn microbial architects.

23.5 Processing Technologies: Thermal and Nonthermal

Processing technologies stand at the crossroads of food science, nutrition, and consumer expectations, shaping not only the safety of what we eat but also its sensory and nutritional character. Thermal treatments remain central to this landscape, yet their effects extend beyond microbial inactivation—they fundamentally alter muscle proteins, shifting digestibility and nutritional outcomes depending on how heat is applied. As Bhat *et al.* (2021a) remind us, gentle techniques such as sous-vide can unfold proteins to make them more digestible, while harsher methods like roasting or stewing can trigger aggregation, oxidation, and reduced gastrointestinal breakdown, demonstrating that the "heat we taste" is also the "heat we digest".

Conventional sterilization processes have long been trusted allies in meat safety, reliably protecting against pathogens, yet they often sacrifice aroma, flavor, and texture along the way. Barbosa-Cánovas *et al.* (2014) highlight that new approaches—from pressure-assisted thermal sterilization (PATS) to advanced retorting—seek to overcome these trade-offs by combining regulatory assurance with improved quality, showing that even within heat-based methods, innovation can balance tradition with progress. Still, widespread adoption requires careful optimization, regulatory approval, and industry trust, underscoring that technological promise must walk hand-in-hand with practical feasibility. Equally important is the recognition that processing technologies must navigate not only the science of preservation but also the art of eating. Gómez *et al.* (2020) emphasize that while methods such as fermentation, marination, or smoking can enrich flavor and functionality, they often come at the expense of nutritional integrity, unless carefully managed. Their call for integrative research—blending nutritional optimization with sensory appeal—reminds us that meat processing is not a zero-sum game but rather a delicate balancing act between taste and health. The meat sector has seen both opportunity and caution in adopting emerging heat-based technologies. Hassoun *et al.* (2021) underline that while microwaving, ohmic heating, and radio frequency (RF) methods offer speed and uniformity, they can also provoke undesirable structural or sensory changes if mishandled. To mitigate these risks, they advocate for rapid, nondestructive spectroscopic monitoring tools, shifting industry practice toward continuous quality oversight rather than reactive correction. Beyond heat, the pressures of sustainability and consumer demand for "clean-label" foods are accelerating the rise of nonthermal technologies. Ghazali *et al.* (2025) show how CP and HPP achieve significant pathogen reduction—up to 5 log cycles—while preserving texture, flavor, and nutrient integrity, often with lower energy and water costs than thermal methods. Yet, challenges of infrastructure cost, scalability, and consumer perception remain, suggesting that hybrid systems and targeted optimization may be the most pragmatic pathway forward for widespread adoption in meat preservation.

Taken together, these perspectives show that processing technologies—thermal and nonthermal alike—form the double helix of modern meat engineering: one strand ensuring safety and compliance, the other striving to preserve quality, nutrition, and sustainability. The story is not one of replacement but of complementarity, where sous-vide meets HPP, where retorting meets CP, and where tradition meets innovation. For meat science, the pressing task is clear: to refine these tools so that what reaches the consumer's plate is not only safe and sustainable but also delicious, nutritious, and trustworthy (Figure 23.4).

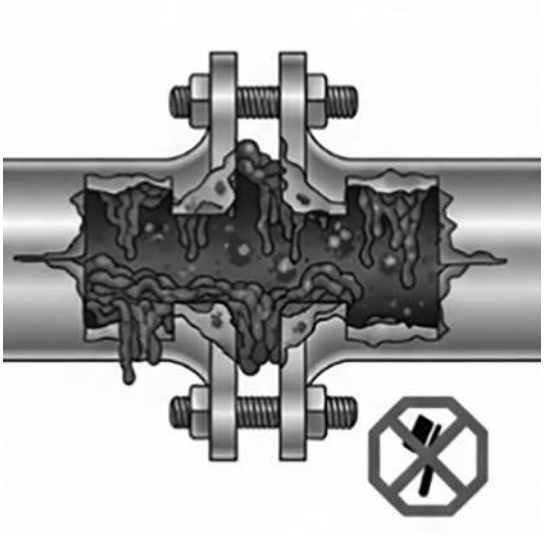

FIGURE 23.4 Graphical comparison of processing technologies: lethality versus quality.

23.5.1 Advanced Thermal Processing: Microwave, Ohmic Heating, and RF Heating for Improved Safety and Quality

Thermal processing remains one of the oldest and most dependable tools in food technology, safeguarding meat products from microbial risks while also shaping their sensory and nutritional profiles. Yet, the very heat that ensures microbiological stability can also transform muscle proteins, altering digestibility and diminishing delicate flavor and textural qualities when treatments are too severe (Bhat *et al*., 2021b). Conventional thermal methods such as roasting, stewing, or frying have long guaranteed safe consumption, but they are increasingly scrutinized for their negative effects on quality, pushing researchers and industry to pursue more refined or alternative solutions (Barbosa-Cánovas *et al*., 2014).

A growing body of research illustrates that combining preservation with quality retention requires a nuanced balance of approaches. Integrative reviews emphasize the importance of both physical and biochemical methods—from sous-vide and dry aging to marination and reformulation—highlighting that while safety is nonnegotiable, sensory experience and nutritional integrity must not be sacrificed (Gómez *et al*., 2020a). Recent advances demonstrate how both traditional and novel heating technologies, including ohmic and RF heating, can be continuously monitored and optimized through nondestructive methods such as spectroscopy, allowing safer products with fewer trade-offs (Hassoun *et al*., 2021).

In parallel, the demand for sustainable preservation methods is intensifying as global meat consumption grows. Conventional thermal systems, though effective for microbial control, consume vast amounts of energy and water while degrading sensitive nutrients. This has positioned advanced technologies such as microwave heating and RF heating as pivotal innovations. These methods not only offer deep microbial inactivation and improved safety but also better preserve sensory qualities, reduce resource use, and align with sustainability and "clean-label" consumer demands (Ghazali *et al*., 2025). Alongside these innovations, microwave heating has reemerged as both a domestic staple and an industrial candidate, offering rapid and efficient heating that contrasts sharply with the slower and more uneven nature of conventional thermal methods. By directly interacting with polar molecules and dielectric properties of foods, microwaves generate internal heat that can reduce processing time, water loss, and microbial risks during tempering or thawing. Yet, the very mechanism that confers speed can also become a double-edged sword, producing uneven energy distribution, "hot spots", and quality deterioration in complex or high-fat matrices (Yarmand and Homayouni Rad, 2011). Over the past decade, new thermal strategies have sought to refine these challenges and push microwave technology into more reliable domains of food safety. Alternative sterilization approaches such as pressure-assisted thermal sterilization (PATS), advanced retorting, and microwave-assisted heating have demonstrated regulatory acceptance and industrial feasibility, though broader adoption still hinges on optimizing consistency and scalability (Barbosa-Cánovas *et al*., 2014). Beyond simple heat delivery, researchers now recognize microwaves as a transformative driver of food structure and nutrition. Their influence on starch, lipids, and proteins, as well as their ability to enhance nutrient availability, modify bioactive compounds, and even alter allergenic potential, suggests both promise and complexity. With these biochemical shifts come opportunities to design new functional foods, but also a need for careful mechanistic insight to avoid unintended nutritional or sensory losses (Deng *et al*., 2022).

At the level of meat safety, microwave heating has been applied to pasteurize mechanically tenderized beef inoculated with pathogens such as *E. coli* O157:H7. By employing staged heating protocols with infrared feedback, researchers have shown complete inactivation at temperatures above 70 °C, thereby establishing a path toward safer ready-to-eat microwaveable meats (Huang and Sites, 2010). Studies with yak meat further revealed that short, high-power microwaving can denature proteins efficiently, lowering shear force and improving tenderness, though often at the expense of color stability and elevated cooking loss. Volatile compound formation and enhanced aroma profiles point to a delicate balance between functionality and flavor outcomes (Li *et al*., 2019).

Spectroscopic and structural analyses deepen this picture. FTIR studies of bovine meat indicate that microwaves partially reduce Maillard reaction pathways compared with conventional ovens, yet they also drive secondary protein structural changes such as β-sheet aggregation and β-turn formation. These conformational shifts underpin both textural modifications and sensory outcomes, underscoring the importance of time–power combinations in preserving product quality(Calabrò and Magazù, 2012).

At a more general nutritional level, evidence shows that microwave and ohmic heating can mitigate severe protein denaturation when higher heating rates are applied, compared to traditional methods that often induce aggregation and cross-linking (Bhat *et al.*, 2021b). Altogether, microwave heating emerges not merely as a convenient tool but as a frontier technology whose role in meat processing is being reshaped by engineering advances and nutritional insights. Its capacity to improve microbial safety, reduce processing time, and enhance tenderness makes it indispensable, yet its limitations in heating uniformity and sensory preservation remain active research frontiers. For the meat industry, the challenge ahead is to turn this fast-acting energy source into a precision instrument—one that balances safety with flavor, nutrition with efficiency, and innovation with consumer trust.

Ohmic heating, meanwhile, represents a different philosophy: instead of applying heat externally, it uses electrical currents to generate heat uniformly within the product matrix. Applied successfully in products from meatballs to sausages, OH drastically shortens cooking times, enhances juiciness, and reduces energy consumption, while maintaining microbial safety and minimizing quality losses (Balthazar *et al.*, 2024; Dal, Gursoy and Yilmaz, 2025; Jafarpour and Hashemi, 2022). Its challenges—electrode corrosion, uneven heating in fatty meats, and investment costs—remain barriers to large-scale adoption, yet advances in design and modeling suggest significant untapped potential (Varghese *et al.*, 2014).

RF heating complements this landscape with its unique ability to deliver rapid, volumetric, and deep-penetrative energy into high-moisture foods such as minced meats, sausages, and ready-to-eat meals. Unlike microwave heating, RF penetrates further and more uniformly, reducing thawing times, pasteurizing or sterilizing products, and even aiding in cryogenic freezing with fewer drip losses (Dragoev *et al.*, 2024; Gao *et al.*, 2023; Popa *et al.*, 2015). Yet, ensuring heating uniformity and controlling hot or cold spots remains a technical challenge, particularly in irregularly shaped meat products, spurring the use of computational modeling and equipment customization to refine its performance (Jiao *et al.*, 2018; Wang *et al.*, 2022b).

Seen through the lens of modern food engineering, microwave, ohmic, and RF heating represent distinct but converging paths toward the same goal. Each offers unique tools to improve microbial safety, preserve nutritional integrity, and enhance consumer trust, while reducing the environmental footprint of processing. Their thoughtful integration signals a new phase in meat processing—one where sustainability, safety, and sensory quality can finally walk hand in hand.

23.5.2 Emerging Nonthermal Technologies: HPP, CP, PEFs, and Ultrasound Applications for Microbial Inactivation and Process Enhancement

Nonthermal technologies have moved from the fringes of food innovation toward the center of modern meat processing, driven by a dual imperative: deliver microbiological safety and shelf life extension while protecting the very qualities that consumers prize—fresh-like flavor, color, texture, and nutritional value. In contrast to traditional heat treatments that often trade sensory integrity for certainty of kill, these approaches act through pressure, electrical discharges, electric fields, or acoustic energy to destabilize microorganisms and modulate tissue structure with little or no thermal load. As regulatory and market pressures converge on "clean-label", energy efficiency, and waste reduction, processors are re-tooling their unit operations around platforms that can achieve safety targets, reduce preservative use, and minimize resource intensity—without dulling taste or texture. Within this landscape, four modalities have crystallized as particularly influential for meat systems: HPP, CP, PEF, and power/high-intensity ultrasound (HIUS). Each technology is distinct in mechanism and process integration, but all are being engineered to work either as stand-alone interventions or as hybrid nodes within multi-hurdle preservation strategies that reconcile safety, quality, and sustainability in one pass (Ahmed, Ranjan and Roy, 2025; Akhtar *et al.*, 2022; Bak and Paulsen, 2023; Bolumar *et al.*, 2021; Dong *et al.*, 2022; Fan *et al.*, 2023; Ghazali *et al.*, 2025; Ghazali, Saleem and Bashir, 2025; Jayasena *et al.*, 2023; Karki *et al.*, 2022; Roobab *et al.*, 2023; Soltani Firouz *et al.*, 2022; Tomasevic *et al.*, 2023; Umair *et al.*, 2023; Zhang *et al.*, 2023, 2025b).

High-Pressure Processing: Among nonthermal options, HPP is the most commercially mature, consistently achieving cold pasteurization of meats at up to ~600 MPa while preserving fresh-like attributes and enabling lower additive loads. It is now deeply embedded in ready-to-eat and cured categories

where uniform in-package treatment extends shelf life, trims food waste, and aligns with regulatory frameworks such as USDA-FSIS guidance on post-lethality controls (Avure, n.d.; Bolumar *et al*., 2021; Campus, 2010). The quality response of muscle foods, however, is cut- and matrix-dependent: pressure-induced unfolding/aggregation phenomena in proteins and pressure–myoglobin interactions can express as color shifts or oxidative susceptibility in certain lamb and beef cuts at higher set points, underscoring the need for pressure/time tuning, antioxidant systems, and packaging control to guard against lipid oxidation (Ma *et al*., 2020). Despite these nuances, the adoption curve continues upward because HPP uniquely couples volumetric safety with label-friendly positioning and international scalability, offering a reliable nonthermal backbone that many processors now treat as a platform rather than a point solution (Bolumar *et al*., 2021; Campus, 2010; Ma *et al*., 2020).

Cold Plasma: If HPP is the workhorse, CP is the agile specialist—a surface-active, room-temperature intervention capable of 2–3 log pathogen reductions on meats with comparatively modest impacts on lipids and color when parameters are well-tuned (Ghazali, Saleem and Bashir, 2025; Jayasena *et al*., 2023). Mechanistically, CP supplies a cocktail of reactive oxygen and nitrogen species (ROS/RNS) that damage microbial membranes and nucleic acids; intriguingly, the same chemistry is being explored for novel curing effects and nitrite substitution, although protein and fat oxidation risks must be carefully managed (Fan *et al*., 2023; Zhang *et al*., 2025a). Because CP is highly configuration-sensitive (gas composition, power, exposure time, gap distance, humidity), study outcomes vary from "improved" to "off-odor" in sensory panels, and relatively few experiments quantify the in situ reactive species that drive quality outcomes; filling this mechanistic gap is pivotal for parameterization that delivers antimicrobial efficacy without compromising aroma and color (Bak and Paulsen, 2023). Beyond direct decontamination, a second wave of CP innovation is unfolding at the packaging interface: plasma-treated bio-based films and intelligent polymers that respond to pH or volatiles can both inhibit spoilage and signal freshness, though industrial validation, lipid-oxidation control, and regulatory clarity remain outstanding workstreams (Ghazali *et al*., 2025; Umair *et al*., 2023). In sustainability terms, CP's low electrical demand and negligible water use give it a favorable resource profile; pairing CP for surface lethality with HPP for volumetric safety is an emerging hybrid strategy that meets clean-label and eco-efficiency targets without the sensory penalties of high heat (Ghazali, Saleem and Bashir, 2025; Jayasena *et al*., 2023).

Pulsed Electric Fields: PEF's promise lies in electroporation—transient or permanent pores in cell membranes that enhance mass transfer, tenderize tougher cuts, and facilitate downstream steps such as curing, marination, drying, and fermentation—all at low thermal load and with attractive energy economics. Across meat, poultry, and seafood, the literature points to process intensification (shorter times, lower energy), opportunities for sodium reduction via improved diffusion, parasite inactivation in select seafood, and valorization of by-products through more efficient extraction—all while better preserving nutrients relative to conventional heat processes(Ahmed, Ranjan and Roy, 2025; Gómez *et al*., 2019; Jeong *et al*., 2025). That said, technology readiness depends on mastering the "electrical recipe": field strength, pulse number/duration, specific energy, frequency, and electrode geometry interact with meat's own heterogeneity (muscle type, fat marbling, collagen) to shape tenderness gains, water-holding, and color. Reports on cooking loss are mixed, and higher specific energies can lighten L while leaving a and b relatively stable; aligning targets (e.g., tenderization vs. minimal color shift) with parameter windows is essential for reproducibility at scale (Karki *et al*., 2022; Tomasevic *et al*., 2023). Flavor chemistry is a burgeoning area: in chicken breast, low- and higher-intensity PEF modulated free amino acids linked to umami (glutamate/aspartate) and precursors (leucine/valine) while suppressing bitter contributors (lysine/tyrosine), suggesting PEF can subtly "tune" taste without injuring baseline physicochemical quality (Roobab *et al*., 2023). On the process side, PEF can accelerate moisture removal and drying kinetics via membrane permeabilization—cutting sausage drying time by ~41–47% in gauze-stuffed formats and boosting pork-loin dehydration under specific 0.1–5.0 kV/cm, 10–200 µs, 0–56 kJ/kg regimes; however, natural casings blunt the effect, highlighting the need to co-design product geometry, casing permeability, and PEF parameters (Anonymous, 2022; Astráin-Redín *et al*., 2019). Strategically, industry adoption will track advances in cost-effective power supplies, hygienic electrodes, and continuous systems that can be slotted before tumbling/brining or as a pre-drying/tenderization node; the energy-efficiency argument is compelling, but standardized parameter sets for different species and cuts will be the lever that

moves PEF from promising pilot to dependable plant utility (Ahmed, Ranjan and Roy, 2025; Alahakoon *et al*., 2016; Gómez *et al*., 2019; Jeong *et al*., 2025; Tomasevic *et al*., 2023).

Ultrasound (HIUS/Power Ultrasound): Ultrasound delivers mechanical energy via cavitation and microstreaming, translating into two families of effects in meat: (i) structural modification—disrupting connective tissues, loosening myofibrillar architecture, and improving water-holding capacity; (ii) process enhancement—accelerating mass transfer (curing/marinating), freezing/thawing, and even fermentation dynamics. Syntheses of the field conclude that HIUS can improve tenderness, speed maturation, reduce cooking energy, extend shelf life, and strengthen the functional properties of emulsified systems, with secondary benefits in equipment hygiene (Alarcon-Rojo *et al*., 2015; Soltani Firouz *et al*., 2022). Mechanistic work on tenderization traces effects at the fiber and connective tissue levels, while application studies show antimicrobial impacts in poultry at 20–850 kHz with power densities from ~10–28 W/cm^2, reducing lactic, mesophilic, and psychrophilic counts and thereby supporting preservation aims (Dong *et al*., 2022; Piñon *et al*., 2019). Not all frequencies or powers are equal: lower-frequency, higher-power probes (e.g., 20 kHz) tend to exert stronger bactericidal and texturizing effects than higher-frequency, lower-intensity baths, and the balance between tenderness gains and potential oxidative/quality shifts must be managed with time–power envelopes and, where relevant, antioxidant or packaging strategies (Alarcon-Rojo *et al*., 2015; Piñon *et al*., 2019). Looking forward, "sonoprocessing" is expanding beyond classical unit ops into green-chemistry-adjacent roles (e.g., aiding enzymatic cross-linking or targeted modifications) and into sustainability programs that seek measurable reductions in time, energy, and water; however, scaling requires investment in efficient transducers and robust process control (Taha *et al*., 2024). In parallel, programmatic initiatives such as Ultratender have demonstrated that high-power ultrasound can be integrated with digital monitoring and real-time control to deliver energy/water savings while improving consistency—an industrial blueprint for embedding acoustics into broader quality-by-design architectures (Rodríguez, 2017), putting the pieces together for meat systems. From an engineering perspective, these technologies occupy complementary "attack planes" against microbial risk and quality decay: HPP treats the whole package volumetrically; CP excels at the product–surface and packaging interface; PEF modulates membranes to unlock mass transfer and texture; HIUS amplifies diffusion and mechanical softening while conferring microbial and energy-savings dividends. The design challenge is not simply selecting a tool but sequencing and coupling them to exploit synergies—for example, CP for surface lethality followed by HPP for internal safety in sliced RTE meats; PEF pre-treatment to hasten curing/drying or to tenderize tough cuts before sous-vide; or HIUS-assisted marination to reduce sodium/time while protecting juiciness(Akhtar *et al*., 2022; Bolumar *et al*., 2021; Jayasena *et al*., 2023; Zhang *et al*., 2025a). Success at scale hinges on three levers. First, *parameter discipline:* define validated windows for pressure, species-specific CP atmospheres/power, PEF field strengths/specific energies, and HIUS frequency–intensity–time pairs that deliver target log reductions or texture outcomes without overshooting color/oxidation thresholds. Second, *matrix-aware design:* account for cut geometry, fat marbling, casing/permeability, and packaging headspace to avoid uneven fields (cold/hot spots in CP, PEF, RF analogues) and to harness mass-transfer or acoustic effects efficiently. Third, *system integration:* embed sensors and real-time control (IR, spectroscopy, impedance, acoustic signatures) to monitor endpoints in-line; the same spectroscopic toolbox championed for thermal monitoring is now essential for nonthermal assurance (Bak and Paulsen, 2023; Jayasena *et al*., 2023; Soltani Firouz *et al*., 2022).

Quality, safety, and sustainability trade-offs. Properly tuned, these nonthermal routes deliver the coveted trifecta—safety, sensory preservation, and resource efficiency. HPP provides reliable 4–5 log vegetative inactivation and longer chill-chain life with minimal heat damage but requires capital expenditure and attention to color and oxidation in particular cuts (Avure, n.d.; Bolumar *et al*., 2021; Campus, 2010; Ma *et al*., 2020). CP can deliver surface lethality at ambient conditions with very low water and energy use, and it is opening new territory in intelligent packaging—yet sensory consistency and mechanistic quantification of reactive species must advance to unlock full regulatory acceptance (Bak and Paulsen, 2023; Ghazali *et al*., 2025; Jayasena *et al*., 2023; Zhang *et al*., 2025a). PEF's impact on tenderization, diffusion, and drying presents clear cost-of-goods opportunities, but commercialization depends on robust, hygienic, and cost-effective power systems and on playbooks tailored by species and cut (Ahmed, Ranjan and Roy, 2025; Anonymous, 2022; Asráin-Redín *et al*., 2019; Jeong *et al*., 2025; Karki *et al*., 2022;

Tomasevic *et al*., 2023). HIUS offers a versatile lever for tenderization and process intensification while contributing antimicrobial effects; the remaining work lies in industrial-grade transducer efficiency, oxidation control, and standardized QA/QC to translate promising trials into repeatable plant routines (Alarcon-Rojo *et al*., 2015; Piñon *et al*., 2019; Rodríguez, 2017; Soltani Firouz *et al*., 2022; Taha *et al*., 2024).

Future directions and industry playbook. What does a pragmatic roadmap look like for a meat processor? For sliced RTE portfolios, pair CP (surface) plus HPP (volumetric) to meet safety and shelf life targets while retiring lactates and nitrites where feasible; invest in spectroscopic QA to verify color/oxidation endpoints (Avure, n.d.; Bak and Paulsen, 2023; Bolumar *et al*., 2021; Campus, 2010; Ghazali, Saleem and Bashir, 2025; Jayasena *et al*., 2023). For whole-muscle and tougher cuts, deploy PEF pretreatments before tumbling, curing, or sous-vide to lift tenderness and shorten diffusion-limited steps; integrate HIUS into marination or thawing to compress cycle times and reduce purge loss (Ahmed, Ranjan and Roy, 2025; Alarcon-Rojo *et al*., 2015; Jeong *et al*., 2025; Karki *et al*., 2022; Soltani Firouz *et al*., 2022). For dry-cured lines, use PEF to accelerate early water removal where casing design allows, and apply CP-enabled smart packaging to both inhibit post-process spoilage and signal freshness states through colorimetric cues(Anonymous, 2022; Astráin-Redín *et al*., 2019; Ghazali *et al*., 2025). Finally, fold these tools into a quality-by-design architecture—sensorized equipment, model-based control, and validated parameter windows—so that innovation scales with predictability rather than trial-and-error (Rodríguez, 2017; Soltani Firouz *et al*., 2022).

In sum, HPP, CP, PEF, and ultrasound are no longer speculative novelties; they are converging into a practical, interoperable toolkit for modern meat operations. Where traditional heat once forced unpleasant compromises, these nonthermal routes make it realistic to pursue safety, flavor, texture, nutrition, and sustainability in the same breath. Deployed with discipline—and often in concert rather than isolation—they give processors levers to fine-tune outcomes at the molecular and meso-structural levels while shrinking energy, water, and additive footprints. The result is a new design space for meat processing: one where science-based parameterization and smart integration turn headline promises into daily plant performance.

For HPP, its global adoption reflects both regulatory confidence and growing demand in ready-to-eat and cured categories, positioning it as the most commercially mature of these interventions (Avure, n.d.; Bolumar *et al*., 2021; Campus, 2010; Ma *et al*., 2020). Its success, however, also reminds us that product-specific factors—from cut type to fat content—still demand careful calibration.

CP, by contrast, is still on the rise but has quickly gained recognition for its antimicrobial power and its potential to act as a novel curing agent. The literature consistently highlights its ability to control pathogens in beef, pork, lamb, and poultry with only minor shifts in physicochemical traits, though concerns around sensory consistency, oxidation, and regulatory clarity remain to be resolved (Akhtar *et al*., 2022; Bak and Paulsen, 2023; Jayasena *et al*., 2023; Zhang *et al*., 2025a). Importantly, comparative studies suggest that when paired with HPP, CP can extend the promise of clean-label, low-input meat preservation, thereby aligning consumer preference for fresh quality with industry imperatives for reduced waste and energy use (Fan *et al*., 2023; Ghazali *et al*., 2025; Ghazali, Saleem and Bashir, 2025; Umair *et al*., 2023).

PEFs add another layer to this landscape. Unlike plasma, which primarily addresses microbial safety, PEF demonstrates clear potential to improve meat tenderness, enhance mass transfer during curing or drying, and reduce energy loads in production. Studies emphasize its versatility, showing how short pulses of high voltage can tenderize low-value cuts, accelerate diffusion, and even shorten drying times in traditional sausage manufacture. Yet, reproducibility depends heavily on parameter control, from field strength to pulse duration, reminding engineers that this is not a "plug and play" technology but one that requires finely tuned precision to deliver consistent benefits (Ahmed, Ranjan and Roy, 2025; Jeong *et al*., 2025; Karki *et al*., 2022; Roobab *et al*., 2023; Tomasevic *et al*., 2023).

Ultrasound rounds out this emerging toolkit, bringing with it a reputation for flexibility. Long studied in agriculture and food processing, it has found new footing in meat applications where tenderization, marination, microbial inhibition, and process intensification are prized outcomes. The technology helps accelerate maturation, improves functional properties in emulsified products, and extends shelf

life while reducing cooking energy requirements. In this respect, ultrasound is often cast as the "silent partner" in nonthermal innovation—less radical than CP or PEF but deeply complementary, particularly when paired with existing thermal or mechanical steps (Alahakoon *et al*., 2016; Alarcon-Rojo *et al*., 2015; Anonymous, 2022; Astráin-Redín *et al*., 2019; Gómez *et al*., 2019; Jayasooriya *et al*., 2004).

Recent demonstrations of high-intensity ultrasound and integrated sonoprocessing push this even further, showing its ability to combine with digital monitoring systems to create smart, responsive production lines. Here, tenderness and microbial safety are achieved alongside reductions in energy and water, underscoring ultrasound's value not only as a process enhancer but as a sustainability driver. These advancements, though still in development, suggest that the sound waves reshaping meat structure today could also reshape the economics and ecological footprint of meat processing tomorrow (Dong *et al*., 2022; Piñon *et al*., 2019; Rodríguez, 2017; Soltani Firouz *et al*., 2022; Taha *et al*., 2024). In a nutshell, these technologies do more than replace conventional heating; they reimagine the very logic of meat processing. Each innovation brings its own strengths and limitations, but their convergence signals a turning point—an era where processors can harmonize safety, flavor, nutrition, and sustainability instead of choosing one at the expense of another.

23.5.3 Comparative Analysis: Impact on Nutritional Quality, Sensory Attributes, and Shelf Life Extension

The quality of meat is a complex interplay of biological, chemical, and technological factors that together define its nutritional value, sensory appeal, and storage stability. At its core, meat is a dynamic biological material composed of muscle fibers, connective tissues, and lipids that continue to undergo biochemical transformations long after slaughter. These postmortem changes—such as glycolysis, proteolysis, and lipid oxidation—govern the attributes consumers recognize as tenderness, juiciness, color, and flavor. Yet these intrinsic qualities are far from static; they are shaped by an intricate web of determinants spanning from animal genetics and feeding regimes to slaughter conditions and subsequent processing techniques (Rodrigues *et al*., 2024).

In the contemporary food landscape, the narrative of meat quality has broadened beyond simple notions of palatability. Today, consumers seek products that are nutritionally balanced, minimally processed, environmentally sustainable, and ethically produced. This has fueled the development and refinement of both thermal and nonthermal technologies that aim to preserve quality attributes while safeguarding food safety. Within this context, comparing the impacts of these technologies on nutritional composition, sensory characteristics, and shelf life has become essential to designing resilient and resource-efficient meat production systems (Gómez *et al*., 2020a; Khalid *et al*., 2023).

23.5.3.1 Nutritional Quality: Balancing Safety and Bioavailability

23.5.3.1.1 Thermal Processing and Nutrient Retention

Thermal processing remains the industry's most established means of ensuring microbial safety and extending product life. However, its very reliance on elevated temperatures brings about structural and biochemical changes that compromise nutritional integrity. The denaturation of myofibrillar and sarcoplasmic proteins during cooking alters their digestibility and bioavailability, while excessive heat promotes Maillard reactions and lipid oxidation—processes that may produce desirable browning and aroma compounds but also destroy heat-sensitive nutrients such as thiamine and ascorbic acid (Khalid *et al*., 2023). Studies on conventional methods—boiling, frying, roasting, and grilling—consistently demonstrate reductions in essential amino acids and the formation of advanced glycation end-products (AGEs) that potentially reduce protein digestibility. In parallel, high temperatures accelerate the peroxidation of polyunsaturated fatty acids, thus diminishing the nutritional value of the meat's lipid fraction and creating off-flavors. While these methods remain indispensable for safety, they require careful optimization of time–temperature parameters to balance microbial inactivation with nutrient preservation (Gómez *et al*., 2020a).

23.5.3.1.2 Nonthermal Processing: Nutrient Preservation through Innovation

In contrast, emerging nonthermal technologies—such as HPP, PEF, CP, ultrasound, and ultraviolet (UV) treatment—operate at ambient or sublethal temperatures, enabling microbial control without the extensive nutrient degradation typical of conventional heat. These techniques use physical forces—pressure, electric pulses, or reactive species—to inactivate microorganisms while largely preserving vitamins, amino acids, and antioxidants (Barbhuiya, Singha and Singh, 2021; White *et al.*, 2025). HPP, for instance, applies pressures up to 600 MPa, disrupting microbial membranes and enzyme systems while causing minimal damage to covalent bonds in nutrient molecules. The result is a product that maintains its nutritional density and biochemical authenticity even after extended storage (Lee and Yoon, 2024). Similarly, PEF induces transient or permanent pore formation in microbial cell membranes—electroporation—that leads to effective microbial inactivation at low thermal loads, preserving labile nutrients and bioactive compounds. When applied to lean meats, PEF has been reported to improve protein digestibility and solubility, possibly by altering tertiary structures in a controlled fashion (Tomasevic *et al.*, 2023). Ultrasound and CP add further nuance to the nutritional landscape. The mechanical cavitation produced by ultrasound enhances mass transfer, promoting marination and diffusion of functional ingredients while reducing salt usage and oxidation. CP, conversely, generates reactive oxygen and nitrogen species capable of surface decontamination but demands careful control to prevent oxidative deterioration of proteins and lipids (Deliza and de Andrade, 2025). Collectively, these nonthermal approaches create what might be termed gentle preservation—methods that achieve microbial safety without stripping away the nutritional soul of the product. Yet they are not immune to limitations: process optimization remains essential to avoid undesirable oxidation, ensure homogeneity, and confirm long-term stability (Rosario *et al.*, 2021).

23.5.3.2 Sensory Attributes: From Structure to Perception

23.5.3.2.1 Flavor, Tenderness, and Texture under Thermal Conditions

The sensory experience of meat consumption—its aroma, tenderness, and juiciness—is shaped by a cascade of chemical reactions, most notably the Maillard reaction and lipid oxidation. These reactions, while responsible for the signature cooked-meat flavor, can also produce bitterness, toughness, or dryness when uncontrolled (Afzal *et al.*, 2022).

Among traditional methods, grilling and roasting are especially effective at developing the roasted and caramelized notes that consumers associate with high-quality meats. However, these benefits come at the cost of moisture loss and textural hardness, particularly when exposure to high heat is prolonged. Khalid *et al.* (2023) reported that the thermal load directly influences myofibrillar shrinkage, which reduces water-holding capacity and elasticity, yielding firmer textures. Such trade-offs highlight the delicate balance between developing desirable flavor and preserving tenderness—a balance often described as walking a tightrope between aroma and moisture.

Sous-vide cooking represents a refined thermal alternative, offering precise temperature control within vacuum-sealed conditions. Stanisławczyk *et al.* (2024) demonstrated that sous-vide treatments at 55–65 °C significantly improved tenderness and juiciness in foal meat while retaining higher water content compared to boiling or roasting. Consumers rated sous-vide samples higher for flavor desirability and texture uniformity, underscoring the method's ability to harmonize sensory pleasure with nutritional retention.

23.5.3.2.2 Nonthermal Effects on Sensory Quality

Nonthermal technologies redefine how sensory quality is achieved. Instead of relying on high temperatures to trigger browning and flavor formation, they subtly modify muscle microstructure and biochemical pathways to influence texture and juiciness. HPP, for example, can alter protein conformation in ways that mimic the tenderizing effects of aging without the prolonged time or microbial risk associated with natural maturation (Gómez *et al.*, 2020b).

PEF has been shown to enhance tenderness and juiciness by increasing cell permeability and promoting uniform water distribution within the muscle matrix. Karki *et al.* (2022) observed that PEF-treated

meat exhibited improved mass transfer and reduced drying time during curing, while Roobab *et al.* (2023) found that low-intensity PEF increased umami-related amino acids such as glutamic and aspartic acid, improving flavor depth. Ultrasound processing, through mechanical cavitation, facilitates tenderization by disrupting connective tissue and accelerating enzymatic activity—achieving what traditional aging does in days within a fraction of the time (Alarcon-Rojo *et al.*, 2015).

CP and pulsed light contribute mainly to surface quality and appearance. They preserve the natural color of fresh meat by reducing microbial spoilage and oxidative browning. Yet excessive exposure can lead to surface dryness or minor discoloration, reinforcing the importance of fine-tuning process parameters (Bak and Paulsen, 2023; Deliza and de Andrade, 2025).

23.5.3.2.3 Consumer Perception and Market Acceptance

Sensory quality, while rooted in biochemistry, ultimately culminates in consumer perception. Rodrigues *et al.* (2024) emphasized that sensory satisfaction—more than nutrient metrics or technical excellence—dictates repeat purchasing and brand loyalty. As consumers increasingly seek "clean-label", minimally processed, and flavor-rich products, nonthermal methods align with this sensibility. They preserve the natural characteristics of meat while meeting safety standards, allowing products to claim freshness and nutritional authenticity without compromise (White *et al.*, 2025).

However, adoption depends on trust and transparency. Deliza and de Andrade (2025) highlighted that acceptance of nonthermal products hinges on clear communication regarding their benefits and safety. When consumers understand that technologies like HPP or CP achieve safety without additives or intense heat, willingness to purchase rises markedly. Thus, technological sophistication must be matched by effective consumer education—translating innovation into appetite.

23.5.3.3 Shelf Life Extension: Preserving Safety and Freshness

23.5.3.3.1 Conventional Preservation and Its Limitations

Historically, shelf life extension in meat relied on refrigeration, salting, smoking, and thermal sterilization. While effective at slowing spoilage, these methods often compromise sensory and nutritional attributes. High-temperature pasteurization, for example, denatures proteins and oxidizes lipids, while curing introduces sodium and nitrite residues that raise health concerns. Moreover, conventional methods generate significant energy demand and environmental load through prolonged heating and cooling cycles (Rosario *et al.*, 2021).

23.5.3.3.2 Nonthermal Preservation for Sustainable Longevity

The pursuit of shelf life extension has thus evolved towards low-energy, nonthermal technologies capable of controlling microbial growth without detrimental heat exposure. Among these, HPP has achieved the most commercial traction, offering reductions of up to 5 log CFU/g in common spoilage organisms while maintaining natural color and flavor. Lee and Yoon (2024) noted that HPP-treated meats retained more nutrients and exhibited fewer sensory deviations than thermally processed counterparts even after extended storage. Ultrasound and PEF further contribute to preservation through different mechanisms. Ultrasound enhances antimicrobial efficacy by generating cavitation bubbles that mechanically disrupt microbial membranes, while PEF applies short electric pulses that induce electroporation in microbial cells, leading to leakage of intracellular contents and death (White *et al.*, 2025). CP acts via a combination of reactive species that oxidize microbial cell walls and deactivate surface pathogens, offering an environment-friendly alternative to chemical disinfectants. Importantly, these methods also integrate seamlessly into hurdle-technology frameworks, wherein multiple mild treatments combine to achieve robust microbial control. Rosario *et al.* (2021) described how coupling HPP or ultrasound with natural antimicrobials such as essential oils, bacteriocins, or nanoparticles not only extends shelf life but also reduces the need for synthetic preservatives. The resulting products align with sustainability and clean-label trends while lowering water and energy consumption—demonstrating that longevity need not come at the cost of integrity.

23.5.3.3.3 Oxidative Stability and Color Preservation

Lipid and pigment oxidation represent critical determinants of meat's visual and sensory shelf life. Consumers often equate color stability with freshness, making the prevention of metmyoglobin formation a priority. Nonthermal technologies, particularly HPP and CP, have shown promise in delaying oxidative discoloration by inactivating oxidative enzymes while maintaining redox balance (Afzal *et al*., 2022; Bak and Paulsen, 2023). In addition, combining antioxidant feed strategies with gentle processing amplifies protection against oxidation. Prates (2025) demonstrated that supplementing animal diets with vitamin E, selenium, and polyphenols improved meat's oxidative stability under both thermal and environmental stress, reinforcing how preslaughter nutrition interacts with post-processing preservation.

23.5.3.3.4 Microbial Safety without Compromising Quality

The microbiological safety of meat underpins its marketability and consumer confidence. Nonthermal technologies deliver substantial microbial reductions without introducing off-flavors or nutritional degradation. For instance, CP and PEF effectively *inactivate L. monocytogenes, Salmonella* spp., and *E. coli* at energy intensities well below those that cause sensory alterations. Moreover, combining these methods with mild refrigeration or modified-atmosphere packaging yields synergistic benefits, extending product life while maintaining a fresh-like profile (Lee and Yoon, 2024). Nevertheless, challenges remain. Certain stress-resistant bacterial spores exhibit resilience to nonthermal treatments, necessitating combined or sequential processes. Future advances may lie in hybrid systems that merge nonthermal mechanisms—such as PEF-assisted plasma or ultrasound-enhanced HPP—to achieve complete safety assurance while maintaining product authenticity (Rosario *et al*., 2021).

23.5.3.4 Integrating Nutrition, Sensory Quality, and Shelf Life: Toward Holistic Processing

A true comparative analysis must transcend isolated metrics of nutrient retention, flavor, or microbial load and instead capture how these attributes intersect. Meat processing is no longer a matter of safety alone—it is a choreography of chemistry and perception that determines how a product nourishes, pleases, and endures. Thermal methods, for all their proven efficacy, walk a fine line between desirable transformation and undesirable destruction. High-temperature grilling brings out Maillard complexity but accelerates oxidative rancidity; boiling ensures tenderness yet leaches minerals into cooking water. In contrast, nonthermal methods offer a gentler hand: they nudge molecules rather than forcing them, creating subtle structural shifts that preserve biological function while enabling innovation (Barbhuiya, Singha and Singh, 2021).

Comparatively, sous-vide and HPP emerge as transitional technologies—bridging the sensory satisfaction of heat with the retention advantages of nonthermal processing. The sous-vide technique, as shown by Stanisławczyk *et al*. (2024), delivers exceptional tenderness and flavor retention at low energy cost, while HPP ensures pathogen control without denaturation. Together, they illustrate how precision rather than intensity defines the new paradigm of meat processing.

From a nutritional standpoint, nonthermal treatments preserve essential micronutrients and amino acids that are often compromised by thermal extremes. They also mitigate the formation of potentially harmful compounds such as heterocyclic amines and AGEs. From a sensory viewpoint, these technologies sustain natural pigments and juiciness, preventing the drying or hardening associated with prolonged cooking. And from a shelf life perspective, their capacity to inhibit microbial growth and oxidative deterioration while conserving freshness exemplifies their multi-dimensional advantage(Deliza and de Andrade, 2025; White *et al*., 2025). Yet the choice between methods should not be framed as a binary. Rather than replacing heat, nonthermal processes complement it, forming hybrid strategies that combine the best of both worlds. For instance, applying mild PEF pretreatment before sous-vide cooking can enhance mass transfer and reduce cooking loss, while subsequent HPP treatment extends refrigerated shelf life without compromising texture.

23.5.3.5 The Role of Sustainability and Consumer Trends

Sustainability now anchors the discourse on meat processing. Conventional thermal operations are energy-intensive and water-demanding, contributing to greenhouse gas emissions and operational costs. Nonthermal systems, conversely, typically operate at ambient temperatures with shorter cycle times, reducing energy consumption by up to 60% in certain HPP applications (Lee and Yoon, 2024). Ultrasound and PEF further cut water use during marination and cleaning steps, aligning production with environmental targets (Rosario *et al*., 2021).

Consumer awareness compounds this momentum. Modern consumers value products that communicate naturalness, transparency, and ecological responsibility. Nonthermal processing aligns perfectly with these expectations by allowing labels that read minimally processed or free from chemical preservatives. However, successful adoption requires clear messaging: consumers must recognize these technologies as tools of protection, not manipulation. Hence, a future-oriented meat industry must pair technological innovation with communication strategies that translate engineering language into everyday trust (Deliza and de Andrade, 2025).

23.5.3.6 Future Perspectives

As the frontier of meat processing evolves, three guiding principles emerge. First, *precision:* technologies must offer fine control over molecular and structural changes to deliver consistent quality. Advances in digital twins and process simulation now allow processors to model temperature, pressure, and electroporation effects *in silico* before industrial application—minimizing trial-and-error and waste. Second, *integration:* hybrid systems combining nonthermal and mild thermal methods are likely to dominate future meat production. By harnessing complementary mechanisms, they balance safety, nutrition, and sensory quality more effectively than single interventions. Third, *personalization:* dietary diversification and functional food trends call for meat products tailored to specific nutritional or sensory profiles. Nonthermal processes, with their precision and flexibility, offer pathways to achieve such differentiation while maintaining safety and shelf stability. Equally vital is the synergy between preharvest and postharvest interventions. Nutritional strategies such as antioxidant supplementation (Prates, 2025) can fortify meat against oxidative stress, enhancing the benefits of gentle post-processing. In this sense, meat quality becomes a continuum—one that begins at the feed trough and culminates at the dinner plate. In conclusion, across decades of innovation, the comparative analysis between thermal and nonthermal technologies reveals a gradual but decisive shift: from domination by heat to collaboration with gentler forces. Traditional methods remain vital for safety assurance and sensory development, yet their limitations in nutrient preservation and sustainability have prompted a renaissance of technological ingenuity. HPP, PEF, CP, ultrasound, and sous-vide cooking now stand as complementary pillars in an integrated approach to meat processing. Each contributes distinct advantages—HPP for microbial safety, PEF for structural enhancement, CP for surface sanitation, ultrasound for tenderization, and sous-vide for flavor precision. Together, they carve out a new paradigm in which meat products are no longer forced to choose between safety and quality, or between longevity and authenticity.

In practical terms, these advances mean that processors can now design products that retain vitamins, preserve natural juiciness, maintain vibrant color, and resist microbial spoilage—all while consuming less energy and water. In philosophical terms, they signify a broader evolution: from processing as degradation to processing as preservation. As Barbhuiya, Singha, and Singh (2021) aptly noted, nonthermal processing transforms the very relationship between food and energy, allowing the industry to "meet customer needs for high-quality, convenient, and minimally processed foods".

Ultimately, the goal is not merely to extend shelf life or enhance texture, but to safeguard the living quality of meat—the qualities that make it nourishing, pleasurable, and sustainable. The convergence of thermal and nonthermal technologies marks the dawn of a new era in meat science—one where innovation respects nature's design, and precision engineering becomes the quiet custodian of taste and nutrition (Table 23.2).

TABLE 23.2

Overview of Advanced Meat Processing Technologies

Technology	Operational Principle	Primary Applications in Meat Production	Key Advantages	Limitations / Considerations
High-pressure processing (HPP)	High hydrostatic pressure (300–600 MPa)	Pathogen inactivation (lethality), shelf life extension for ready-to-eat (RTE) products and raw meats	• *Nonthermal*: Preserves sensory (flavor, color) and nutritional quality • Enhances food safety	• High initial investment cost • Batch process (not continuous) Ineffective against spores or dry products
Pulsed electric fields (PEF)	Short duration, high-voltage electric pulses are applied to the product	• Cell permeabilization (electroporation) for enhanced extraction, tenderization, or microbial inactivation	• Continuous process • Low energy consumption • Minimal thermal impact • Improves efficiency of other processes (e.g., drying)	• Efficacy depends on product conductivity • Lethality efficacy varies
Ultrasound (sonication)	High-frequency sound waves (>20 kHz) create cavitation (microbubbles) within the product	• Tenderization (breaking down muscle fibers) • Acceleration of curing/brining • Emulsification (sausage production)	• Improves texture • Reduces processing time • Enhancing mass transfer	• Unwanted temperature increase if not controlled • Scalability can be a challenge
Cold plasma	Ionized gas (plasma) is applied to surfaces, generating reactive species (e.g., ozone, UV radicals)	Surface decontamination of fresh meat and packaging Surface pathogen inactivation	• *Nonthermal and chemical-free*: rapid method for surface sanitation without affecting internal product	• Very shallow penetration (surface-only) • Relatively new technology with evolving industrial adoption
Ohmic heating (Joule heating)	Electric current is passed through the product; the product's internal resistance generates rapid, uniform heat	Rapid heating, pasteurization, and sterilization of pumpable products (e.g., meat slurries, sauces, stews)	• Extremely fast and uniform heating throughout the volume • Reduces quality degradation from overheating	• Only for electrically conductive products • High equipment cost
Computer vision and smart portioning	3D cameras, X-ray, or MRI scanners analyze carcasses or meat cuts in real time	Precise cutting and portioning Fat/lean separation Detection of bones or foreign objects	• *Optimized yield*: maximizes value from each cut • Reduces waste • Product consistency • Reduces labor costs	• High capital and maintenance costs • Requires complex software
Sous-vide (low-temperature, long-time cooking)	Meat is vacuum-sealed and cooked in a water bath at low temperatures (e.g., 55–65 °C) for extended periods	Precise cooking for tenderization Pasteurization High-quality ready-to-eat (RTE) products	• Exceptionally tender and juicy texture • Minimal cooking loss • Precise temperature control	• Very long processing times • Food safety risks if temperature is not strictly controlled

23.6 Digital Integration and Industry 4.0

The twenty-first century is witnessing a remarkable convergence of the physical, biological, and digital worlds—a transformation widely known as the Fourth Industrial Revolution, or Industry 4.0. Unlike previous industrial shifts powered by steam, electricity, or automation, this revolution is driven by data, connectivity, and cognition. Its foundation technologies—AI, IoT, robotics, blockchain, big data, augmented

reality (AR), and digital twins—allow seamless feedback between systems and users, creating intelligent operations that can learn, predict, and adapt (Hassoun *et al.*, 2023). The agri-food sector, long perceived as traditional and labor-intensive, is now at the heart of this digital transformation. Global challenges such as population growth, climate instability, resource scarcity, and recurring pandemics have exposed the limits of conventional production. Industry 4.0 technologies promise to bridge these gaps by building smart, traceable, and self-optimizing food systems that minimize waste, enhance safety, and improve transparency (Semercioz-Oduncuoglu and Luning, 2025). In this data-driven era, the notion of "quality" evolves—from a static attribute verified at the end of production to a dynamic state monitored and optimized in real time.

Digital transformation in food manufacturing—often termed Food 4.0—extends across the entire value chain. Intelligent systems now link farms, factories, logistics, and consumers through connected networks of sensors and cyber-physical systems. Real-time data collection enables predictive maintenance, automated inspection, and adaptive process control. Kamalapuram and Choudhury (2024) note that this integration allows upstream and downstream processes to self-adjust to fluctuations in demand, resources, and safety requirements, creating more resilient supply chains. Within this broader revolution, Quality 4.0 represents the digital reinvention of quality management. By combining AI, ML, smart sensors, and blockchain, companies can shift from reactive inspection to continuous improvement based on predictive modeling (Bisht *et al.*, 2025). Errors and contamination can be anticipated and prevented rather than detected after the fact, turning quality assurance into a living, learning process rather than a final checkpoint.

Meat 4.0 translates these principles into the specific realities of the meat sector—from breeding and slaughtering to packaging and retail. It integrates robotics, IoT, and data analytics to modernize what was once a heavily manual chain. According to Echegaray *et al.* (2022), robotic cutting, AI-based grading, and IoT-enabled traceability are transforming traditional abattoirs into smart factories where precision and hygiene are enhanced by automation. The COVID-19 pandemic accelerated this shift by revealing the vulnerability of labor-dependent systems. During lockdowns, automation and remote monitoring became vital for maintaining productivity and ensuring food safety. Digitalization proved not only a safeguard against disruption but a strategic path toward greater transparency and resilience. Thus, Meat 4.0 is best understood as both a technological evolution and a socioeconomic necessity.

At the heart of Meat 4.0 lies a network of mutually reinforcing technologies. AI and ML serve as its cognitive engine, enabling pattern recognition in quality data and predicting spoilage, contamination, or yield variations. IoT systems interconnect machines, storage facilities, and transport vehicles, giving managers real-time visibility of temperature, humidity, and production status. Robotics and machine vision automate cutting, sorting, and packaging, improving safety and precision. Blockchain ensures traceability, providing consumers with verifiable information from animal origin to point of sale (Hassoun *et al.*, 2023). Equally transformative are digital twins—virtual models that replicate physical production lines to test adjustments without interrupting operations. Coupled with big data analytics, these simulations convert millions of data points from pH sensors, imaging systems, and environmental monitors into actionable insights (Bisht *et al.*, 2025). As Semercioz-Oduncuoglu and Luning (2025) describe, this "techno-managerial synergy" fuses machine intelligence with human decision-making to deliver unprecedented control over quality and sustainability.

Digital integration yields benefits that reinforce one another across three pillars: efficiency, safety, and sustainability. Operational efficiency rises as smart factories deploy robotics and predictive maintenance to reduce downtime and waste. Automated trimming and deboning lines operate continuously with minimal supervision, while AI-driven scheduling aligns production with real-time demand to avoid surplus and spoilage(Echegaray *et al.*, 2022). Food safety and traceability are strengthened through blockchain and advanced sensing. Each carcass or product can be tracked through an immutable digital ledger, and contamination can be detected instantaneously by spectroscopic sensors powered by ML (Semercioz-Oduncuoglu and Luning, 2025). Environmental sustainability improves as digital twins and optimization algorithms enable precise resource management. Plants can simulate heat recovery, water recycling, or carbon-reduction strategies before implementation, converting data into a new kind of environmental currency (Hassoun *et al.*, 2023). These technologies collectively align profitability with responsibility—doing more with less, while protecting both people and planet.

Despite rapid progress, the journey toward Meat 4.0 faces notable obstacles. Kamalapuram and Choudhury (2024) highlight that digital infrastructure demands substantial investment, particularly challenging for small and medium enterprises. The transition also requires expertise in data analysis, system integration, and cybersecurity—skills still scarce in many regions. Cybersecurity itself is a growing concern: interconnected devices create new vulnerabilities for data breaches and operational sabotage. Protecting sensitive information—from animal welfare records to proprietary formulations—necessitates robust encryption and risk-management protocols. Beyond technology, organizational culture must also evolve. Real-time analytics decentralize decision-making, calling for new competencies in data interpretation and strategic agility. As Semercioz-Oduncuoglu and Luning (2025) observe, digital success depends as much on people's adaptability as on machines' capability.

Quality control in the digital age has become an integrated, predictive system. AI-driven models analyze images, chemical spectra, and sensor data simultaneously, identifying minute deviations invisible to human inspectors. Bisht *et al.* (2025) describe how hybrid ML, convolutional neural networks, and hyperspectral imaging can classify marbling, color, and microbial load in real time with exceptional precision. This capability shifts quality management from reactive inspection to predictive prevention. Instead of rejecting defective batches, processors can intervene at the first sign of deviation, tracing contamination pathways immediately and adjusting parameters on the fly. In this framework, quality control becomes quality foresight—a continuous loop of learning that keeps improvement perpetual.

The cultivated-meat (CM) sector represents the most digitally intensive expression of Meat 4.0. Its reliance on controlled bioreactors naturally aligns with sensors, automation, and simulation. Kamalapuram and Choudhury (2024) report that integrating digital twins, AI-driven process control, and robotic sampling enables CM production to self-optimize, guaranteeing consistent tissue growth and biosecurity. Digital twins model nutrient flow, pH, and temperature dynamics without interrupting live cultures, while IoT networks collect real-time process data. Robotics ensures sterility and precision in handling. Though high costs and limited digital expertise still hinder wide adoption, cultivated-meat systems illustrate the potential of fully autonomous, data-centric food production—a prototype for future meat systems that are both sustainable and scientifically exact.

Data is now the primary raw material of the meat industry. Every sensor reading or logistics update adds to a digital ecosystem rich with predictive power. IoT-based analytics anticipate equipment failure, while spectroscopy predicts microbial growth before it becomes a risk (Semercioz-Oduncuoglu and Luning, 2025). Blockchain secures this information in decentralized ledgers, ensuring authenticity and transparency across the supply chain. However, managing such vast datasets introduces ethical and technical challenges. Data must be harmonized, interoperable, and used responsibly. Echegaray *et al.* (2022) argue for standardization frameworks and blockchain verification to maintain trust and interoperability. Inclusivity is equally vital: smaller producers risk exclusion if digital technologies remain expensive or proprietary. Public–private partnerships and open-source platforms can help democratize innovation, ensuring that Meat 4.0 benefits entire ecosystems rather than elite segments.

Beyond efficiency, digitalization drives measurable sustainability gains. Sensors embedded throughout production quantify emissions, water use, and energy consumption in real time. Algorithms optimize refrigeration and transportation to lower carbon footprints (Hassoun *et al.*, 2023). Digital tracking of by-products—bones, fats, or trimmings—enables their conversion into biofuels, fertilizers, or nutraceutical ingredients, reinforcing circular-economy principles. Smart logistics powered by IoT further reduce waste and emissions by adjusting delivery routes and temperatures dynamically. Thus, digital integration is not only a technological advance but a strategic enabler of climate responsibility—turning sustainability from aspiration into quantifiable performance.

Contrary to fears of widespread job loss, Industry 4.0 in meat processing promotes collaborative automation. Robots perform repetitive, hazardous, or precision-intensive tasks, while humans supervise, interpret, and refine. This human–machine partnership enhances safety, consistency, and worker well-being. As Echegaray *et al.* (2022) note, cobots are already redefining abattoir workflows, freeing people from physically taxing roles. Training becomes the cornerstone of this transformation. Future professionals must master data analytics, AI interfaces, and mechatronics alongside traditional

food-science skills. The new "meat technologist" is both engineer and analyst—a steward of data-driven quality who bridges the physical and digital worlds.

While Industry 4.0 emphasizes automation and efficiency, the forthcoming Industry 5.0 paradigm seeks to recenter humanity in technological progress. Hassoun *et al.* (2023) describe it as the stage where creativity, ethics, and social value guide innovation. For meat producers, this means systems that uphold animal welfare, nutritional integrity, and employee dignity alongside productivity. Industry 5.0 envisions digital meat ecosystems—networks connecting producers, processors, regulators, and consumers through transparent data exchanges. Technology amplifies human judgment rather than replacing it, creating an industry that is intelligent yet empathetic, efficient yet ethical.

As an upshot, integrating Industry 4.0 principles into the meat sector marks the beginning of a digital renaissance—where craftsmanship meets computation. From abattoir to analytics dashboard, data now acts as both tool and language for improvement. Robots carve, sensors measure, algorithms learn; yet human intention gives these systems direction and meaning. Meat 4.0 is not solely about automation but augmentation: augmenting efficiency with insight, safety with transparency, and sustainability with intelligence. As Echegaray *et al.* (2022) emphasize, smart sensors, robotics, and AI are redefining how quality and trust are built. Still, as Semercioz-Oduncuoglu and Luning (2025) remind us, success depends on thoughtful management, ethical design, and inclusive participation. The meat industry's future will rest on how well it merges mechanical precision with human values. If accomplished wisely, this fusion can reinvent production itself—transforming digital progress into genuine well-being for people, animals, and the planet alike.

23.6.1 Smart Sensors and IoT: Real-Time Monitoring of Critical Control Points (CCPs)—Temperature, pH, Moisture

The growing digitalization of food systems has turned data from a by-product into a working ingredient of safety, quality, and sustainability. At the heart of this shift sits the IoT: dense networks of sensors, connected devices, and cloud platforms that allow conditions to be measured, recorded, and acted upon in real time. For a sector as perishable, risk-sensitive, and resource-intensive as meat, IoT is not just a technological curiosity; it is fast becoming the nervous system of a modern, accountable supply chain. When paired with well-established frameworks such as hazard analysis and critical control points (HACCP), smart sensors give processors, farmers, regulators, and retailers the capability to move from periodic checks and paper records to continuous verification, predictive alerts, and traceable decisions.

23.6.1.1 From Smart Agriculture to Connected Meat Chains

The move toward connected monitoring begins upstream, in smart farming and livestock systems. As Thilakarathne *et al.* (2025) emphasize, pressure from population growth, labor scarcity, and climate uncertainty has accelerated the shift from traditional agriculture to smart agriculture, where IoT, cloud computing, AI, and big data are harnessed to automate decisions, improve yields, and reduce waste. In livestock, this translates into thermal cameras, GPS collars, ingestible and wearable biosensors, and wireless sensor networks that track activity, feeding, rumination, body temperature, and stress in real time. These tools allow more informed and timely interventions on health, welfare, and productivity, replacing intuition-driven management with evidence-based oversight.

Within this broader landscape, dedicated initiatives such as the IoF2020 project demonstrate how IoT architectures can be deployed across meat supply chains at scale. Maselyne *et al.* (2017) describe how pig farm management, poultry chain monitoring, and meat transparency use cases leverage environmental and animal-based sensors, early warning algorithms, and EPCIS-enabled traceability to close long-standing information gaps. By wiring barns, transport, lairage, and early processing stages into shared data infrastructures, actors gain continuous visibility over conditions affecting disease risk, boar taint, mortality, feed conversion, and welfare. Rather than reacting to symptoms after they appear in the plant, producers can correct deviations at their source. This logic—measure early, act early—sets the stage for real-time control of critical parameters further down the chain.

23.6.1.2 CCPs in a Connected World

The conceptual anchor remains HACCP: a structured, preventive framework that identifies CCPs where hazards must be controlled to acceptable levels (FAO, 1998). Traditional HACCP monitoring at these points—such as scalding temperatures, evisceration hygiene, chilling performance, or packaging integrity—has relied heavily on manual measurements, checklists, and batch sampling. However, there are importances and fragilities of this approach, such as misidentified CCPs, poorly set limits, weak documentation, and intermittent monitoring can undermine even well-designed systems (Anonymous, 2024). Smart sensors and IoT infrastructures provide a way to hardwire HACCP into day-to-day operations. Anonymous (2025a) outlines how advanced CCP monitoring now uses networked temperature probes, pH and conductivity sensors, flowmeters, metal detectors, and cloud-based dashboards to enable continuous, tamper-evident surveillance. Instead of a few readings per shift, plants can log thousands of data points per minute, with automated alarms triggered the moment a critical limit is approached or breached. In this model, compliance shifts from retrospective "box ticking" to live process control. Hasanah and Indrawan (2020) extend this thinking to poultry slaughter, proposing conveyor-mounted sensors capable of detecting biological and chemical hazards in real time and automatically signaling food safety officers when thresholds are exceeded. Such systems embed HACCP logic directly into equipment, closing the loop between sensing, human oversight, and corrective action. In practical terms, real-time monitoring of temperature, pH, moisture, and contamination risk reduces blind spots and makes it far less likely that unsafe product will slip through solely due to human oversight or timing gaps.

23.6.1.3 Smart Sensors along the Meat Chain: From Barns to Slaughter Lines

At farm level, smart sensing and IoT create the first layer of assurance. Thilakarathne *et al.* (2025) describe how GPS-based tags, environmental probes, and wearable biosensors help farmers monitor animal movement, heat stress, illness risk, and grazing efficiency. This information feeds into breeding, feeding, and biosecurity decisions that shape carcass quality and pathogen load arriving at the abattoir. Maselyne *et al.* (2017) show how integrating these data streams into IoF2020 architectures enables early warning for diseases, welfare breaches, or suboptimal performance, making preventive action the norm rather than the exception.

In primary processing, the same principles unfold under more stringent time and hygiene constraints. Lin and Suhendra (2025) present an IoT-enabled AI vision system for monitoring electrical stunning effectiveness in red-feathered Taiwan chickens: by using YOLO-v4-based object tracking and feature extraction, the system differentiates stunned from unstunned birds with high precision in real time, ensuring humane slaughter and reducing handling variability. This is a striking example of how smart cameras and edge AI become embedded CCP tools, directly linked to animal welfare and operator safety. Kolikipogu *et al.* (2025) and Hasanah and Indrawan (2020) outline complementary designs where sensor modules installed above slaughter lines detect physical debris or hygiene deviations and immediately alert inspectors. Rather than depending solely on periodic visual checks, processors gain continuous digital "eyes" at critical points such as defeathering, evisceration, and washing. When such sensing arrays feed into plant-wide IoT platforms, deviations can trigger immediate slowdowns, diversions, or corrective sanitation, preventing a local lapse from becoming a systemic failure.

23.6.1.4 Real-Time Monitoring of Temperature, pH, and Moisture

Among the many process variables in meat systems, temperature, pH, and moisture sit at the crossroads of microbial safety, shelf life, and sensory quality. IoT-integrated sensor networks make it feasible to monitor these parameters continuously across chilling tunnels, storage rooms, deboning halls, and distribution node. Jagtap, Garcia-Garcia, and Rahimifard (2021) demonstrate how IoT frameworks for monitoring energy and water use can be extended to track process conditions, enabling root-cause analysis when deviations occur and linking environmental efficiency with product protection.

Temperature probes embedded in carcasses or packaging, wireless data loggers in cold rooms, and smart pallets equipped with RFID and thermistors allow operators to verify cold chain integrity in real time. pH sensors in brines, marinades, or surface washes provide insight into acidification, fermentation, or decontamination efficacy. Moisture and humidity sensors in storage environments guide airflow and condensation control, limiting microbial growth and package failure. When aggregated on cloud platforms, these continuous measurements support predictive models that can estimate remaining shelf life and flag lots at risk before quality visibly deteriorates (Anonymous, 2025c; FAO, 1998).

In this sense, smart sensors turn classic CCPs—such as minimum core cooking temperature, maximum chill temperature, or acceptable pH ranges—from static numbers on a chart into live, data-rich control levers. The plant does not merely record compliance; it "knows" its status at each moment and can respond accordingly.

23.6.1.5 Intelligent Packaging and Freshness Indicators

Smart sensing does not end at the plant door. Intelligent and active packaging extend real-time monitoring into retail shelves and home refrigerators, offering both industry and consumers a window into product status. Husin *et al.* (2020) demonstrate a natural anthocyanin-based freshness indicator for beef, where pH-sensitive color changes reflect volatile compound buildup and spoilage progression under both chilled and ambient storage. Such indicators translate micro-level biochemical changes into clear visual signals—a low-tech but powerful form of decentralized sensing. Broader reviews by Singh *et al.* (2018), Dodero *et al.* (2021), and Mani *et al.* (2025) catalogue a diverse toolbox of smart packaging technologies: time–temperature indicators (TTIs), gas sensors for CO_2, O_2, and NH_3, electrochemical and optical sensors for total volatile basic nitrogen (TVB-N), biosensors for pathogens, and pH-responsive films embedded within packs. For meat, where spoilage and pathogen risks are tightly linked to temperature abuse and moisture dynamics, these systems offer a second line of CCP-like monitoring beyond the factory gate. Although commercial uptake is still constrained by cost, regulatory clarity, and material compatibility, the direction of travel is clear. Intelligent packaging, coupled with IoT connectivity, enables "living labels" that report actual history instead of static expiry guesses. For producers, this promises better inventory control and reduced waste; for consumers, it offers confidence grounded in evidence rather than assumption (Dodero *et al.*, 2021; Mani *et al.*, 2025; Singh *et al.*, 2018).

23.6.1.6 IoT, CCPs, and Resource Efficiency

Smart sensors deployed for food safety increasingly double as tools for resource stewardship—an alignment that is hard to ignore in an energy- and water-hungry sector like meat. Jagtap, Garcia-Garcia, and Rahimifard (2021) propose an IoT-based framework to monitor food waste, energy use, and water consumption in real time, allowing manufacturers to diagnose inefficiencies and redesign processes accordingly. The same temperature and flow sensors that verify refrigeration performance or scalding conditions can inform heat recovery opportunities, equipment optimization, and leak detection. Several technical and economic studies provide the complementary sustainability backdrop. Take for instances, AMPC (2016), Anonymous (2025b), Ashrafi *et al.* (2015), and Pollock, Mason, and Corporation (2015) show how integration of heat recovery, CO_2 capture, cogeneration, and optimized refrigeration can substantially cut fuel use and emissions in red meat processing. Bruno, Belusko, and Halawa (2019) and Nair (2025) advances in CO_2 and cascade refrigeration systems that, when coupled with precise sensor control, can maintain strict temperature CCPs with improved energy performance. Steffen, Robertson and Kirsten Inc. (1989) as well as Ware and Power (2016) illustrate the broader potential for water, wastewater, and by-product monitoring to underpin recycling, anaerobic digestion, and circular economy strategies within abattoirs. IoT architectures tie these elements together: process historians, cloud dashboards, and digital twins assimilate data from cooling systems, boilers, packaging lines, and effluent treatment. Meat plants can then evaluate how safety-critical conditions (e.g., blast-chill profiles) interact with energy demand and identify configurations that respect CCPs while minimizing waste. In practice, this is where "smart factory" rhetoric becomes measurable: fewer losses, fewer recalls, and a lower environmental bill for the same or better level of protection.

23.6.1.7 Toward Predictive, Human-Centered Meat Safety

Looking ahead, smart sensors and IoT are moving meat safety from snapshot control toward predictive ecosystems. Anonymous (2025a) notes that continuous, high-resolution CCP monitoring enables early detection of weak signals—slight drifts in temperature, subtle changes in pH or humidity—that previously went unnoticed until manifested as spoilage, off-odors, or test failures. Combined with AI, these data streams support models that forecast contamination risks and recommend interventions before thresholds are breached. Singh *et al.* (2025a) frame this trajectory within the emerging paradigm of Industry 5.0, where advanced computation is integrated with human-centric, sustainable design. In such a vision, IoT networks, smart packaging, robotics, and digital twins do not replace people; they augment inspectors, operators, veterinarians, and quality managers with better information and decision support. Shehzad, Munir, and Ali (2025) highlight how AI-driven sensing and analytics are already shaping precision cutting, alternative protein design, and supply chain optimization—demonstrating that the same logic of real-time feedback can be applied across conventional and novel meat systems.

Yet, the path is not without obstacles. Jagtap, Garcia-Garcia, and Rahimifard (2021), Maselyne *et al.* (2017), and Singh *et al.* (2025a) all underline challenges around investment costs, interoperability, data management, cybersecurity, and skills gaps, especially for small and medium enterprises. Implementing IoT-based CCP monitoring demands not only sensors and networks, but also robust validation, staff training, clear governance of who owns and interprets data, and safeguards against manipulation or system failure. This reminds us that even the most sophisticated tools are only as sound as the underlying hazard analysis and critical-limit setting (Anonymous, 2024). Despite these hurdles, the direction is both coherent and compelling. Smart sensors and IoT do not rewrite the principles of meat hygiene and HACCP; they give those principles sharper teeth and better eyesight. By enabling continuous measurement of temperature, pH, moisture, and related indicators from farm to fork, they transform CCPs from static checkpoints into dynamic sentinels. At the same time, by linking safety with resource monitoring and intelligent packaging, they open a practical route to doing more with less—less waste, less energy, less doubt. In sum, the integration of smart sensing and IoT in the meat sector is steadily turning real-time monitoring from a luxury into an expectation. For processors willing to invest thoughtfully, these technologies offer a tangible way to align regulatory compliance, market trust, and sustainability goals within a single, connected architecture—where every sensor reading is not just a number, but a decision-making ally.

23.6.2 AI and ML: For Quality Prediction, Defect Detection, and Predictive Maintenance

AI and ML are transforming how food systems operate, marking a shift from reactive control to predictive, data-driven intelligence. In the global food industry—particularly within meat production—AI bridges the gap between biological complexity and industrial precision. The growing need for consistent quality, safety assurance, and resource efficiency has placed data analytics, computer vision, and intelligent sensing at the center of modern food engineering. Once confined to computer science, these technologies now shape how meat is produced, processed, and protected from spoilage and fraud (Hassoun *et al.*, 2020; Khaled, Parrish and Adedeji, 2021; Kutsanedzie, Guo and Chen, 2019).

The integration of AI within the food sector aligns with the larger vision of Industry 4.0—an ecosystem that fuses automation, data exchange, and cyber-physical systems to enhance resilience and sustainability (Figure 23.5). Within this framework, AI functions as the cognitive layer, converting vast quantities of unstructured data from sensors, images, and equipment into actionable insights. ML models recognize subtle patterns invisible to humans, while deep learning architectures such as convolutional neural networks (CNNs) and three-dimensional networks (3D CNNs) enable autonomous decision-making at unprecedented speed and accuracy (Al-Sarayreh *et al.*, 2020). In the meat sector, these tools are redefining how processors monitor quality, detect defects, and anticipate equipment failures before they occur—collectively shaping the emergence of "cognitive meat factories".

FIGURE 23.5 Schematic of an Industry 4.0 meat processing line.

23.6.2.1 Intelligent Perception: From Spectroscopy to Hyperspectral Imaging

One of the most compelling advances in this field is the combination of hyperspectral imaging (HSI) with deep learning. HSI captures both spatial and spectral information, enabling a multidimensional fingerprint of food products. Al-Sarayreh *et al.* (2020) demonstrated that integrating snapshot HSI with deep 3D convolutional neural networks allowed highly accurate classification of red meat species and authenticity. By analyzing the entire image cube instead of isolated spectra, their 3D CNN achieved accuracy rates exceeding 96%, significantly outperforming conventional models. This integration of spectral–spatial analysis and AI sets the foundation for real-time, nondestructive authenticity testing—paving the way for mobile HSI applications in meat inspection.

These methods are particularly relevant for an industry where subtle differences in tissue composition, color, or marbling can signal major quality deviations or adulteration. Feng *et al.* (2018) similarly highlighted how HSI and multispectral imaging (MSI) systems can inspect both raw and processed meat, capturing surface defects, fat distribution, and microbial spoilage indicators. Combined with ML algorithms, these imaging systems automate what once relied on subjective visual assessments—making quality control faster, more objective, and standardized.

Beyond imaging, spectroscopy remains a cornerstone of AI-enabled food analysis. Techniques such as visible/near-infrared (vis/NIR), Raman, and mid-infrared (MIR) spectroscopy, when paired with ML algorithms, offer powerful tools for predicting composition, detecting contamination, and assessing process changes (Hassoun *et al.*, 2020). Spectroscopic data, though inherently complex, can be decoded through AI models that learn correlations between spectral features and physical properties such as pH, water activity, or protein oxidation. This fusion of optics and computation transforms every pixel or wavelength into a quality descriptor—essentially creating a new language for understanding meat beyond human sensory limits.

23.6.2.2 Nondestructive Intelligence: Moving beyond Chemical and Sensory Testing

Traditional methods of assessing meat quality—such as sensory panels, microbial plating, and chemical titration—are laborious, time-consuming, and destructive. Khaled, Parrish, and Adedeji (2021) and Kutsanedzie, Guo, and Chen (2019) both emphasized that these approaches fail to provide continuous or large-scale monitoring. In contrast, AI-enhanced nondestructive technologies—such as electronic noses

(e-nose), computer vision (CV), spectroscopy, and HSI—enable fast, reliable, and contactless evaluation of freshness, tenderness, and spoilage.

The e-nose, for instance, mimics the human olfactory system but with sensor arrays that detect volatile compounds. When coupled with ML classifiers like support vector machines or neural networks, e-noses can predict spoilage stages, microbial load, or adulteration. Similarly, computer vision systems trained on thousands of meat images can recognize defects in marbling, color uniformity, or surface texture—providing rapid grading in slaughterhouses or packaging lines. These technologies not only streamline quality control but also enhance traceability and reduce human error.

However, both Khaled, Parrish, and Adedeji (2021) and Kutsanedzie, Guo, and Chen (2019) warn that the field still faces fragmentation. Many studies focus on single technologies in isolation, overlooking the benefits of data fusion. Integrating multiple sensing modalities—such as combining e-nose data with spectral imaging—can yield more holistic and reliable models. Yet this integration requires robust algorithms capable of handling heterogeneous datasets, an area where AI and ML continue to make strides.

23.6.2.3 Deep Learning for Defect Detection and Authenticity

Defect detection in meat processing extends far beyond visual inspection. Modern AI systems can detect anomalies—foreign objects, bruises, incomplete cuts, or packaging faults—within milliseconds using computer vision integrated with robotics. The synergy between AI and machine vision allows precise, hygienic, and repeatable operations that minimize human involvement.

The work by Al-Sarayreh *et al.* (2020) showcases this paradigm: by training a 3D CNN on HSI data, researchers achieved exceptional accuracy in identifying meat species and detecting adulteration. Such capability is vital for maintaining consumer trust and regulatory compliance, especially where substitution or contamination scandals can have economic and ethical consequences. The 3D CNN approach also demonstrates robustness under limited spectral resolution—suggesting real-world adaptability for handheld or on-line inspection systems.

In parallel, nanotechnology-based AI sensing is emerging as a frontier in detecting contaminants. Stephen Inbaraj and Chen (2016) summarized the use of nanomaterials—metal oxides, quantum dots, and carbon nanotubes—in designing biosensors for detecting bacterial pathogens and toxins. By coupling nanoscale sensitivity with AI analytics, these biosensors can rapidly identify harmful microorganisms or chemical adulterants without extensive sample preparation. Similarly, Ge *et al.* (2022) introduced a portable wireless intelligent nanosensor (PWIN) for detecting terbutaline residues in meat, achieving detection limits comparable to high-performance liquid chromatography but at a fraction of the cost and time. The combination of nanosensors and AI-driven data processing is thus reshaping the future of on-site safety monitoring, moving laboratories directly onto the production floor.

23.6.2.4 Predictive Quality Modeling and Shelf Life Estimation

Predicting how long a meat product will remain safe and palatable is one of the most valuable capabilities in digital food systems. Kim *et al.* (2020) proposed a mean kinetic temperature (MKT) approach that uses temperature history data to estimate remaining shelf life. By applying simple kinetic models and AI-assisted pattern recognition, it becomes possible to predict degradation trajectories in products such as packaged chicken and pasteurized milk. This methodology illustrates how AI transforms routine temperature logging into predictive shelf life intelligence, reducing waste and preventing foodborne illness.

Integrating such models with IoT data from cold-chain sensors allows processors to simulate and forecast freshness dynamically. Rather than relying solely on fixed expiry dates, AI models can calculate "dynamic use-by dates" based on real conditions—a major advancement for both sustainability and safety. The result is a feedback-driven ecosystem where product quality is continuously known rather than periodically inferred.

23.6.2.5 AI for Halal Integrity and Ethical Quality

The application of AI extends into domains where quality intersects with ethics and faith-based compliance. Within the *halal* meat supply chain (HMSC), ensuring authenticity and traceability is paramount.

The review of Industry 4.0 applications to *halal* systems by Ellahi *et al.* (2025) underscores how AI, robotics, AR, digital twins, and blockchain can enhance transparency and reduce cross-contamination (Industry 4.0 *Halal* review). AI-driven pattern recognition can detect non-*halal* adulteration through spectral or DNA-based fingerprints, while AR and digital twins can simulate and verify process integrity at each stage of slaughtering and packaging. By integrating robotics with intelligent vision, processors can standardize *halal*-compliant cutting angles or cleaning steps, minimizing human error. The review further notes that emerging technologies like 3D printing and in vitro meat production pose new questions for *halal* verification—questions that AI can help answer through real-time compositional analysis and blockchain-enabled certification. Thus, AI not only safeguards physical quality but also sustains moral and cultural trust in a globalized market.

23.6.2.6 Predictive Maintenance: Intelligence within Machines

Beyond product quality, AI is revolutionizing how equipment is maintained. Predictive maintenance uses ML algorithms to forecast when machines—such as slicers, chillers, or vacuum pumps—are likely to fail based on vibration, temperature, and acoustic data. This prevents unplanned downtime, extends asset life, and ensures hygienic continuity.

In meat plants, where downtime can jeopardize both productivity and food safety, predictive maintenance serves as a crucial control layer. AI systems analyze sensor data from motors, conveyors, and refrigeration units, identifying subtle deviations that indicate wear or inefficiency. Integrated with enterprise resource planning (ERP) systems, these models can automatically schedule maintenance when performance indicators cross thresholds—aligning engineering operations with production flow. The same principles underpin energy optimization and environmental monitoring, as AI analyzes historical data to suggest heat recovery or cleaning cycles with minimal energy impact (AMPC, 2016; Pollock, Mason and Corporation, 2015).

Predictive maintenance is, in essence, quality control for the machines themselves. It ensures that every piece of equipment supporting food safety—from boilers to vision systems—operates within optimal parameters. As more plants adopt AI-driven maintenance, reliability will become an intrinsic component of meat quality assurance.

23.6.2.7 Toward Cognitive Food Safety: AI in HACCP and Risk Forecasting

AI's contribution to food safety can also be framed through its enhancement of HACCP systems. By analyzing historical process data, AI models can identify patterns preceding deviations in temperature, microbial counts, or contamination events. Unlike traditional HACCP, which prescribes fixed critical limits, AI-enhanced HACCP adapts dynamically based on evolving conditions (Alexopoulos, 2025).

For instance, pattern recognition algorithms can anticipate the likelihood of *Listeria* growth in cold rooms given specific humidity and temperature fluctuations, or forecast microbial load on carcasses based on slaughtering speed and washing efficacy. This transition from rule-based control to predictive reasoning represents the next frontier of preventive food safety. The shift mirrors a philosophical transformation—from compliance to foresight, from detection to prevention (Sun *et al.*, 2025).

23.6.2.8 Future Outlook: Humanized AI for Sustainable Meat Systems

As AI and ML mature, their integration in meat production moves beyond automation toward augmentation. The technologies are most effective when they amplify human expertise rather than replace it. Trained operators interpret AI insights, calibrate models, and provide the contextual understanding that pure computation cannot. This human–machine collaboration embodies the emerging paradigm of Industry 5.0, where empathy, ethics, and creativity accompany data-driven precision.

Hassoun *et al.* (2020) and Kutsanedzie, Guo, and Chen (2019) point out that the biggest challenge lies not in developing AI algorithms, but in validating them across diverse product types, processing environments, and cultural expectations. The success of AI systems in meat processing will depend on robust data governance, open standardization, and shared responsibility between technologists and food professionals.

Moreover, AI has a role to play in sustainability. By predicting energy use, optimizing logistics, and minimizing waste, intelligent systems can reduce the environmental footprint of meat production. Combining predictive quality modeling with resource analytics transforms factories into adaptive organisms that learn from every batch, every cut, and every deviation.

Stephen Inbaraj and Chen (2016) foresee AI-enabled nanosensors evolving into ubiquitous biosafety guardians; Al-Sarayreh *et al.* (2020) imagine handheld hyperspectral devices as real-time authenticity checkers; and Kim *et al.* (2020) envision dynamic shelf life forecasting becoming standard across supply chains. These perspectives converge on a single reality: AI is the silent partner ensuring that every gram of meat reaching consumers is genuine, safe, and responsibly produced.

To sum up, AI and ML are redefining how the meat industry perceives, measures, and manages quality. From spectral analysis and hyperspectral imaging to nanosensors and predictive maintenance, these technologies embed intelligence at every level—from the molecular to the mechanical. They transform vast data into clarity, routine monitoring into foresight, and industrial precision into ethical assurance. Yet, their true power lies not in automation alone, but in symbiosis: the marriage of data with human discernment, of prediction with responsibility. As the industry evolves toward the intelligent, transparent ecosystems envisioned by Industry 5.0, AI and ML will serve as the connective tissue linking safety, sustainability, and social trust. In the words implicit across these studies, the future of meat is not only smart—it is sentient in its understanding of quality, aware of its impact, and adaptive to the world it feeds (Al-Sarayreh *et al.*, 2020; Ge *et al.*, 2022; Hassoun *et al.*, 2020; Khaled, Parrish and Adedeji, 2021; Kim *et al.*, 2020; Kutsanedzie, Guo and Chen, 2019; Stephen Inbaraj and Chen, 2016).

23.6.3 Digital Traceability and Blockchain: Ensuring Transparency and Provenance from "Stable to Fork"

In an era marked by food scandals, climate anxiety, and hyper-connected consumers, traceability has shifted from a regulatory checkbox to a core promise: tell me where my meat comes from, what it has been through, and why I should trust it. For meat systems—biologically complex, temperature-sensitive, highly globalized—that promise cannot be upheld by paper logs, siloed databases, and faith alone. Digital traceability and blockchain technologies are emerging as the nervous system of Meat 4.0: continuously sensing, recording, and verifying product identity and history from stable to fork, while aligning safety, quality, economics, and ethics in one interoperable infrastructure (Ren *et al.*, 2022).

At its simplest, traceability means being able to track and trace meat "one step forward, one step back". In practice, meaningful traceability demands more: real-time capture of process conditions, robust linkage of animal identity to carcass and cuts, trusted records across independent actors, and the ability to translate this invisible journey into clear signals for auditors, buyers, and consumers. Digitalization of the meat cold chain—through IoT sensors, smart packaging, and advanced analytics—has laid the ground for this shift. Ren *et al.* (2022) emphasize that intelligent packaging, multi-parameter quality evaluation, and real-time cold chain logistics monitoring now form the backbone of next-generation meat systems, enabling not only safer and longer shelf life but also richer data streams to feed into traceability architectures. Blockchain enters this landscape not as a fashionable add-on, but as a structural solution to a structural problem: multiple actors, asymmetric information, and low tolerance for error or fraud. A distributed ledger can store tamper-evident records of key events—animal birth and health status, slaughter details, carcass grading, processing parameters, storage temperatures, transport conditions, *halal* certification, and retail handling—each validated by authorized nodes rather than a single gatekeeper. When combined with IoT-based sensing and time–temperature logging, blockchain transforms traceability from a retrospective reconstruction into a secure, living history of the product. In doing so, it directly addresses the vulnerabilities that have long plagued meat chains: mislabeling, origin fraud, cold chain abuse, and opaque certification.

Digital traceability also reframes how we think about shelf life and risk. Rather than treating expiry dates as rigid, one-size-fits-all estimates, dynamic models leverage real-time environmental data to calculate remaining shelf life more intelligently. (Kim *et al.*, 2020) demonstrated that temperature history can be translated into mean kinetic temperature and used to estimate residual shelf life of chilled foods; embedded in connected systems, such models can be updated continuously as products move through

the chain. Ren *et al.* (2022) and others argue that such dynamic quality perception—where packaging, sensors, and cloud analytics interact—will be essential for a smart, green meat cold chain. When these dynamic estimates are recorded on a blockchain, downstream actors gain not only a number, but also a verifiable explanation of how that number was generated, reinforcing both safety decisions and commercial trust.

The logistics dimension reveals just how powerful this can become. Bogataj *et al.* (2020) propose a planning and control framework in which real-time remaining shelf life, continuously recalculated based on temperature and delay events, is directly linked with Net Present Value (NPV) optimization. If predicted Customer Remaining Shelf Life (CRSL) falls below contractual thresholds, the system can automatically redirect loads to nearer markets, initiate reverse logistics, or adjust routing to minimize waste and economic loss. Recorded on a secure ledger, these decisions are traceable and auditable, turning shelf life into a managed financial and sustainability variable rather than a passive constraint (Bogataj *et al.*, 2020).

From the consumer's side, robust digital traceability is closely intertwined with perceptions of robustness, safety, and fairness. Abbas *et al.* (2022) highlight how more resilient and data-rich supply networks—illustrated through large-scale, strategically optimized corridors—reduce vulnerability, shorten lead times, and narrow the window in which fraud and mishandling can occur. Faster, better-documented flows are not merely efficient; they are less permissive of tampering and better able to deliver on the promise of "what you see is what you get". In premium and export-oriented segments, such as Brazilian beef, traceability further underpins differentiation based on origin, welfare, and environmental performance. Malafaia *et al.* (2021) identify "meat with a designation of origin" and end-to-end digital technology as central megatrends toward 2040, where value is increasingly linked to verified narratives rather than volume alone.

Traceability takes on an additional ethical and spiritual dimension within the *halal* meat supply chain. Ellahi *et al.* (2025) emphasize that Industry 4.0 technologies—AI, AR, robotics, digital twins, big data, and blockchain—are well positioned to address persistent concerns around cross-contamination, fraudulent labeling, and noncompliance in *halal* systems. Blockchain-based records, enriched by sensor and vision data, can securely link each stage of slaughter, processing, and logistics to certified *halal* practices, while AR and virtual inspection tools provide real-time verification for regulators and certifiers. This architecture does more than monitor; it restores confidence where trust is easily eroded and offers a blueprint for other value-based or identity-preserved meat chains (Ellahi *et al.*, 2025).

The cold chain is where traceability's promises are often tested most harshly. Bruckner *et al.* (2012) showed that even short-lived temperature upshifts—representing less than 5% of total storage time—can reduce fresh pork and poultry shelf life by over 30%. Such sensitivity means that "minor" abuses, unrecorded or invisible in traditional systems, can have disproportionate food safety and economic consequences. Digital cold chains, relying on continuous IoT monitoring of temperature, humidity, and atmosphere, make these fluctuations visible; blockchain ensures that such records cannot be quietly edited after the fact. Together, they create accountability not only for whether a product arrived cold, but for how cold it truly stayed along the way.

Intelligent and active packaging technologies extend this visibility directly onto and even inside the product. Ren *et al.* (2022) highlight composite packaging and sensing-enabled films as essential to modern cold chain management, while related work on freshness indicators, pH-responsive labels, and volatile amine sensors demonstrates how color changes or electrochemical signals can reveal spoilage in real time. When such indicators are digitally readable—via RFID, QR, or NFC—they can be linked to cloud platforms that aggregate and analyze condition data at batch or item level. If this information flow is anchored in blockchain, each package becomes both a sensor and a storyteller: not just labeled "use by", but evidencing its journey, handling, and current status. This convergence of smart packaging, IoT, and blockchain is central to transforming traditional "static" traceability into dynamic, quality-aware provenance systems (Ren *et al.*, 2022).

In parallel, the evolution of digital traceability is pushing supply chains toward circularity and low waste. By making flows of products, by-products, and energy visible and verifiable, digital systems allow processors to identify where trimmings, bones, blood, and fat can be valorized instead of discarded, or where inefficient routes and holding times generate unnecessary spoilage. While detailed zero-waste

frameworks are often explored through digital twin architectures, their effectiveness depends fundamentally on trustworthy traceability layers feeding accurate input data. As such, blockchain-secured records of origin, quality, and transformation steps provide the informational backbone for circular meat systems and for emerging environmental claims, from carbon footprints to climate-smart branding.

Despite its potential, the path to mature digital traceability and blockchain in meat systems is neither linear nor trivial. Technical challenges include data standardization across heterogeneous devices and scales, integration of legacy systems, latency and storage costs, and the validation of sensor accuracy in harsh industrial environments. Governance questions arise around data ownership, liability, interoperability, and the role of regulators: who is allowed to write, who can read, and how disputes are resolved when digital and physical narratives diverge. Economically, the initial cost of infrastructure can deter small and medium enterprises, even when long-term gains in efficiency, reduced recalls, and market access are compelling. Socially, successful systems must be designed to include, rather than marginalize, smallholders and processors in less digitized regions, ensuring that transparency does not become a new barrier to entry.

Nonetheless, the trajectory is clear. Ren *et al.* (2022) position smart, connected cold chains as the cornerstone of future-ready meat logistics; Ellahi *et al.* (2025) frame digital tools as enablers of trust in sensitive religious markets; Bogataj *et al.* (2020) and Abbas *et al.* (2022) show that dynamic, data-driven control can be both more robust and more profitable; Malafaia *et al.* (2021) see digital identity as intrinsic to high-value beef exports; and Bruckner *et al.* (2012) remind us that without hard data on conditions, even the best-designed systems remain fragile. Collectively, these works converge on a single insight: digital traceability and blockchain are not simply technical novelties, but institutional technologies. They rewrite how responsibility, value, and information move through meat chains.

From "stable to fork", then, the emerging vision is of an ecosystem where each calf, carcass, carton, and coded event is part of an unbroken, intelligible storyline. Sensors watch, models interpret, ledgers remember. But at its heart, this transformation is profoundly human: it is about giving farmers recognition for good practice, giving processors tools to act before problems escalate, and giving consumers clear reasons to trust what is on their plate. In that sense, digital traceability and blockchain do not replace relationships in the meat chain—they illuminate them, making integrity visible, verifiable, and, increasingly, nonnegotiable.

23.6.4 Digital Twins: Virtual Modeling of Processing Lines for Optimization and Troubleshooting

The accelerating digital transformation across industrial sectors has fundamentally reshaped how processes are designed, monitored, and optimized. In this transformation, the Digital Twin (DT) has emerged as one of the most influential paradigms in the Fourth Industrial Revolution, bridging the physical and virtual worlds through real-time data connectivity and advanced simulation. Originally developed in aerospace and manufacturing, digital twin technology is now permeating the agri-food sector, offering the ability to simulate complex biological and mechanical systems with unprecedented accuracy and dynamism. In essence, a digital twin is a virtual replica of a physical entity—whether a machine, process, or an entire production line—continuously updated through sensor data and analytics to mirror and predict real-world behavior (Verboven *et al.*, 2020).

In food processing, this approach represents a major leap from static models toward living systems of insight, where processes are continuously recalibrated based on sensor feedback, predictive algorithms, and big data analytics. Verboven *et al.* (2020) note that digital twins integrate multiphysics, multiscale, and multiphase modeling within industrial digitalization frameworks, enabling a nuanced understanding of food systems' thermodynamics, rheology, and biochemical transformations. Unlike traditional process models that rely on fixed assumptions, digital twins evolve in tandem with the physical plant, learning and adapting through data assimilation and ML. Yet, as Verboven *et al.* (2020) also acknowledge, implementing these systems demands a multidisciplinary framework, uniting food engineers, data scientists, control specialists, and computational modelers. Despite clear potential, real-world agro-food applications are still in their infancy, reflecting both the complexity of food matrices and the historically low level of digitalization in the sector.

Across other industries, digital twins have already proven their ability to reduce workload, cut costs, and boost process efficiency—all goals that align closely with food manufacturers' current challenges. Abdurrahman and Ferrari (2025) emphasize that the food industry, operating under tight margins and strict quality expectations, is under pressure to adopt advanced solutions that ensure safety and consistency while minimizing resource use. The integration of digital twins in this context offers a game-changing opportunity to model, predict, and optimize performance before physical interventions are made. Their review shows that although DT applications in industrial-scale food formulation are still limited, they enable personalized product design, where recipes are virtually tested and tailored to meet specific nutritional or sensory targets. For example, food formulation using DTs allows iterative optimization of texture, flavor, and shelf life without the time and cost of extensive pilot runs. This capacity to link formulation to virtual performance prediction introduces a more circular and efficient innovation cycle, one that aligns directly with the sustainability and safety goals of modern meat industries (Abdurrahman and Ferrari, 2025).

The concept extends beyond simple process optimization. As Paris *et al.* (2025) explain, digital twins bring new possibilities for monitoring and controlling food transformation phenomena such as heat and mass transfer, chemical reactions, and structural changes during cooking or preservation. Their work highlights how virtual modeling of cooking—using inputs like size, cut type, and temperature—can accurately simulate heat penetration and predict doneness across different methods, from conventional roasting to sous vide. Such models account for the interplay of thermal degradation, Maillard reactions, and flavor compound formation, offering a deeper understanding of how each parameter influences both safety and sensory quality. In meat processing, where texture, juiciness, and color are tightly linked to precise thermal control, the ability to simulate these dynamics allows producers to optimize yield and energy efficiency simultaneously. This combination of predictive physics and real-time feedback enables operators to move from experience-driven decision-making to data-driven mastery, ensuring consistency across batches and facilities.

The multiscale dimension of digital twin systems is crucial. Udugama, Kelton, and Bayer (2023) propose a layered architecture comprising five modeling scales—from consumer behavior and sensory perception to plant-level operations and physical phenomena—integrated within a unified digital environment. Their conceptual framework captures both upstream and downstream behaviors, connecting microlevel transformations like protein denaturation with macro-level outcomes such as consumer satisfaction and sales. For meat systems, this kind of multiscale modeling can reveal how parameters in chilling or cooking influence not only shelf life and safety but also brand reputation and profitability. By enabling bidirectional feedback between these layers, digital twins can harmonize short-term process control with long-term strategic goals. However, Udugama, Kelton, and Bayer (2023) also caution that challenges remain in harmonizing data acquisition across scales and quantifying the economic value of model integration—a persistent barrier to full industrial adoption.

The integration of AI, IoT, and big data analytics further amplifies the power of digital twins. Abdurrahman and Ferrari (2025) point out that when coupled with AI and IoT networks, DTs evolve from passive simulators into cognitive systems capable of predictive maintenance, autonomous control, and quality forecasting. For instance, real-time sensory data from machinery, temperature probes, and vision systems can be processed by AI algorithms to detect anomalies, simulate outcomes, and automatically suggest process adjustments. This shift from monitoring to reasoning represents the essence of Industry 4.0: a self-learning ecosystem where machines "talk" to each other and to their digital replicas, enabling a closed feedback loop between prediction and action. Within the meat industry, this integration supports fine-grained control of thermal, mechanical, and microbiological variables, ensuring safer, more sustainable, and more profitable production cycles.

Concrete industrial cases demonstrate how these concepts are being translated into practice. One of the most advanced examples comes from Maple Leaf Foods in Canada, which implemented a large-scale digital twin to virtualize and optimize its deli-meat production lines (Deslandes, 2024). In collaboration with Cygnus Consulting and Braincube, the company used IoT sensors and data analytics to model entire processes—from brining and stuffing to cooking, chilling, and slicing—within a 3D virtual environment. By feeding real-time data from its ovens, slicers, and chillers into the digital twin, Maple Leaf could test "what-if" scenarios to identify the ideal cooking temperature, brining ratio, or slicing speed for each batch.

This integration not only eliminated under- and overcooking but also reduced product loss, improved energy efficiency, and standardized product quality across shifts. Deslandes (2024) reports that after implementation, the project increased gross profit by 10–12%, primarily through reduced waste and optimized energy consumption. The case illustrates how digital twins can translate abstract data into tangible operational and financial gains—serving as a decision compass for plant managers and engineers alike.

Beyond operational optimization, digital twins offer substantial environmental benefits, aligning with the growing push toward sustainable and circular meat systems. Valero, Hicks and Nassehi (2022, 2023) argue that the meat sector, responsible for significant resource use and emissions, stands to gain greatly from virtual modeling and simulation-based optimization. They propose a "zero-waste" digital twin framework that integrates sensors, IoT, and data analytics to monitor flows of raw materials, by-products, and energy across the supply chain. By mapping the complete life cycle—from slaughterhouse to packaging to logistics—the twin identifies inefficiencies, predicts spoilage risks, and suggests interventions to reduce waste or repurpose secondary products. Such systems can also quantify real-time carbon footprints, enabling producers to assess sustainability trade-offs dynamically rather than retrospectively. In an age where food waste contributes to nearly 10% of total greenhouse gas emissions, digital twins provide a critical instrument for closing the loop between production, consumption, and waste management (Valero, Hicks and Nassehi, 2023).

At the policy and consortium level, initiatives like the EU-funded BBTWINS project demonstrate how large-scale deployment can drive systemic change. The project developed digital-twin platforms across agri-food value chains—including the pork sector—to model process flows, optimize curing and weighing parameters, and improve traceability through virtual replicas of operations (European Commission, 2025). The results were compelling: reduced batch variability, improved homogeneity, faster return on investment, and more transparent data flows across multiple actors. The BBTWINS approach illustrates how digital twins can bridge the gap between private innovation and public sustainability goals, turning abstract visions of digital agriculture into operational realities. Yet, as the European Commission (2025) notes, challenges persist in standardizing data architectures, ensuring regulatory compliance, and scaling digital infrastructures across diverse production systems.

The cultivated meat sector provides another frontier where digital twins are rewriting the rules of innovation. Bambridge-Sutton (2025) describes how the French start-up Gourmey, in partnership with biotech firm DeepLife, employs digital twins of poultry cells to simulate the effects of molecular and media changes on cell behavior. By combining sequencing data from millions of cells with causal AI models, the team can virtually predict how modifications in nutrient flow or temperature affect tissue growth and quality. This allows them to refine production parameters before physical trials, drastically reducing wet-lab costs and time-to-market. In cultivated meat, where bioprocesses are inherently complex and costly, such in silico experimentation accelerates learning cycles and makes industrial scalability more feasible. The virtual cell twin effectively acts as a sandbox for testing biological, mechanical, and nutritional hypotheses—an embodiment of how digital technology can bring biotechnological production closer to economic reality (Bambridge-Sutton, 2025).

In traditional meat systems, similar digital-twin applications are emerging through immersive visualization and training tools. The Australian Meat Processor Corporation (AMPC, 2022) with Virtual Method to create an interactive digital twin of a red meat processing facility using high-fidelity 3D scanning and virtual–reality environments. The resulting model allows staff to explore boning and offal rooms remotely, simulating operations for maintenance planning, engineering design, and operator training without halting production. This approach transforms complex facilities into digital learning ecosystems, improving safety and knowledge transfer while reducing downtime. In parallel, digital twins provide a platform for production analysis and real-time collaboration between engineers and plant managers, fostering a more connected and adaptive workforce (AMPC, 2022).

The conceptual strength of digital twins lies in their duality: they are both mirror and oracle—faithfully reflecting current conditions while forecasting future performance. As Verboven *et al.* (2020) highlight, successful deployment depends on the harmonious interaction of physics-based models and data-driven algorithms. Physics-based modeling offers interpretability and generalizability, capturing fundamental transport and reaction phenomena; data-driven layers bring adaptability and pattern recognition. When combined into hybrid twins, they enable not only process optimization but also troubleshooting, where

deviations are traced back to their root causes via counterfactual simulation. In meat processing, where quality deviations can stem from subtle shifts in temperature, pH, or mechanical stress, such diagnostic power can prevent costly recalls or product downgrades.

The transition toward widespread adoption of digital twins in the meat industry will, however, require addressing several systemic barriers. Abdurrahman and Ferrari (2025) and Udugama, Kelton, and Bayer (2023) both note the need for harmonized data standards, cybersecurity frameworks, and skilled human capital capable of operating at the intersection of food science and data analytics. The cost of digital infrastructure remains significant, particularly for small and medium-sized enterprises, but collaborative consortia and open-access platforms may help democratize access. Additionally, questions of data ownership and ethics must be clarified to prevent monopolization and to protect intellectual property while still encouraging data sharing.

When effectively implemented, digital twins become a strategic bridge between technology and sustainability, enabling food systems that are transparent, adaptive, and resilient. Their capacity to model the interplay of physical and digital realities allows producers to rehearse change before committing resources, foresee disruptions before they occur, and continuously align operations with environmental and economic objectives. As Deslandes (2024) and the European Commission (2025) have shown, their value is not only in efficiency gains but in cultivating a culture of foresight—a shift from reacting to managing, and from managing to innovating.

Ultimately, digital twins in the meat sector represent a new grammar of precision and prediction. From molecular biology to macro logistics, they integrate the once-disparate languages of engineering, computation, and sensory science. They enable companies to visualize their operations as dynamic ecosystems rather than linear chains, to test scenarios without waste, and to elevate decisions from guesswork to evidence-based orchestration. Whether modeling thermal gradients in a steak, airflow in a chiller, or workforce dynamics in a boning hall, the digital twin's promise lies in turning complexity into clarity. As the boundaries between physical and digital continue to blur, the future of meat processing will depend on how effectively these technologies are scaled and humanized. The twin will not replace human expertise but rather extend it, offering a digital ally that remembers every fluctuation, tests every hypothesis, and anticipates every outcome. In doing so, it redefines what it means to understand, optimize, and sustain a food system—transforming factories into living laboratories, and data into the lifeblood of a more intelligent, sustainable meat industry.

23.7 Sustainable Engineering Strategies

The global meat industry is at a pivotal juncture, balancing its crucial nutritional role with mounting environmental and ethical challenges. Sustainable engineering offers a systems-based response, merging technology, efficiency, and moral responsibility. As outlined in *Sustainable Meat Production and Processing*, future-ready meat systems must adopt a circular bio-economy—transforming by-products into valuable co-products such as proteins, collagen, and bioactives while generating renewable energy from residues (Galanakis, 2018). This shift from linear to regenerative processes demands synergy between animal welfare, resource efficiency, and technological innovation.

Advanced and nonthermal technologies—like HPP and CP—minimize energy and water use while preserving quality and extending shelf life, reducing food loss. Automation, real-time monitoring, and AI-driven control further enhance process stability and sustainability. Meanwhile, packaging transitions toward monomaterial, bio-based, and recyclable systems, guided by EU 2030/2040 reuse targets, reflect the industry's broader commitment to closing material loops (Anonymous, 2025c).

Modern meat factories are also deploying waste-heat recovery, industrial heat pumps, and water recycling technologies such as reverse osmosis to cut energy and water consumption dramatically. Even smaller processors benefit from smart drives, servo-motors, and energy-optimized control. As Anonymous (2025c) emphasizes, sustainability and efficiency are now inseparable—digitalization, design, and circular thinking yield both ecological and economic returns. In uniting ethics, engineering, and enterprise, sustainable meat production envisions an industry that regenerates resources, strengthens competitiveness, and ensures food security for a changing planet.

23.7.1 Energy-Efficient Machinery: Heat Recovery Systems and Low-Energy Consumption Equipment

Energy efficiency has emerged as a defining pillar of sustainable transformation in the global food sector. Within this landscape, the meat industry remains one of the most energy-intensive branches of food manufacturing, with significant consumption associated with slaughtering, refrigeration, thermal processing, and packaging. Improving energy efficiency is therefore both an economic and environmental imperative—essential to lower operating costs, meet emissions targets, and preserve product quality. Modern sustainability frameworks increasingly regard energy conservation not as an auxiliary initiative but as a core engineering function shaping the competitiveness and climate resilience of the meat sector (Arul Selvaraj *et al.*, 2025).

23.7.1.1 Energy Demand Patterns, Integration Opportunities, and Technological Pathways to Conservation

In a typical meat-processing facility, heating and cooling dominate total energy use. Water heating for cleaning, scalding, and sterilization requires large amounts of thermal energy above ambient temperature, while refrigeration and freezing processes below ambient consume most of the mechanical shaft work on-site. Studies applying process-integration methods show that interaction between these two regimes—heat demand and cooling supply—offers considerable potential for cross-utilization (Fritzson and Berntsson, 2006). By coupling heat-recovery loops or installing industrial heat pumps, thermal energy released during refrigeration can be reused to preheat process water. Such integration may reduce external heat demand by up to 30% and mechanical power by more than 10%, translating into meaningful cost- and emission-savings. The actual economic benefit, however, depends on plant scale, fuel prices, and local energy infrastructure.

Energy conservation has long been a focus for the sustainable development of food processing, and continuous innovation has diversified the available technological pathways. Novel thermodynamic cycles, nonthermal processes, and advanced heat-transfer systems increasingly complement or replace conventional high-energy operations such as sterilization, dehydration, and freezing. For instance, microwave and ohmic heating can pasteurize meat products with shorter residence times and lower overall energy use compared to traditional water-immersion systems. In comparative trials, microwave in-package pasteurization achieved *L. monocytogenes* inactivation rates of 0.41–0.94 log (CFU/pk)/min at 65–85 °C, delivering faster processing and comparable microbial lethality to immersion pasteurization (Wang, 2014).

Across the broader food sector, such novel techniques promise to reduce production costs, cut carbon emissions, and improve resource efficiency. Yet the meat industry's high dependency on refrigeration remains a dominant concern: chilling and freezing can account for 40–90% of electricity use during production and nearly 100% during non-production hours. Solutions therefore center on improved insulation, heat-exchanger design, and novel refrigeration cycles powered by waste heat. By upgrading conventional vapor-compression systems with ammonia or CO_2 heat pumps, operators can simultaneously reduce compressor workload and harness condenser heat for water or space heating (Wang, 2014).

23.7.1.2 Process Integration, Plant Engineering, Low-Energy Equipment, and Smart Control

From a plant-engineering perspective, efficiency gains often arise from practical retrofits rather than entirely new systems. The Meat Industry Association of New Zealand highlights that substantial reductions in hot-water use can be achieved through in-house modifications such as flow restrictors or optical ("magic-eye") sensors on sterilizer units. These sensors deliver water only when utensils are present, preventing continuous flow and yielding water-reduction rates exceeding 50% in many facilities. However, supervisory vigilance or automated control is essential to ensure operators do not override sensors, which would negate savings (MIA, 2024).

At a systemic level, waste-heat capture remains one of the most promising strategies. Energy lost from refrigeration compressors, boilers, and condensers can be recovered via plate or shell-and-tube heat exchangers and repurposed for hot-water generation, space heating, or cleaning. Integration of ammonia–CO_2 cascade systems and hybrid chillers has achieved up to 30% cuts in natural gas consumption, while condensate-return and effluent-heat exchangers further reduce discharge temperatures and thermal pollution (MIA, 2024).

Modern meat-processing lines are also adopting low-energy machinery across auxiliary systems. Variable-speed drives on compressors and pumps deliver 5–15% electrical savings, adjusting motor speed to real-time load rather than running continuously. Servo-driven cutting and packaging systems minimize mechanical losses and ensure consistent precision, while LED lighting and smart-motor upgrades improve both illumination quality and component longevity. Additionally, insulated steam networks and vacuum-condensate recovery systems can enhance boiler efficiency by 10–12%, preventing heat dissipation and recycling condensate back into the feedwater system.

Beyond hardware optimization, digitalization has become the connective tissue of energy management. IoT-enabled sensors, cloud dashboards, and data-analytics platforms now monitor compressor efficiency, temperature deviations, and water intensity in real time. These tools underpin ISO 50001 energy-management compliance by allowing predictive maintenance, automated load-balancing, and continuous benchmarking across production shifts (MIA, 2024). Such digital integration elevates sustainability from a one-time engineering project to an adaptive operational culture driven by data visibility and accountability.

23.7.1.3 Benchmarking Energy Intensity, Combined Heat–Power, and Renewable Synergies

Comparative analyses underscore how energy use varies across food subsectors and regions. In Europe, the meat and dairy sectors rank among the largest consumers of refrigeration energy, with meat processing alone responsible for 10–15% of total energy input to the entire food industry(Wang, 2014). Energy indicators measured in megajoules per ton of finished product increased by up to 48% through the 1990s, partly due to stricter food safety regulations demanding lower processing temperatures and extended cold chains. In the United States, meat manufacturing represents the single largest segment by shipment value, followed closely by dairy and grain milling. Each of these sectors spends well over half its energy budget on purchased electricity—58.8% for meat and 57.3% for dairy—highlighting the financial stakes of conservation.

Process-integration studies like that of Fritzson and Berntsson (2006) demonstrate that even modern, already-optimized facilities retain technical potentials for 30% thermal and 10% mechanical savings, suggesting that the path to efficiency is iterative rather than finite. Incremental advances—improved cleaning-in-place (CIP) systems, regenerative heat exchangers, or pressure-controlled refrigeration valves—often yield quick paybacks, reinforcing the notion that sustainability and profitability are co-dependent rather than competing goals. Case studies within the MIA (2024) report further reveal how combined heat-and-power (CHP) units and integrated heat-pump recovery can lower total site energy intensity by up to 25%. CHP systems simultaneously produce electricity and usable heat from a single fuel source, raising overall thermal efficiency to 80–90%. When coupled with renewable inputs—such as biogas derived from rendering residues or wastewater digesters—they transform plants into miniature energy hubs capable of offsetting grid dependency. This symbiosis between waste valorization and energy generation epitomizes circular-economy thinking within the meat industry, linking environmental stewardship directly to operational resilience.

23.7.1.4 Toward Future-Ready Energy Management

Despite demonstrable progress, several barriers persist. Upfront capital costs, limited technical expertise, and fragmented data systems can hinder adoption, especially among small- and medium-sized processors. Nonetheless, the trajectory is clear: energy-efficient machinery and heat-recovery systems are evolving from optional upgrades into foundational infrastructure for competitiveness. Future advancements may

involve AI-assisted control architectures, phase-change materials for thermal storage, and integrated renewable microgrids tailored to the cyclical demands of meat processing.

As Arul Selvaraj *et al.* (2025) emphasize, the sustainable meat factory of tomorrow will rely on automation and energy-management systems that dynamically balance efficiency with hygiene and product integrity. By merging engineering precision with environmental foresight, these systems will enable plants to achieve higher throughput using less energy—turning kilowatts saved into profit gained.

Ultimately, energy efficiency in the meat industry is not only a matter of technology but of strategic alignment—linking process innovation, workforce training, and policy incentives into a coherent vision of low-carbon productivity. Whether through reclaiming waste heat, modernizing equipment, or embedding digital intelligence, the result is a production ecosystem that consumes less, wastes less, and sustains more. As the case studies by Fritzson and Berntsson (2006), MIA (2024), and Wang (2014), collectively demonstrate, such integration yields dividends well beyond energy bills: it strengthens food security, enhances corporate reputation, and charts a path toward a truly sustainable and regenerative meat-processing future.

23.7.2 Water Conservation and Recovery: Advanced Filtration, Recycling, and Reuse Systems in Processing Plants

Water stands at the center of sustainable food production, yet it is increasingly recognized as a finite resource under escalating global stress. Rapid population growth, industrialization, and climate change have compounded freshwater scarcity, pressing food industries to pursue new paradigms of rational use, recycling, and reuse. Among all manufacturing sectors, food processing ranks as one of the largest water consumers—after chemicals and refineries—accounting for nearly 15% of industrial withdrawals in Europe (Ölmez, 2014). Within this landscape, the meat sector occupies a unique position: highly water-intensive, strictly regulated for hygiene, and endowed with immense potential for conservation through engineering innovation and process redesign.

When it comes to a viewpoint from a global context, the journey from water scarcity toward the concept of circular water thinking reflects a gradual shift in how industries and governments perceive water not merely as a resource to be consumed but as a system to be sustained and regenerated through mindful design and policy. Sustainable water management in the food industry begins with acknowledging that less than 0.3% of the planet's freshwater is readily accessible for human use. As global demand intensifies, water reclamation and reuse have become indispensable tools to protect natural reserves and ensure industrial continuity. Contemporary frameworks such as the Zero Water Discharge (ZWD) and Water Pinch Analysis (WPA) concepts advocate an integrated approach—optimizing source, process, and discharge simultaneously (Ölmez, 2014). Cleaner-production philosophies complement these tools, promoting process redesign, dry cleaning, and counter-current washing, capable of reducing freshwater intake by up to 90% in some food subsectors.

At the strategic level, industries are moving from compliance-driven treatment to closed-loop water management, in which wastewater is reconditioned through multi-barrier systems and reintroduced into noncritical operations. The dual objective is clear: safeguard product safety while achieving measurable reductions in both consumption and effluent load. Understanding this transformation requires examining the regulatory and technological landscape, where frameworks, standards, and innovations have jointly shaped the pace and direction of sustainable water management. These elements collectively define how industries respond to both environmental challenges and compliance pressures. Legal and microbiological constraints remain the decisive factors shaping reuse feasibility. International frameworks—such as the US EPA Guidelines for Water Reuse (2004) and the Australian National Water Recycling Guidelines—define performance targets in terms of microbial log-reductions, chemical thresholds, and validation protocols. In many emerging economies, however, only nonpotable reuse is formally regulated. For instance, in Brazil, Matsumura and Mierzwa (2008) implemented rational-use strategies in a poultry-processing plant under a national policy that authorizes nonpotable reuse but lacks specific potable standards. By identifying high-consumption units, detecting leaks, and rerouting final-rinse water for cleaning, the study achieved a 31% reduction in total water use—demonstrating that operational optimization alone can yield substantial savings without compromising hygiene.

Similarly, Onbaşı (2007) investigated reclamation at the MIGROS TURK T.A.Ş. TAN-ET meat-processing facility in Turkey, where effluent quality was evaluated against potential reuse options. The findings revealed that direct reuse was infeasible for agricultural irrigation, boiler feed, or process water without additional treatment to remove organics and hardness. The recommended solution combined coagulation–flocculation pretreatment with biological processing, followed by reverse osmosis (RO) polishing. Depending on the chosen membrane configuration, subsequent disinfection—via chlorination, UV, or ozone—ensured pathogen control, with UV preferred for health safety and ozone offering an economical alternative.

In particular, the Australian framework demonstrates a mature integration of risk assessment and technological adaptation, where regulation and innovation work in tandem to ensure that water reuse and recycling are both safe and economically feasible. Australia's success lies in aligning its scientific research, industrial practice, and policy enforcement under a coherent water stewardship model.

Australia's red-meat sector provides one of the most advanced regulatory and technical blueprints for sustainable water reuse. The Australian Meat Processor Corporation (AMPC) has produced a series of technical reports and projects (2013; 2017) addressing both the engineering design and HACCP-based risk management required for implementation. The guideline by Prasad *et al.* (2017) adopts a multiple-barrier approach, integrating microfiltration (MF) and reverse osmosis (RO) within Advanced Water Treatment Plants (AWTPs). It establishes microbial log-reduction targets aligned with the Australian Drinking Water Guidelines (2016) and provides validation protocols and cost–benefit scenarios for potable-quality recycling.

The AMPC (2013) project further demonstrated that properly treated process water could substitute up to 30–40% of freshwater intake, provided treatment trains meet microbiological and chemical standards. Reuse applications include condensate from rendering, noncontact cooling water, and recovered rinse water for equipment washing. Combining physical treatments (filtration, UV, membranes) with chemical disinfection (chlorination, pH control) secured compliance, while real-time monitoring ensured ongoing verification. Together, these studies confirm that sustainable water reuse in meat processing is technically feasible, economically viable under certain conditions, and fully compatible with food-safety assurance when guided by HACCP principles.

Moving from governance to process, integration of systems and combined technologies plays a pivotal role in reducing waste and enhancing efficiency. By merging physical, chemical, and biological treatment processes, industries are now achieving higher recovery rates and greater consistency in effluent quality Slaughterhouse wastewater (SWW) presents distinctive challenges: high organic load, fats, oils, and grease (FOG), suspended solids, and pathogens derived from blood and tissue residues. Single-stage treatments seldom meet reuse standards; hence combined processes are required. Philipp *et al.* (2021) evaluated such combinations, identifying the sequence of dissolved-air flotation (DAF) followed by membrane bioreactor (MBR) and then reverse osmosis (RO) as particularly promising. DAF effectively removes FOG and suspended solids (achieving up to 98% FOG and 97% TSS reduction), while MBR ensures biological polishing, and RO produces near-potable permeate suitable for cleaning or cooling water. An additional advantage arises from the energy potential of meat-processing effluent: by harnessing the organic fraction for biogas generation, the energy demand of wastewater treatment can theoretically be offset. This coupling of energy and water recovery exemplifies the broader eco-efficiency paradigm underpinning modern plant design (Philipp *et al.*, 2021).

Among these, membrane technologies and advanced filtration stand out as the cornerstone of modern water recovery systems. Their precision in separating impurities, coupled with advances in materials science, has transformed the feasibility of treating complex industrial wastewater streams into high-quality reusable water. Membrane processes—microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO)—have become the cornerstone of high-quality water recycling in food industries. Garnier *et al.* (2022) provide a detailed review of these pressure-driven technologies, classifying wastewater by sector, COD load, and reuse potential. Their findings reveal that NF and RO can retain up to 99% of pollutants and generate permeates of near-potable quality when treating low-strength effluents (COD < 1 g/L). However, for highly contaminated streams—typical of meat and poultry plants—multistep pretreatment and post-disinfection are essential. Membrane applications extend beyond water polishing to brine recovery, addressing a long-standing environmental issue in meat, fish, and cheese industries.

As McMahon (2006) explains, brine streams rich in salt, protein, and microorganisms are difficult to treat once mixed with other effluents. Employing UF or MF membranes for selective recycling allows prolonged brine use and drastically lowers both discharge volumes and treatment costs. In meat chilling, this approach also improves thermal stability and reduces the need for continuous brine replacement.

However, technology alone is insufficient without attention to cleaner production and operational efficiency. This principle reinforces that minimizing waste at its source, optimizing production cycles, and adopting proactive maintenance are as vital as end-of-pipe solutions in achieving long-term sustainability.

Technological solutions must be embedded within broader cleaner-production strategies, where resource efficiency is achieved not only through hardware but also through behavioral and procedural optimization. Bailone *et al.* (2022), reviewing cleaner production in meat and fresh-produce sectors, advocate water sustainability through recycling, effluent treatment, and pollution prevention. Their synthesis shows that integrating water reuse with process redesign yields environmental and economic benefits: reduced effluent loads, lower utility costs, and added value through sustainability branding. However, such transitions require coordinated support from policymakers, industries, and consumers to normalize reclaimed water use and overcome perceptual barriers.

At the plant level, simple interventions—such as counter-current washing, automated shut-off valves, and high-pressure nozzles—often achieve immediate reductions before major capital investments. The study by Matsumura and Mierzwa (2008) in Brazil provides an excellent example: through improved leak detection and equipment calibration, the facility saved nearly one-third of its water without new treatment infrastructure. These incremental measures pave the way for larger, technology-intensive systems.

Beyond the engineering perspective, economic and risk assessment dimensions determine the real-world applicability of water recovery technologies. Balancing cost efficiency, energy consumption, and regulatory compliance ensures that sustainability goals remain financially viable and strategically scalable.

Financial viability remains a decisive factor in the adoption of advanced water-recovery systems. The cost-benefit models developed by Pype *et al.* (2018) for red-meat facilities compare conventional lagoons and biological nutrient-removal plants with advanced anaerobic–aerobic–membrane (AAnMBR) configurations. Results indicate that while capital expenditures rise with membrane integration, life cycle costs decline due to water-purchase and discharge-fee savings. Payback periods shorten when reuse volumes exceed 25% of total consumption, particularly in water-stressed regions.

Risk management is equally crucial. The AMPC framework (Prasad *et al.*, 2017) embeds quantitative microbial-risk assessment (QMRA) and multiple-barrier validation, ensuring that any system—from DAF to RO—meets targeted log-reductions for pathogens. Monitoring via Recycled Water Management Plans (RWMPs) ensures continuous control, while stakeholder engagement and staff training build the organizational culture needed to sustain performance. Recent progress also highlights the momentum toward technological innovation aimed at zero liquid discharge (ZLD). This vision, which seeks to eliminate any wastewater release, represents the pinnacle of circular water use—transforming effluent management from a disposal issue into a resource recovery opportunity.

Emerging research points toward the feasibility of Zero Liquid Discharge (ZLD) systems in future meat facilities, where every liter entering the plant is either incorporated into product or recovered for reuse. The review by Garnier *et al.* (2022) notes that hybrid membrane systems combining NF/RO with UV, ozone, and activated-carbon polishing can achieve permeate purity levels suitable for equipment cleaning and cooling. Integration with advanced oxidation processes (AOPs) further ensures removal of trace organics and residual disinfectants. Complementary innovations such as Water Pinch Analysis and Simultaneous Water and Energy (SWE) optimization enable facility designers to map water flows alongside thermal and electrical energy exchanges. This digital-simulation approach identifies reuse opportunities and minimizes combined utility loads, reinforcing both environmental and economic gains (Ölmez, 2014).

Ultimately, these developments converge toward a broader vision of sustainable water stewardship in the meat processing sector. By embedding ecological responsibility, technological excellence, and socioeconomic awareness into every stage of production, the industry moves closer to achieving genuine circularity—where every drop of water counts, and every process contributes to the resilience of the ecosystem that sustains it.

Across all cited works, several unifying principles emerge. First, multi-barrier treatment chains—from DAF to membranes—are essential for achieving water of reusable quality. Second, regulatory alignment with HACCP and risk-management frameworks legitimizes water reuse within food safety systems. Third, economic optimization through cost–benefit and energy-recovery coupling ensures long-term viability. And finally, cultural and organizational adaptation—training, monitoring, and consumer communication—remains vital to overcome the psychological barrier surrounding reclaimed water use. In practice, modern abattoirs and meat plants are moving steadily toward semi-closed water loops. Recovered condensate from rendering and chilling systems is reintroduced for cleaning or boiler feed; treated effluent from MBR–RO trains is reused for yard washing or irrigation; and brine is partially recycled through UF polishing. Collectively, these interventions can cut freshwater intake by 30–40%, curtail wastewater volumes by half, and reduce energy use through lower pumping and heating demand (AMPC, 2013; Philipp *et al.*, 2021). As water scarcity intensifies, the meat industry's ability to secure its own water future will define its competitiveness and social license to operate. Advanced filtration, recycling, and reuse systems transform what was once waste into an asset—a closed-loop resource that safeguards both productivity and the planet. The transition from linear consumption to circular stewardship is not merely a technological upgrade but a profound cultural shift. As Matsumura and Mierzwa (2008) succinctly put it, rational water-use programs are "important tools for industry economy and its sustainability, and for the environment by preserving freshwater resources".

23.7.3 Waste Valorization Technologies: Equipment for Converting By-Products (Blood, Bones, Fat) into High-Value Ingredients (Protein Hydrolysates, Biofuels)

Modern meat systems no longer have the luxury of treating blood, bones, fat, and offal as waste. As environmental pressures, raw-material costs, and societal expectations converge, these streams are increasingly recognized as co-products—rich, designable resources at the heart of a circular bioeconomy. Waste valorization in slaughterhouses and meat-processing plants is not simply an add-on to environmental compliance; it is an engineering, economic, and ethical strategy that links resource efficiency, greenhouse gas reduction, and innovation in food, feed, biomaterials, nutraceuticals, and bioenergy (Ashilenje *et al.*, 2025).

Over the past decade, scholarship and industrial practice have moved from piecemeal waste treatment toward integrated waste-to-resource platforms. Advanced biochemical processes, thermochemical routes, and separation technologies are now combined to recover nutrients, extract bioactives, and generate bioenergy from slaughterhouse waste (Ashilenje *et al.*, 2025; Hashim *et al.*, 2023). Case studies—including underrepresented regions such as Africa—demonstrate that valorization systems can simultaneously cut disposal burdens, generate local income, and mitigate pollution, provided they are supported by suitable policy, infrastructure, and context-specific technological choices (Ashilenje *et al.*, 2025).

Within the wider food system, this transition is framed by the recognition that one-third of produced food is wasted, much of it rich in proteins, lipids, minerals, fibers, and polyphenols (Liu *et al.*, 2023; Mia, Ahmed and Zzaman, 2025). Reviews on food-waste valorization emphasize that discarded fractions often contain higher concentrations of bioactive compounds than edible portions, and that green extraction technologies—enzymatic hydrolysis, membrane separation, supercritical fluids, high-pressure and other "mild" processes—can preserve functionality for applications in functional foods, preservatives, and clean-label ingredients (Mia, Ahmed and Zzaman, 2025). This systemic view naturally converges on the meat sector, where by-products are voluminous, compositionally dense, and tightly regulated (Figure 23.6).

In the evolving context of sustainable meat processing, what was once viewed merely as waste is increasingly being recognized as a valuable resource. This transformation in perception reflects a broader industrial shift—from treating by-products as a disposal burden to integrating them into circular value chains that recover nutrients, energy, and functional compounds. The scale of meat production—exceeding 340 million tons annually—inevitably generates substantial quantities of hides, skins, offal, bones, feathers, fat, blood, paunch contents, and high-strength effluents (Liu *et al.*, 2023). Historically, rendering has served as the primary route, converting tissues into meat-and-bone meal, blood meal, feather meal, and tallow. While rendering remains indispensable, its products are often channeled into relatively low-value uses. Contemporary valorization research challenges this hierarchy, demonstrating

FIGURE 23.6 Sankey diagram of energy and water flows in a modern plant.

that the same streams can be processed into high-value protein ingredients, bioactive peptides, biomedical minerals, biofuels, and single-cell protein substrates, without compromising safety (Boboua *et al*., 2024; Bou *et al*., 2025; Hashim *et al*., 2023).

Ashilenje *et al*. (2025) position slaughterhouse waste management explicitly within circular-economy thinking, documenting successful combinations of biogas plants, nutrient recovery, and material reuse that reduce environmental load and enhance local resilience. They highlight the need for region-specific technology choices, robust governance, and capacity-building so that valorization becomes the norm rather than the niche. In parallel, Iskakov and Sugirbay (2023) survey equipment landscapes for animal-waste processing—dryers, grinders, mixers, fat separators, pelletizers—underscoring how modern plants can be configured as integrated resource factories, not just abattoirs (Figure 23.7).

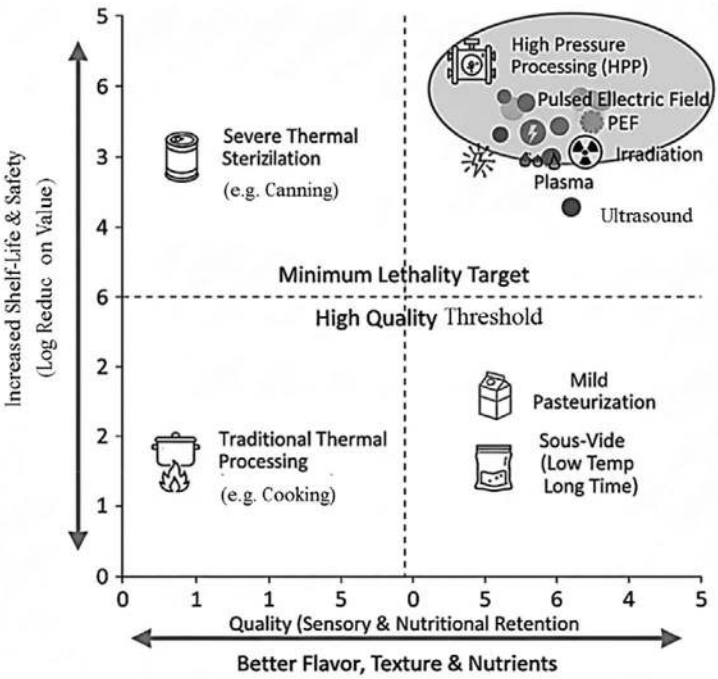

FIGURE 23.7 Comparison of conventional and emerging food processing technologies based on microbial lethality and product quality.

Within this renewed perspective, protein-rich by-products have gained attention as promising sources of protein hydrolysates and bioactive peptides. Through targeted hydrolysis and purification, these compounds not only enhance nutritional value but also provide functional and health-promoting properties, bridging food technology with the growing bioactive ingredient market. One of the most dynamic frontiers is the conversion of animal by-product proteins into bioactive peptides and functional hydrolysates. Instead of incineration or low-grade feed, targeted enzymatic hydrolysis allows precise tailoring of peptide size, solubility, and bioactivity. In a notable example, Borges *et al.* (2022) developed a combined process for porcine by-products in which enzymatic hydrolysis with Alcalase yielded protein hydrolysates with >50% degree of hydrolysis, enriched in low-molecular-weight peptides (<1.2 kDa) exhibiting strong antioxidant capacity (ABTS and ORAC assays), while the residual mineral fraction was transformed by calcination into nanostructured hydroxyapatite with near-stoichiometric Ca/P ratio. The elegance of this dual-stream process lies in its parallel valorization of organic and inorganic fractions, generating inputs for nutrition, catalysis, environmental remediation, and biomedical applications from a single by-product source (Borges *et al.*, 2022).

Similarly, Szucs *et al.* (2021) systematically evaluated commercial proteases (e.g., Alcalase, Protamex, Neutrase, Flavourzyme, PTN) for simultaneous recovery of protein hydrolysates, lipids, and collagen from meat-processing residues. They showed that tailored enzyme selection could maximize specific targets: Alcalase for high hydrolysis and lipid recovery; Neutrase for collagen enrichment; blends for balanced outputs. Crucially, the fatty acid profiles remained stable, indicating that hydrolysis conditions preserved lipid integrity (Szucs *et al.*, 2021). These findings confirm protease-based hydrolysis as an eco-friendly, controllable, and scalable route to generate high-value ingredients for foods, feeds, and cosmetics.

At a broader level, Boboua *et al.* (2024)) synthesize a decade of work on animal-waste proteins, highlighting peptides with antioxidant, antimicrobial, antihypertensive, antidiabetic, and antithrombotic activities suitable as core ingredients for nutraceuticals and functional foods (Table 23.3).

TABLE 23.3

Waste Valorization Pathways for Meat Processing By-Products

By-Product	Primary Composition	Valorization Pathway	Resulting High-Value Product(s)	Key Technologies / Equipment
Blood	Proteins (albumin, globulin), minerals, heme compounds	Enzymatic hydrolysis Separation and fractionation	Protein hydrolysates, bioactive peptides, blood plasma powders, colorants	Hydrolyzers, centrifuges, spray dryers
Bones	Collagen, minerals (Ca, P), lipids	Thermal/enzymatic extraction Calcination	Gelatin, collagen peptides, hydroxyapatite, mineral supplements	Rendering cookers, pressure tanks, hydrolysis reactors, calcination kilns
Fat (tallow/lard)	Triglycerides, fatty acids	Transesterification Purification	Biodiesel, lubricants, oleochemicals	Biodiesel reactors, separators, filtration units
Skin and connective tissue	Collagen-rich protein	Enzymatic or acid–alkali treatment	Collagen peptides, gelatin, film-forming biopolymers	Enzymatic hydrolysis systems, vacuum evaporators
Feathers (poultry)	Keratin (tough fibrous protein)	Hydrothermal processing Microbial/enzymatic keratinolysis	Keratin hydrolysates, animal feed additives, biodegradable films	Hydrothermal digesters, keratinase bioreactors
Offal (liver, heart, kidneys)	High-value proteins, enzymes, micronutrients	Enzyme-assisted extraction Dehydration	Bioactive protein extracts, nutraceutical powders, pet-food ingredients	Freeze-dryers, membrane filters, enzymatic reactors
Sludge and wastewater solids	Organic matter, proteins, lipids	Anaerobic digestion Composting	Biogas, biofertilizers, methane	Anaerobic digesters, biogas capture systems

(Continued)

TABLE 23.3 ***(Continued)***

Waste Valorization Pathways for Meat Processing By-Products

By-Product	Primary Composition	Valorization Pathway	Resulting High-Value Product(s)	Key Technologies / Equipment
Trimmings and mechanically separated residues	Mixed lean meat, fat, connective tissue	Mechanical separation Fractionation	Recovered meats, protein concentrates, emulsifiers	Separators, decanters, mechanical deboners
Rendering residues	Mixed fat–meat matrix	Heating, separation, purification	Meat-and-bone meal (MBM), industrial fats, feed ingredients	Rendering cookers, screw presses, centrifuges
Glycerin from biodiesel processing	Crude glycerol	Purification and chemical conversion	Refined glycerol, biopolymers, platform chemicals	Distillation units, catalytic conversion reactors

Zou *et al.* (2021) focus specifically on liver proteins, demonstrating how enzymatic processes can unlock bioactive hydrolysates and enzyme preparations for food, healthcare, veterinary and agricultural uses, while reducing the environmental burden of underutilized livers. Collectively, this literature reframes meat by-products as reservoirs of precision biofunctionality, contingent on appropriate extraction, characterization, and regulatory frameworks. Beyond biochemical extraction, the valorization of by-products also extends to bioenergy generation and low-carbon co-products. Converting organic residues into biogas, bioethanol, or biochar exemplifies how circular thinking can simultaneously address waste reduction, renewable energy production, and carbon footprint mitigation across meat-processing facilities. In parallel with ingredient-oriented valorization, animal by-products and effluents offer substantial potential as bioenergy feedstocks. High-strength waste streams rich in proteins and lipids can be converted via anaerobic digestion, fermentation, transesterification, and thermochemical processes into biogas, biodiesel, bio-alcohols, and bioelectricity.

Hashim *et al.* (2023) emphasize that blood, bone, sludge, manure, lipids, and meat effluent form an energy-dense biomass resource that can displace fossil fuels, mitigate climate impacts, and reduce solid waste. Anaerobic digestion not only generates methane but also stabilizes sludge, lowers pathogen loads, and supports integrated waste-management systems. Examples of biodiesel production from pork fat, eggshell-catalyzed transesterification, and manure-derived biochar-based catalysis illustrate how engineering design and catalysis can match heterogeneous wastes with appropriate conversion pathways (Figure 23.8) (Hashim *et al.*, 2023).

These bioenergy strategies, when embedded within processing plants, contribute to energy self-sufficiency, lower greenhouse gas emissions, and improved economics—especially when aligned with heat recovery, water reuse, and rendering optimization. Ashilenje *et al.* (2025) and Liu *et al.* (2023) both highlight that such integrated systems are particularly transformative in regions struggling with waste infrastructure, offering decentralized, low-waste solutions that turn liabilities into strategic assets.

Equally significant is the use of by-products for feed, fertilizer, and single-cell protein production, which closes the nutrient loop between livestock and agriculture. By redirecting protein-rich streams and organic residues toward microbial or agricultural applications, industries reinforce the principles of bio-efficiency and food system resilience. Classic valorization routes such as meat-and-bone meal, feather meal, blood meal, and tallow remain central, but are being refined through better process control and blending strategies. Iskakov and Sugirbay (2023) identify multiple animal-waste-derived feeds and note that combining these with plant proteins optimizes amino-acid balance, supporting animal nutrition while reducing reliance on virgin protein sources.

At the same time, food-waste and slaughterhouse effluents are being explored as substrates for single-cell proteins (SCP) and microbial biomass, offering high-protein ingredients without competing directly with human-edible crops (Liu *et al.*, 2023; Meduri *et al.*, 2025). These approaches illustrate a tiered logic: first, maximize direct human consumption of edible co-products; second, valorize remaining fractions into high-quality feed and SCP; third, channel residual organics to bioenergy and soil amendments.

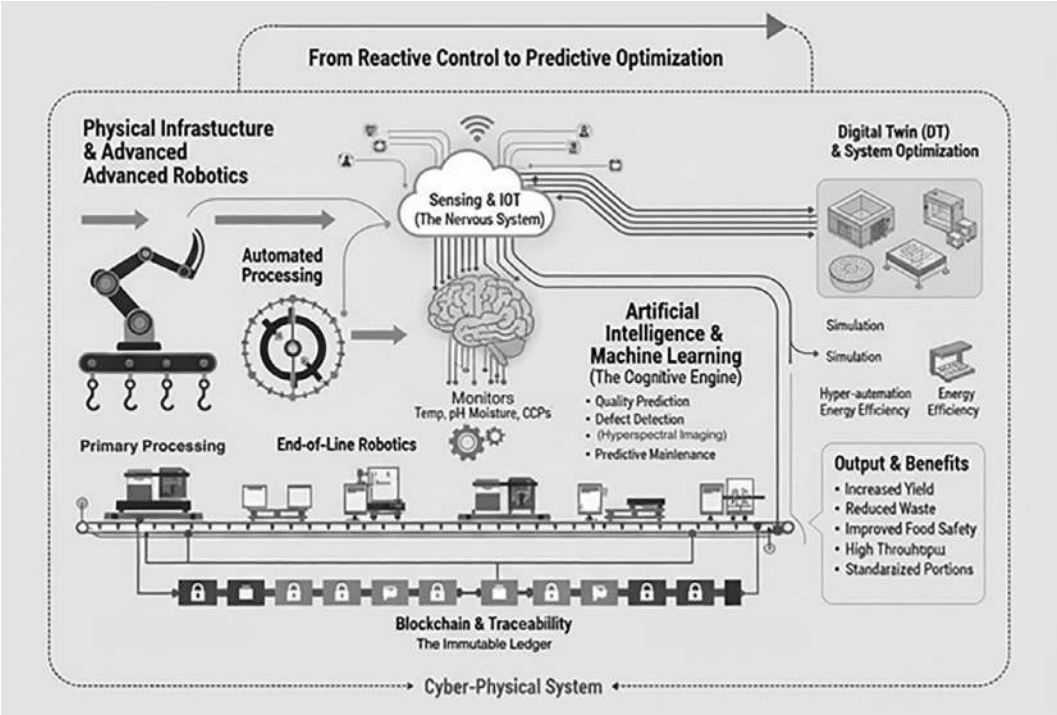

FIGURE 23.8 Smart slaughterhouse 4.0 framework integrating artificial intelligence, IoT, digital twins, and robotics.

Meanwhile, innovative research continues to explore high-value extracts and functional biomaterials from meat by-products—ranging from collagen-based films and edible coatings to antioxidant and antimicrobial compounds. These niche applications demonstrate how interdisciplinary innovation can elevate low-value waste streams into premium, marketable materials. Waste valorization is not limited to bulk commodities. Mia, Ahmed, and Zzaman (2025) and Meduri *et al.* (2025) showcase how polyphenol- and fiber-rich residues, propolis extracts, and winery by-products such as wine lees can be incorporated into meat systems as natural antioxidants, antimicrobial agents, or functional extenders, improving shelf life, nutritional value, and sensory properties while reducing reliance on synthetic additives. These strategies, while not exclusive to meat by-products, can be synergistically integrated into meat-processing value chains—for instance, using non-meat food waste to stabilize meat products, closing loops across sectors (Figure 23.9).

In parallel, Bou *et al.* (2025) draw attention to the underexploited potential of edible co-products and offal as ingredients for food and pharmaceutical applications, as well as scaffolds, gels, or bioactive matrices in biomedical domains. They stress that technological capability is advancing faster than consumer perception and regulation, and call for clear communication, improved processing technologies, and alignment with pet-food and premium-feed innovation to unlock this latent value.

Ultimately, such initiatives converge in the vision of an engineered circular abattoir—a facility where every output, whether solid, liquid, or gaseous, is rerouted into a productive pathway. Integrating advanced treatment systems, data-driven monitoring, and life cycle thinking allows abattoirs to function not as waste producers but as hubs of bio-industrial innovation. Across these contributions, a coherent engineering narrative emerges: the "circular abattoir" is built on deliberately designed process trains and equipment configurations that separate, stabilize, and upgrade by-products at source. Core unit operations include the following:

a. Segregated collection of blood, bones, offal, fat, and effluents to preserve quality.
b. Thermal and enzymatic reactors for targeted hydrolysis and fat separation (Szucs *et al.*, 2021; Zou *et al.*, 2021).

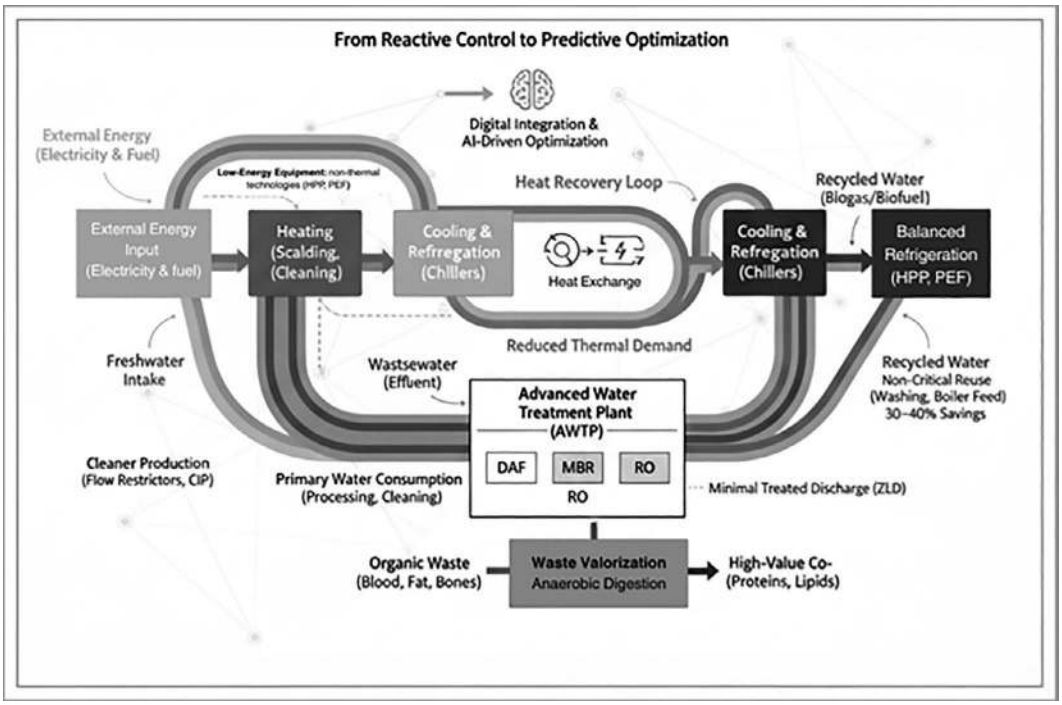

FIGURE 23.9 Integrated resource recovery and AI-driven optimization in meat processing: From reactive control to predictive sustainability.

c. Membrane systems, centrifuges, and crystallizers for purification, concentration, and mineral recovery (Borges *et al.*, 2022; Garnier *et al.*, 2022—style technologies conceptually aligned).
d. Anaerobic digesters, bioreactors, and transesterification units for biogas and biodiesel (Hashim *et al.*, 2023).
e. Dryers, pelletizers, and blenders for producing consistent feed and fertilizer products (Iskakov and Sugirbay, 2023).

Rather than viewing each technology in isolation, leading studies advocate integrated process networks, where high-value fractions (bioactive peptides, hydroxyapatite, SCP) are prioritized, and residual streams are successively cascaded into energy and soil-health applications (Ashilenje *et al.*, 2025; Boboua *et al.*, 2024). The result is a hierarchy of uses that aligns with circular-economy principles and supports both regulatory compliance and profitability. Nevertheless, the pathway toward full circularity remains fraught with technical, economic, and regulatory challenges. Realizing this vision will require continued collaboration across disciplines, investment in scalable technologies, and the establishment of supportive policy frameworks. Future progress will depend on balancing innovation with practicality—ensuring that the circular transformation of the meat sector is both sustainable and economically attainable. Despite clear promise, several hurdles temper widespread adoption. Economic viability depends on stable markets for hydrolysates, biofuels, and specialty ingredients; process complexity demands skilled operation; and stringent hygiene and regulatory controls must be met at every stage (Bou *et al.*, 2025; Mia, Ahmed and Zzaman, 2025). Consumer perceptions around "recovered" animal ingredients, especially in foods and nutraceuticals, require careful framing grounded in safety, functionality, and sustainability evidence (Boboua *et al.*, 2024; Bou *et al.*, 2025).

Yet, the direction of travel is unmistakable. Waste valorization technologies recast meat plants as biorefineries, where every liter of blood, kilogram of bone, and fraction of fat has a defined technical destiny. As Ashilenje *et al.* (2025) emphasize, this is not merely an environmental obligation but a

development opportunity—particularly for regions seeking local value creation from existing agro-industrial streams. When implemented with rigorous science, robust equipment, and thoughtful policy, valorization closes loops, lifts margins, and anchors the meat industry within a genuinely regenerative food system.

23.8 Conclusion and Future Perspectives

The modernization of the meat industry is fundamentally an engineering endeavor, defined by the convergence of technological advancement and systemic responsibility. Engineering innovations are serving as crucial drivers that simultaneously advance the industry across the three pillars of safety, efficiency, and sustainability.

Engineering drives safety by embedding hygiene and precision directly into manufacturing systems. Hygienic equipment design—using materials like stainless steel alloys and incorporating features like smooth, drainable surfaces—minimizes microbial harborages and reduces water and chemical use during sanitation. Automation and robotics in critical areas like evisceration and carcass handling minimize human-carcass contact, thereby mitigating cross-contamination risk. Furthermore, safety is secured by nonthermal technologies such as HPP and CP, which achieve reliable microbial inactivation and extended shelf life while preserving the fresh-like sensory and nutritional attributes often compromised by traditional heat. Digital systems, including smart sensors, biosensors, and blockchain, reinforce safety by enabling continuous, real-time monitoring of CCPs and providing immutable, verifiable records of welfare, process history, and cold chain integrity from farm to fork.

Efficiency is maximized through automation and digital integration, redefining cutting, processing, and logistics. Robotics and computer vision systems enable high-speed processing lines, allowing identification, grading, and routing decisions to be made "on the fly". Innovations such as smart cutting and portioning systems (e.g., 3D-guided water-jet cutting) optimize yield, standardize pack weights, and relieve workers from physically demanding, repetitive tasks, addressing chronic labor shortages. AI serves as the "cognitive engine", shifting quality management from reactive inspection to predictive prevention by forecasting risks, optimizing complex nonthermal treatments, and enabling predictive maintenance of machinery to reduce costly downtime.

Engineering solutions are crucial for achieving environmental stewardship and resource efficiency. In terms of energy, advanced machinery incorporates heat recovery systems and variable-speed drives, which reduce energy consumption in heating and refrigeration—the most energy-intensive processes in meat plants. For water, multi-barrier systems incorporating advanced filtration and recycling technologies (e.g., membrane bioreactors and reverse osmosis) enable the safe reuse of treated effluent, significantly cutting freshwater intake. Most fundamentally, sustainability is driven by waste valorization technologies. These innovations transform high-volume by-products (blood, fat, bones) from disposal burdens into high-value revenue streams, producing ingredients like protein hydrolysates, bioactive peptides, and bioenergy (biogas/biodiesel), thus embodying the principles of a circular bioeconomy. The trajectory of the meat industry is toward sophisticated, adaptable, and human-centric systems, framed by the principles of Industry 4.0 and the emerging Industry 5.0 paradigm. The future will see processing facilities evolve into fully-fledged cyber-physical systems. Hyper-automation signifies the fusion of robotics, AI, and IoT networks to create self-optimizing "cognitive meat factories". This goes beyond basic mechanization; it involves AI dynamically adjusting processing parameters in real time (e.g., optimizing stunning voltage or nonthermal treatment intensity). Technologies like Digital Twins—virtual replicas of production lines—will allow operators to simulate and optimize complex processes (like cooking, chilling, or slicing) for quality and energy efficiency without interrupting live operations, accelerating innovation and troubleshooting.

Engineering will increasingly support the customization of meat products to meet specific consumer, dietary, and ethical demands. Flexible manufacturing will be enabled by technologies like dimensional reduction, which manipulates meat proteins into nanofibrils for customized textures (e.g., soft foods for clinical nutrition or the elderly). This flexibility is further amplified by 3D printing technologies, which allow for the customization of shapes, fat-to-lean ratios, and flavor profiles in both cultured and

traditional meat products. AI will play a critical role in personalized product design, where models virtually test formulations to meet precise nutritional and sensory targets.

The industry will move decisively toward zero-waste models. This involves maximizing the recovery of every output. Traceability systems anchored by blockchain will follow not just the meat but also the by-product streams (e.g., blood, fat, bone). This data visibility will enable continuous optimization, channeling residuals into high-value markets for nutraceuticals, biomaterials, or bioenergy. The goal is to establish integrated biorefinery abattoirs where sustainability and profitability are structurally linked through closed-loop resource management, energy self-sufficiency, and Zero Liquid Discharge (ZLD) systems.

The sheer complexity of biological materials, coupled with the rapid pace of digital and nonthermal innovation, underscores the continuous need for interdisciplinary research and development (R&D). Modern meat processing is a systemic challenge that cannot be solved by a single discipline. Success depends on the following:

1. *Fusing Biomechanics and Computation:* Integrating food science, microbiology, and physics-based modeling with data analytics, AI, and mechatronics. This collaboration is required to overcome fundamental hurdles, such as adapting robots to biological variability (e.g., non-standard, flexible meat tissue) and validating new technologies like nonthermal processing for regulatory acceptance.
2. *Harmonizing Technology and Governance:* Developing governance frameworks (e.g., regulatory sandboxes) that can safely validate ML-based processes which adjust dynamically, moving beyond traditional validation of fixed parameters.
3. *Cultivating New Expertise:* Addressing skills gaps by training a new generation of professionals who are proficient in data analytics, AI interfaces, and system maintenance alongside traditional food safety skills.

Ultimately, the future of the meat industry will depend on designing intelligent ecosystems where precision engineering, ethical imperatives, and sustainability goals converge. Through collaborative innovation—spanning food science, automation, and data intelligence—the sector can transition from reactive manufacturing to proactive stewardship of resources and trust. Such a transformation ensures that engineering progress remains inseparable from the broader social mission of securing resilient, transparent, and sustainable food systems for generations ahead.

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24

The Technology and Processing of Canned Meat Products

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24.1 Introduction

Meat, being a perishable product, needs to be preserved immediately after slaughter to avoid contamination by microorganisms and spoilage due to the action of their enzymes. To increase the shelf life of meat, preservation methods such as canning, smoking, pickling, and storage in a cold chain are employed. Canning, one of the oldest and most effective methods of preserving meat, involves processing and packing meat in a sealed container. This process is very effective in increasing the shelf life of meat by reducing the chances of meat-borne diseases and oxidative spoilage, thus increasing the nutritional value of meat products (Chellaiah, Shanmugasundaram and Kizhekkedath, 2020). It is worth noting that canning does not require refrigeration.

Canning of meat involves packaging of meat in a container, then placing the container in hot water for 8–10 minutes with the lid for heating it to a temperature to kill the harmful microorganisms and immediately cooling to 38 °C. Vacuum sealing prevents the entry of air or microbes in the jar, thus canned meat products can be stable for months without refrigeration. Canning must be done properly to ensure food safety. Improper canning can lead to serious health concerns, such as foodborne illness and botulism, a potentially harmful condition caused by *Clostridium botulinum*, an anaerobic bacterium (Vellini, 2024). *C. botulinum* grows primarily in low-acid foods such as vegetables, meat, and fish. If canning is done properly, these bacteria can produce neurotoxin that leads to botulism.

Canning mainly depends on the type of food, such as high-acid food (pH below 4.6), which has enough acid to control bacteria. These foods are fruits, pickles, tomatoes, and plums. Low-acid foods contain very little or no acid (pH > 4.6). They include most vegetables, meat, poultry, and seafood (Rajput *et al.*, 2022; Vellini, 2024). Low-acid foods require a pressure canner to reach a higher temperature (116 °C) in order to destroy *C. botulinum* spores. High-acid foods can be processed in a boiling water bath (100 °C). The different food requires a predetermined time–temperature to destroy the microbes and enzymes that cause quality deterioration during storage (Premi and Khan, 2018). Containers such as glass, plastic, and metal cans are generally suitable for canning. The use of high-temperature steam sterilizes the meat by killing all the microorganisms. The vacuum created by cooling the jar seals the jar tightly. Canning meat also helps the economy because it increases shelf life and improves public health by preventing microbial growth. It saves the consumer time (Shaltout, 2024).

24.1.1 Historical Background and Global Relevance

Traditionally, food was preserved using drying, smoking, salting, and fermenting before canning was used. These methods preserve the food by increasing shelf life, but they completely alter the physicochemical and textural properties of food. Hence, the need for better preservation led to the invention of the canning technique for long-term food storage and supply to fulfill the needs of an increased population.

The food preservation by canning was invented during the years of the Napoleonic War in the late eighteenth century in France—when Emperor Napoleon Bonaparte was in search of a cheap and effective

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method of preservation to provide a large amount of safe and varied food to his military forces during the war. Hence, in 1809, French confectioner and brewer Nicolus Appert first discovered the technique of cooking food in a hermetically sealed glass container. His work is based on the principle that food heating in a sealed glass container kills the microorganisms that initiate spoilage (Rajput *et al.,* 2022) until the seal is opened. Due to the fragile nature of glass, in 1810, Scientist Peter Duran took one step further and patented the usage of unbreakable tin cans for canning. These tin cans are more practical and durable than the glass jars for transportation and usage (Sethi *et al.,* 2025). In 1813, Bryan Donkin and John Hall established the first commercial canning factory in London to supply canned meat to the British army and Royal Navy. Modern advancements in canning include the use of pressurized retorts for uniform heat treatment, automated filling and sealing machines, and the use of modern packaging material.

In spite of the old traditional technology of the early nineteenth century, canning technology still plays an important role in the global food system. By combining scientific principles with engineering innovations, processing efficiency has been improved, and safety standards have been improved to provide nutritious, safe, and convenient canned food products to consumers. Even today, this is widely used and is the most popular preservation technique to preserve fruits, vegetables, soups, sauces, meat, and dairy products (Squires, 2025). Canning of meat improves the preservation quality and saves cooking time for consumers.

People are more aware of health and sustainability, which makes it very challenging to provide them with safe, sustainable, and nutritious food. Hence, there is a need for continuous advancement in developing more energy-efficient processing methods, improvement in sensory qualities, retention of nutrients in canned foods, and development of new, biodegradable, and recyclable packaging technologies. Meat canning is an important process in food industry and continuous advancement is needed to fulfill the growing population's needs and demands; therefore, this chapter focuses on raw material selection, additives used during canning, preprocessing of meat, standardization during product development, post-processing operations, quality safety attributes, and innovative and emergent technologies and safety standards in meat canning. The objective of this chapter is to explain the presently followed methods and new developments in meat canning and to highlight the challenges, quality factors, and future opportunities in meat canning.

24.2 Raw Materials and Ingredients

24.2.1 Meat Selection and Quality Parameters

Selection of meat is a critical step in canning. Select only meat that has been properly removed of gristle, bruised portions, and excess fat to ensure better quality (Rashid and Khidhir, 2021). Quality of meat and meat products depends on various parameters such as appearance, texture, juiciness and flavor, proportion of lean meat and fat, low microbial load for sterilization efficiency, overall freshness, desired physiochemical properties, and use of minimal additives and meat extenders for safety and quality of canned meat (ElMasry, Sun and Sun, 2010). Different parameters of meat quality are assessed by different methods, such as organoleptic evaluation for assessment of appearance, flavor, texture, physical taste for tenderness and water-holding capacity, chemical analysis to check composition, and microbial examination to check microbes (FAO, 1990).

The safety, texture, flavor, and overall acceptability of the final product depends on the preslaughter and post-slaughter handling of meat. Poor handling and operational techniques may result in reduced meat quality and lead to spoilage of the meat (Dave and Ghaly, 2011).

Skill and a high level of hygienic practices are required to prevent contamination after slaughtering, during meat cutting, and processing for canning. Safety, quality, consistency, and productivity are necessary factors during meat canning.

24.2.2 Additives, Curing Agents, and Functional Components

Canning meat is a convenient and effective means to preserve the meat product, but at the same time, one needs to ensure proper safety. Sometimes, microorganisms can remain while canning, in such cases, additives are used. The ingredients, such as salt and saturated fat, have been used for many years for

curing and preserving meat. Salt controls the growth of microorganisms by decreasing the water activity of the food (Rahman *et al.*, 2023).

Many other additives are used for longer times, such as sodium benzoate and benzoic acid; calcium, sodium propionate, and propionic acid; calcium, potassium, sodium sorbate, and sorbic acid; and sodium and potassium sulfite, calcium, sodium ascorbate, and ascorbic acid (vitamin C); lecithin; and sodium and potassium sulfite and sulfur dioxide. Benzoic acid, citric acid, propionic acid, sorbic acid, and their salts are effective mold inhibitors. Acetic acid and lactic acid prevent bacterial growth, whereas sorbate and acetate are capable of arresting the growth of yeasts in food (Chellaiah, Shanmugasundaram and Kizhekkedath, 2020). Butylated hydroxyanisole (BHA), butylated hydroxytoluene (BHT), tertiary butylhydroquinone (TBHQ), and propyl gallates (PG) are synthetic phenolic compounds that have long been used to inhibit the oxidation-induced changes in meat, which affect sensory properties (Ciobanu, Flocea and Boișteanu, 2024; Dave and Ghaly, 2011).

The potassium (potassium nitrite—E249—and potassium nitrate—E252) and sodium (sodium nitrite—E250—and sodium nitrate—E251) salts are food additives used in the curing of meat for their antimicrobial properties against *Listeria monocytogenes* and *C. botulinum*, but also to prevent rancidity and enhance the quality parameters such as color and flavor. Nitric oxide is produced from nitrites, and it combines with the iron of myoglobin and metmyoglobin to produce the desired pink color of cured meat. Nitrites also act as an antioxidant as they protect the lipids of meat from oxidation. Sodium ascorbate (E301) is also used for curing as an antioxidant; it helps in faster conversion of nitrite to nitric oxide and also reduction of ferric ion (Fe^{3+}) to ferrous (Fe^{2+}) ion, which improves the attachment of nitric oxide to myoglobin to stabilize the pink color (Molina *et al.,* 2024). Sodium erythorbate and polyphenols are used as other alternatives to sodium ascorbate. But high levels of salts, chemical additives, and nitrites are linked to health concerns such as nitrosamine formation from nitrites, which has a carcinogenic effect. Hence, various strategies are used to overcome the side effects of these chemicals, such as the use of plant-derived or microbial fermentation-derived nitrates and nitrites. Extracts from plant fungi and dairy provide antioxidant and colorant properties to meat, new processing and packaging technologies, and the use of hurdle techniques (Molina *et al.,* 2024). To keep uniform scattering of fat and to prevent loss of water, binder additives, phosphates, thickener, starches, sodium alginate, and carrageenan are used (Selvaraj Arokiyaraj, Dinakarkumar and Shin, 2024).

Nowadays, people are aware of a healthy diet; therefore, they are demanding meat products with a clean label. The use of plant-based extracts from broccoli, celery, spinach, and red beet is used as a natural source of nitrates and nitrites, used to control microbial growth, and as a coloring and flavoring agent. Other sources, such as raspberry, tea polyphenols, grape pomace, and black currant leaf extracts, are also explored as an alternative to nitrite natural sources. Plants rich in bioactive compounds, mainly polyphenols, are used to replace synthetic antioxidants in meat products. These plant-derived antioxidants are in extract or essential oil from fruits, vegetables, and herbs and spices (Ciobanu, Flocea and Boișteanu, 2024). To increase the functional properties and nutritional value, it is necessary to enrich meat with various functional components. Meat is enriched with dietary fiber, for its health benefit as it decreases fat content and improves water and fat retention, for oxidative stability and modified texture in meat products (Abzhanova *et al.*, 2022; Jimenez-Colmenero and Delgado-Pando, 2013). Plant proteins from soybean, sunflower, wheat, cottonseed, oatmeal, and whey protein are used as a fat substitute; they improve the binding of water and fat (Gomez *et al.*, 2020; Uzakov *et al.*, 2021). The phytonutrients (phenolic diterpenes, flavonoids, tannins, and phenolic acids) present in herbs and spices are also used as natural antioxidants in canned meat to prevent lipid deterioration and improve taste (Uzakov *et al.*, 2021).

24.2.3 Storage and Handling of Raw Materials

Proper storage and handling must be followed to prevent microbial contamination, ensure product safety and quality, and extend shelf life. Immediately after slaughter, meat should be chilled at a temperature below 4 °C until it is canned; can it within a few days of slaughter. It is easier to handle the meat when it is cold. If a longer duration is required for canning, one needs to freeze the meat at 18 °C to preserve its freshness and to avoid microbial growth (Rashid and Khidhir, 2021). Thawing must be carried out under controlled refrigeration at 4 °C or below to eliminate all ice crystals to prevent bacterial growth

and loss of functional properties. Hygiene during handling, segregation of raw and processed meat, clean equipment, and proper lot labeling, batch tracking ensure traceability, and use of FIFO (First in first out) system to use material within optimal freshness period further improves consistency and safety (FAO, 1990).

24.3 Preprocessing of Meat

Preprocessing is one of the most important steps in the manufacturing process of canned meat products. It transforms heterogeneous carcass meats into a coherent and reproducible state regarding composition, hygiene, pH, temperature, and particle size, making their functionalities defined. In standardized commercial preprocessing, it involves series of operations such as raw material selection, cutting, trimming and washing, partial thermal treatments like blanching, and application of curing or marination. All these components must be well combined with the subsequent formulation and schedules of retorting to achieve commercial sterility without compromising its quality (Gomez *et al*., 2020).

24.3.1 Cutting, Trimming, and Washing

Cutting and trimming are initial unit operations after carcass breakdown. The objectives are to obtain uniform piece size, eliminate visible defects and maximize lean-to-fat ratio. In the dicing process, control on the number of heads in a package minimizes headspace variation, improves packing efficiency, and ensures uniform heat transfer in the retorting process. All these steps will contribute to a lower risk of cold-spot incidents in canned meat products. On the other hand, excessively fine particles favor fat separation during storage and increase purge, while particles that are excessively large result in a nonuniform heat transfer and variations in texture. Trimming removes visible fat, connective tissue, bruises, lymph nodes, and pieces of bone that may otherwise act as hotspots for rancidity, physical hazards, and off-flavor development. From a microbiological perspective, trimming also reduces surface contamination caused by handling—hide and hair effects during the deboning and killing operations. To remove visible contamination—blood, bone dust, and loose tissues from cut surfaces—washing generally employs potable or chlorinated water sprays. In canned products with relatively mild pre-cooking or in situations where post-cooking contamination must be minimized, good washing improves appearance, while reducing the initial microbial count. However, excessive washing has some negative effects, such as the leaching of soluble proteins, vitamins, and pigments, as well as increased surface moisture to promote microbial growth, if it is not promptly drained and chilled (Gomez *et al*., 2020; Hui, 2012; Yohannes, Agegnehu and Biruk, 2020). Therefore, processors should monitor the exposure time and mechanical action in order to execute the process under a controlled environment.

24.3.2 Blanching, Curing, and Marinating

Blanching as a form of pre-canning treatment for meat parts or meat blends can significantly improve the product's texture and reduce purge during retorting. The primary objective of blanching meat is to inactivate the enzymes present in the meat itself, reduce the amount of bacteria on the surface, remove entrapped air, and increase the firmness of proteins to the right extent. This will make the meat ready for packaging and retorting, resulting in improved texture and lower purge. While most discussions about blanching relate to vegetables, the same concept can be applied to meat as well, as the rapid treatment with heat retards the action of enzymes such as proteases and lipases and prevents the texture of the meat from becoming too soft and the breaking down of lipids (Maurya, Thapa and Diana, 2025).

The curing process remains at the basis of most canned meat products such as luncheon meat, canned ham, or corned beef. The combination of nitrite (either sodium nitrite or nitrate/nitrite) with meat myoglobin forms nitrosylmyoglobin. After heating, this product provides the characteristic stable pink color as well as the characteristic cured flavor. Moreover, it provides antioxidant as well as antimicrobial preservative functions, particularly against *C. botulinum*. The curing brine may contain salts, sugars, phosphates, and, in some cases, ascorbate or erythorbate, which are added to the meat by immersion,

pumping, or tumbling. Modern attempts at "natural" curing methods mean the use of vegetable sources of nitrates such as celery, spinach, radish, beet green juice powder, and bamboo leaf extract, in combination with cultures. Nonetheless, natural methods must meet the same standards of safety and quality (Zhang *et al*., 2023).

Marination is a widely used method in processed and canned meats, for increasing tenderness, juiciness, yield, flavor, and safety. Marination accelerates the proteolytic process in the natural metabolic activity of the muscles post-slaughter by reducing pH, thus encouraging the muscle's enzymatic processes to get triggered during maturation. Conventional formulas for the process use salt and phosphates, though newer combinations of the two may comprise "organic acids, lactates, natural plants, citric, acetic, and tartaric acids, as well as apple cider vinegar, fermented milk, and juices of fruits/vegetables to satisfy the "clean label'' requirement and provide antioxidant/microbial properties. If designed properly, the process can enhance the water-holding quality, improve slicing and binding of pieces of meat, and reduce growth of spoilage and pathogenic bacteria, particularly in canned meats, cold-filled, semi-cooked, and then retort (Ertbjerg *et al*., 1999).

24.3.3 Functional Roles of Pretreatments

The pretreated processes affect four major functional characteristics, which determine the nature of canned meat based on protection from microbes, water-holding capacity, ability to create the emulsion or binding effect, and overall appearance and flavor.

Microbial Safety and Spoilage Control: Before filling and sterilization, the aggregate effects of washing, blanching, and curing are to reduce the initial microbial loads in the product and to create the conditions for it to inhibit the growth of pathogenic and spoilage microorganisms. The blanching process allows the reduction of the amount of surface spores, apart from reducing the enzymatic activity that otherwise accelerates the product spoilage, due to curing using nitrite, which offers additional protection from anaerobic spore formers (Gomez *et al*., 2020).

Water-Holding Capacity and Yield: Adding salt and phosphate promotes increased WHC through the swelling of myofibrils and the solubilization of myofibrillar proteins, subsequently gelling upon heat sterilization. An increased WHC reduces cooking loss, increases slice yield, and improves juiciness, which are important parameters for consumer acceptability. However, excessive application of salt or phosphate poses a series of health and sensory trade-offs (Cornet *et al*., 2021).

Emulsification and Binder Functionality: Well-trimmed and marinated meat will provide solubilized myofibrillar proteins that help in the stabilization of water-in-fat emulsions. However, overdenatured proteins due to excessive branching in preprocessing will reduce emulsification properties, leading to fat separation during the sterilization process. Optimal tumbling along with proper salt uptake will help enhance the protein-binding capacity (Xiong, 2014).

Sensory and Color Development: Nitrite curing preserves the characteristic cured color and flavor, while the marinades meld their flavors and the various acids. These acids could be flat or discordant when cooked, yet in the marinade they remain clear and in balance. Blanching and proper enzymatic processing can reduce unpleasant smells and create a more even final product. These processes are critical to control so as to lock in the desirable flavor after the heavy heat of industrialization (Zhang *et al*., 2023).

24.4 Formulation and Product Development

Canned meat product formulation integrates raw materials, processing parameters and regulatory limits together in a reproducible recipe that meets safety, flavor, and nutritional and economic objectives. Product development embraces the standardization of meat mixtures, selection and utilization of non-meat ingredients, emulsion, and comminution engineering, and the drive toward value-added or specialty formulations. A successful formulation or development process involves a multidisciplinary effort that considers the consumer demands for quality, the shelf life of the product, and the functionality of the formulations with retort and package interactions.

24.4.1 Standardization of Meat Mixtures

Standardization of meat blends and particle sizes signifies adjusting the proportions of lean meat, fat, connective tissue, and added water toward predetermined compositional limits. Manufacturers seek a standard proportion of lean meat to fat and adjust their products with trim, industrial fats, or lean meat. The standardization procedure also includes particle sizes. Grinding coarsely results in a coarser canned product, and a sliceable loaf or smooth emulsion requires a very fine uniform grind. These quality control analyses are conducted using several objective tests for standard product release, including the use of proximate composition, pH, water-holding capacity, emulsion stability, and ease of extraction of myofibrillar proteins (Comer and Dempster, 1981; Cornet *et al*., 2021).

24.4.2 Ingredient Selection for Flavor, Texture, and Color

The main factor contributing to the characteristics of canned meats is the type and quality of meat, including the type of animal, muscle, natural content of intrinsic fat, and pre-rigor meat. Nonetheless, nonmeats have important roles as ingredients. Salt is still a cornerstone of flavor enhancement, protein solubilization, and preservation, yet usage is increasingly aligned with nutritional demands to reduce sodium content. Phosphates are used extensively in canned and cooked meats up to permitted regulatory standards to enhance water-holding capacity, emulsification, and textural stability, yet alternatives such as fibers and vegetable proteins are being researched in the emerging "clean-label" products (Comer and Dempster, 1981; Yum *et al*., 2018).

Color and flavor systems depend on the product style. In uncured canned meats, color stabilization tends to minimize oxidation and pigment denaturation by proper retort control and application of antioxidants such as rosemary extracts and tocopherols, among others. In cured meat canning, nitrite/nitrate systems remain central, though most of the time complemented by ascorbate/erythorbate to accelerate curing reactions and improve color stability. For flavor systems in canned meats, herbs, spices, oleoresins, smoke flavorings, and umami-rich components (yeast extracts and hydrolyzed proteins) are used in developing distinctive flavor profiles and to mask potential warmed-over flavors associated with prolonged ambient storage (Hussain *et al*., 2025; Zhang *et al*., 2023). Texturizers are ingredients used to control firmness, juiciness, and spreadability, which include starches, flours, proteins (soy, whey, pea), and dietary fibers. These texturizers also impact on syneresis, emulsification, water, and fat-binding, and their selection and level must therefore be aligned with thermal load and storage conditions typical of canned foods (Abzhanova *et al*., 2022).

24.4.3 Emulsion and Comminution Processes

Emulsion formation is especially important for canned meat products (luncheon meat, corned beef, and spiced loaves). Emulsions are generally based on a fat-in-water dispersion where the fat particles are suspended in a continuum of water, salt, and solubilized proteins. The process of comminution removes salt-extractable myofibrillar proteins, comprising myosin and actin, and these accumulate at the interface between the fat particles and water, creating a viscoelastic layer, thus stabilizing the fat droplets and forming a gel on heating (Ugalde-Benítez, 2012).

These are known by different names, such as bowl choppers, colloid mills, or high-pressure homogenizers, which create particle size distribution and protein extraction ratio essential for defining texture. Overchopping causes protein denaturation, along with loss of viscosity, while underchopping causes coarse texture, along with unstable emulsion. Therefore, temperature becomes a crucial parameter, where meat batters are kept at lower temperatures by adding ice or cold water to avoid protein denatured prematurely. Adding fat subsequent to protein solubilization, proper binder addition, along with gradual addition of spices, helps to create a more stable emulsion, along with preserving volatile components. Viscosity, or stability tests, including centrifugation, or cook-out tests, are carried out for analyzing its ability to withstand sterilization processing. While undergoing heat sterilizing, solubilized myofibrillar proteins create a gel with three-dimensional network structure that entraps water, along with fat. Strength of this protein-based gel network changes with variations in ionic

strength, pH, protein concentrations, along with heat, where consideration of every parameter becomes essential to avoid gaping or hardening of gels (Mandigo and Sullivan, 2014; Santhi, Kalaikannan and Sureshkumar, 2017).

24.4.4 Value-Added and Specialty Formulations

Presently, there has been a trend in developing packaged meat products for the value-added segments such as low-fat, low-sodium, high-fiber, "natural or clean label", functional, and convenience-type products. Technological approaches to reformulation involve the partial substitution of animal fat by structured vegetable oils, double emulsion systems (water in oil in water), and the addition of fibers or plant proteins to ensure juiciness and texture, while enhancing nutritional characteristics. Researchers in meat processing institutions have established the possibility of developing low-fat, high-fiber-type emulsion meat products with preferred sensory characteristics and enhanced cooking yield properties by means of edible fat replacers and fibers, which could easily be applied to canned products (Ayuso, García-Pérez and Nieto, 2025).

Phosphate-free or phosphate-reduced canned meats are another specialty category driven by health concerns and consumer perceptions. Protein-based ingredients—pea, soy, whey, egg, blood plasma, potato proteins, and process aids such as ultrasound and high-pressure tumbling—can partially or fully replace phosphates while maintaining water-holding, emulsion stability, and texture, although formulations often require careful optimization to avoid defects such as syneresis or increased purge (Glorieux *et al.,* 2017).

Cleaning label trends are also favorable toward natural marinating ingredients and plant extracts as sources of antioxidants and antimicrobials. Research studies have been conducted on natural marinating ingredients, highlighting that ingredients derived from fruit and vegetable juices, wine beverages, beer drinks, and fermented dairy products can enhance shelf life and exhibit limitations in lipid and protein oxidation when marination conditions are properly controlled and combined with heat-processing techniques (Latoch, Czarniecka-Skubina and Moczkowska-Wyrwisz, 2023).

Finally, functional canned meats enriched with bioactive components such as omega-3 fatty acids, plant sterols, peptides, and antioxidants, which are targeted for specific groups like the elderly, athletes, or children, are emerging, although their development is made more difficult because stability during retorting and long-term storage has to be assured (Rodrigues *et al*., 2023). A growing body of work underlines how nutritional reformulation should be balanced with sensory acceptability and safety, and that successful specialty canned meats demand an integrated approach to preprocessing, formulation, and thermal process design.

24.5 Filling and Packaging Systems

For canned meat products to achieve commercial sterility, preserving sensory and nutritional quality and providing convenience, effective filling, and sturdy packaging are essential. In contemporary plants, approved retort schedules and HACCP plans are closely linked with container selection, filling accuracy, headspace control, vacuum generation, and package integrity testing (Jimenez *et al*., 2024; Khodaei *et al*., 2023).

24.5.1 Types of Containers and Packaging Formats

Because of their mechanical robustness, superior gas and light barrier, and suitability for high-temperature retorting, conventional rigid metal cans continue to be the most popular format for shelf-stable meat products (Table 24.1). The most common materials are aluminum alloys and electrolytic tinplate (tin-coated low-carbon steel), both of which can tolerate retort temperatures of 115–130 °C with little distortion when seam design and internal coatings are suitable. While aluminum cans offer weight reduction and high recyclability but require careful control of inside lacquers to minimize metal–product interactions,

TABLE 24.1

Common Container and Packaging Formats for Canned and Retorted Meat Products

Container/Format	Typical Materials and Structure	Key Advantages	Limitations/Considerations
Three-piece or two-piece cans	Electrolytic tinplate or aluminum with internal lacquer and double seams	• Excellent mechanical strength • Very low O_2 and H_2O vapor transmission • Well-established seam integrity standards • High recycling rates for steel and aluminum	• Higher material mass • Seam and enamel integrity must be closely controlled • Risk of corrosion with aggressive formulations
Retort pouches	PET/Al foil/nylon/PP (or high-barrier Al-free laminates)	• Rapid heat penetration and reduced F_0 for equivalent lethality • Lower weight and storage volume • Good printability	• More sensitive to handling and flex cracking • Recycling of multilayers is challenging • Seal quality is critical
Semi-rigid trays	CPET or PP trays with multilayer lidding films	• Suitable for sliced meats and ready meals • Good consumer convenience and presentation • Compatible with MAP or vacuum	• Higher risk of seal defects and delamination • Often shorter ambient shelf life • Higher packaging volume per unit product
Vacuum/MAP thermoformed packs for processed meats	Multilayer co-extruded films (e.g., PA/PE, PA/EVOH/PE)	• Enable vacuum or MAP for chilled distribution • Good optical properties • Tight fit around product	• Typically for refrigerated rather than fully canned products • Gas composition must be optimized to avoid discoloration and spoilage

tinplate offers inherent stiffness, magnetic recoverability, and comparatively low cost (Deshwal and Panjagari, 2020). For ready-to-eat meat curries, pâtés, and portion-controlled meals, retortable pouches and semirigid trays have become increasingly popular. Retort pouches are usually made of three to four layers of laminate (such as PET, aluminum foil, nylon, or cast polypropylene) that combine sealability, high oxygen and moisture barriers, and heat resistance. It was found that their compactness allows for quicker heat transfer and quicker process times compared to ordinary cans, contributing to the preservation of the sensory qualities of meat dishes such as black clam curry and rogan josh over an ambient storage trial for 12 months. For in-can cooking and retorting of sliced meats or prepared meals, semirigid CPET or polypropylene trays with high-barrier lidding films are often utilized, frequently aiming for chilled distribution or a shorter ambient shelf life (Deshwal and Panjagari, 2020; Li *et al.*, 2022).

Flexible material advancements include bio-based polyesters that largely replace PET and nylon in retort structures, as well as aluminum-free high-barrier laminates based on orientated polyamide and EVOH to enable transparent pouches. Due to their vulnerability to flex cracking and delamination during retort and distribution, these formats for processed meats allow portion control and convenience but necessitate more complex seal design and integrity testing (Deshwal and Panjagari, 2020).

24.5.2 Filling Operations and Headspace Management

Declared net weight, heat transfer dynamics, and safety margins in retorting are all determined by accurate filling. While overfilling can result in seam distortion, high internal pressure, and inadequate vacuum after cooling, underfilling increases headspace, which can impede heating due to decreased convective mixing. Controlling the distribution of piece sizes and the quantity of pieces in each container is crucial for particle canned meats (such as corned beef and luncheon meat) in order to reduce voids and create consistent cold-spot placements (Adepoju *et al.*, 2017; Jimenez *et al.*, 2024; Mugale *et al.*, 2018).

Oxygen availability, internal pressure profile, and the capacity to create a sufficient vacuum during cooling are all impacted by headspace volume and composition. Particularly in high-fat formulas and enamel-sensitive cans, too much residual air encourages oxidative rancidity, color fading, and corrosion. However, extremely low headspace might lead to false seams, hinder venting, and raise the possibility of product extrusion during retorting. In order to standardize headspace and eliminate trapped air, modern filling systems combine volumetric or mass-flow fillers with in-line checkweighers, deaeration procedures (such as preheating or steam injection), and vacuum closure or steam-flow closing (Cichello, 2015; Deshwal and Panjagari, 2020; Jimenez *et al.*, 2024).

In packaged foods that have undergone light processing and pasteurization, the functional role of headspace oxygen has been reexamined. Oxygen diffusion from headspace into high-moisture matrices is mostly limited to the surface layers, according to modeling studies, and thus is not a dependable barrier against anaerobic spore formers in low-acid systems. Therefore, rather than using residual oxygen as a safety barrier, low-acid canned meats still rely on verified heating methods and hermetic closing (Muñoz *et al.*, 2017).

24.5.3 Vacuum Sealing and Modified Atmosphere Packaging (MAP)

The main sources of vacuum for shelf-stable canned meats are steam condensation during post-retort cooling and air exhaustion prior to seaming (by hot filling or mechanical vacuum closure). Target vacua are usually between 30 kPa and 50 kPa below atmospheric pressure, which is adequate to prevent oxygen from entering during storage and to give stacking strength. High residual oxygen from inadequate exhausting speeds up lipid oxidation and can raise internal pressure variations with temperature, damaging lacquers, and seams. On the other hand, when purge is released from emulsified materials during heating, overexhausting can cause lids to bend or provide low fill weights (Cichello, 2015; Jimenez *et al.*, 2024).

For cold meat products, such as prepared and sliced meats that may subsequently be retorted in flexible or semirigid containers, vacuum and MAP technologies are significantly more commonly used. Vacuum packaging can encourage the growth of lactic acid bacteria and change surface color to deeper deoxymyoglobin hues, although it significantly inhibits aerobic deterioration and oxidation, according to numerous studies. By suppressing Gram-negative spoiling microorganisms, modified atmospheres that combine CO_2 and N_2 (e.g., 20–40% CO_2 with balance N_2) prolong refrigerated shelf life, often at the cost of somewhat lower tenderness scores as compared to vacuum. For 10–12 days at 0–4 °C, MAP regimes with 20–40% CO_2 have produced satisfactory sensory quality and microbiological stability for lamb and chicken meat (Hur *et al.*, 2013; Nauman *et al.*, 2022; Tahseen and Gurunathan, 2024; Ząbek *et al.*, 2021).

When it comes to retorted meats, MAP is important for semi-preserved items (such moderate heat treatments) and pre-retort staging, which involves sterilizing vacuum-sealed or gas-flushed pouches. In these situations, residual gas composition influences package expansion during cooling and come-up; nitrogen-rich environments reduce oxidative changes but must be weighed against the requirement to prevent excessive internal pressure that could jeopardize seals. In order to further reduce residual oxygen and maintain color and flavor over extended storage, emerging solutions incorporate active oxygen scavengers into laminates or lids (Cichello, 2015; Li *et al.*, 2022; McMillin, 2025).

24.5.4 Packaging Integrity and Functional Performance

Because post-process leakage can reintroduce spores into an otherwise commercially sterile product, package integrity is essential to the safety of low-acid canned meats. Leakage and "container swell" spoiling are known to be caused by defects in double seams, microcracks at the side-seam–double-seam junction, corrosion pinholes, and inadequate or contaminated heat seals in pouches and trays. Dimensional measurements (cover hook, body hook, overlap, tightness) are combined with destructive disassembly and visual microscopic analysis in classical seam examination; composite seam scores are correlated with the likelihood of leakage under distribution loads (Davidson and Pflug, 1981).

Integrity evaluation for flexible and semirigid containers includes resistance to delamination under retort and storage conditions, bond consistency across numerous laminate layers, and seal strength. Due to its 100% in-line or at-line inspection capabilities and quantitative sensitivity in the low-micron range,

deterministic, nondestructive leak-detection technologies like vacuum decay and gas-tracer procedures are currently preferred by industry and regulatory guidelines over traditional dye immersion tests. These techniques are becoming more and more integrated as crucial control points in HACCP plans for retorted foods as they have been verified for both rigid cans and intricate laminates (Khodaei *et al.*, 2023).

Packaging is expected to provide more functional performance than just hermeticity, such as mechanical resistance to denting and buckling, compatibility with retort conditions (steam, water spray, and overpressure), resistance to product–package interactions (e.g., migration of metals, monomers, or additives), and occasionally active or intelligent functions. The potential of intelligent indicators (such as time–temperature indicators, freshness sensors, and RFID-enabled traceability) and active packaging (such as antimicrobial or antioxidant releasers) to extend shelf life, decrease food waste, and report temperature abuse for meat products has been highlighted in recent systematic reviews. Integration of such systems for canned meats must take into account potential interactions with cured meat compositions, regulatory limits on active chemicals, and retort survivability of indicator chemistries (Dhillon *et al.*, 2025; McMillin, 2025; Muñoz *et al.*, 2017).

24.6 Thermal Sterilization and Retort Processing

The biggest obstacle to ensuring commercial sterility and a long ambient shelf life for low-acid canned meats is still thermal sterilization. Process design strikes a compromise between energy and sustainability concerns, texture, flavor, and nutrient retention, and microbiological safety, particularly inactivation of *C. botulinum* spores (Soni *et al.*, 2022).

24.6.1 Principles of Thermal Sterilization

Thermal sterilization of low-acid canned goods is conceptualized as a probability-based lethality process; rather than achieving complete sterility, the goal is to reduce the population of target spores to an acceptable probability of survival (e.g., 10^{-12} per container). Proteolytic *C. botulinum* spores have traditionally been employed as the standard; in conventional test media, they show D-values (duration at a given temperature necessary for 1-log reduction) of approximately 0.2–0.3 minute at 121.1 °C, with *z*-values (temperature increase required for a tenfold change in D) of roughly 10 °C. Therefore, designing a "botulinum cook" usually entails delivering the equivalent of 12 decimal reductions (12D) at 121.1 °C, which, depending on formulation and risk tolerance, is commonly calculated as $F_0 >> 3$–6 minutes for many canned meat products (Soni *et al.*, 2022).

In order to deal with spoilage thermophiles (such as *Geobacillus stearothermophilus*), process variability, and worst-case cold patches, canned meat sterilization procedures often surpass these minimum lethality limits. Studies in canned tuna, meat paste, and mixed dishes show that higher F_0 at lower temperatures (longer time) favors furan accumulation compared with higher-temperature, shorter-time regimes at equivalent F_0. However, overprocessing increases nutrient degradation, textural softening, and the formation of process contaminants like furans. In order to achieve safety goals with the least amount of overprocessing, recent research has focused on optimizing time–temperature profiles and implementing alternate heating technologies (Ahn *et al.*, 2024; Pflug, 1987; Soni *et al.*, 2020; Tsao *et al.*, 2022; Zhang *et al.*, 2016).

24.6.2 Time–temperature Relationships and F_0 Value

The *F*-value, which is defined as the comparable duration at a reference temperature (often 121.1 °C for low-acid meals) required to achieve the same lethality against a particular organism, assuming a certain z-value, summarizes the time–temperature history experienced by the cold spot in a container. Instantaneous lethality contributions are integrated throughout the process for varied temperature profiles typical of retorts; F_0 thus captures the combined effects of come-up, holding, and come-down phases. When F_0 is not indicated, industry and regulatory guidelines frequently assume $z = 10$ °C above 100 °C (Adepoju *et al.*, 2017; Jimenez *et al.*, 2024; Soni *et al.*, 2022).

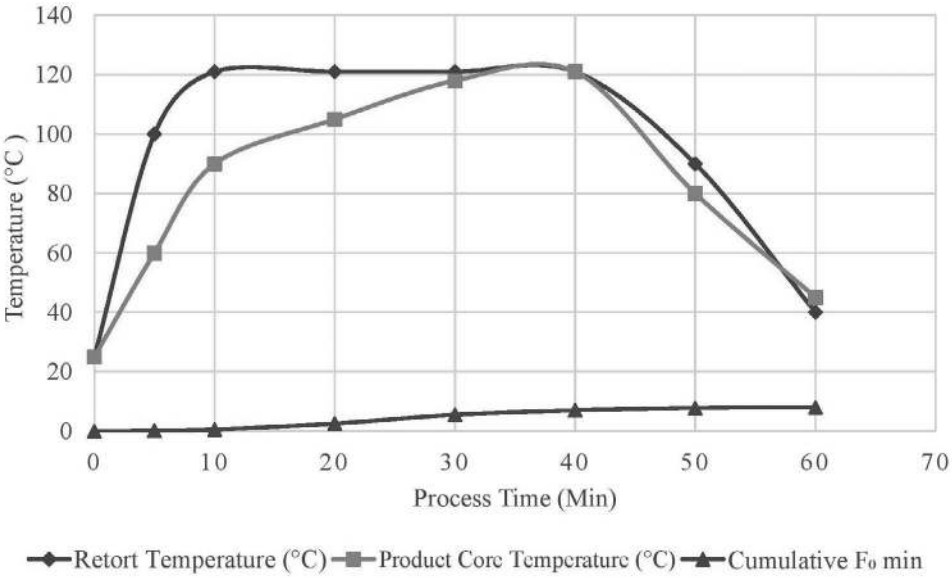

FIGURE 24.1 Typical time–temperature and lethality (F_0) profile for retort processing of canned meat.

The effects of container shape, product rheology, headspace, filling technique, and agitation on F_0 and cook value (C_{100}, a measure of nutrient loss) are demonstrated by experimental heat-penetration experiments in canned and retorted products. For instance, steam-air retorts produced faster come-up times and higher heating rates than water-immersion systems in fish and meat meals processed in retort pouches, which led to shorter process durations overall and lower cook values at equivalent F_0. Similar to this, modeling of $F_0 = 4$ processes at 115–125 °C for meat pastes and oily mackerel showed that higher temperatures with shorter periods can satisfy safety regulations while limiting furan formation and maintaining sensory quality (Adepoju *et al.*, 2017; Mugale *et al.*, 2018; Tsao *et al.*, 2022).

For low-acid canned meat, a typical retort cycle looks like Figure 24.1: (i) come-up phase, where the retort temperature rises from ambient to 121.1 °C while the product core temperature lags behind; (ii) holding phase, where the product and retort both approach quasi-steady temperatures; and (iii) cooling phase, where the product temperature drops but still contributes to lethality. Plots of product temperature versus time and cumulative F_0 versus time demonstrate that, particularly in conduction-heated products, a significant amount of total lethality may build during early cooling, highlighting the necessity of including cooling in process calculations and validation (Adepoju *et al.*, 2017; Etzel *et al.*, 2015).

Trade-offs between F_0 and product quality are frequently measured in process design. Processors are encouraged to operate near the lower bound that is compatible with their risk assessments and distribution chains because studies on retorted meat dishes and surimi products show that increasing F_0 beyond about 6–8 minutes at 121.1 °C yields diminishing safety gains but significant additional losses of thiamine, color, and texture. Modern software enables dynamic process time adjustment to account for load change and initial product temperature variances, as well as real-time F_0 tracking (Ahn *et al.*, 2024; Jimenez *et al.*, 2024; Xue *et al.*, 2023).

24.6.3 Retort Types and Operating Modes

Batch and continuous designs, each having static or agitated operating modes, can be used to broadly classify modern retort systems. Because they provide great versatility across container types (cans, pouches, trays, jars) and recipes, batch retorts (horizontal or vertical) are still widely used in the preparation of canned meat. In order to safeguard flexible packages, they can function with saturated steam, water spray, water immersion, or steam–air mixes, frequently under overpressure. For liquid or semiliquid

goods, agitation methods, including end-over-end rotation or horizontal reciprocation (like the SHAKA process), greatly improve convective heat transmission, cutting process times by 30–50% when compared to static retorts and enhancing product quality (Jimenez *et al.*, 2024).

For very high-throughput applications, continuous retorts—mainly hydrostatic and rotary systems—are utilized. Continuous rotary retorts provide both axial and rotary agitation by moving cans in a helical pattern through a pressurized shell while rotating them on their axes. These devices can process thousands of containers per hour with precisely regulated lethality. Tall water columns at the inlet and outlet of hydrostatic retorts allow containers to enter and exit continuously while maintaining process pressure. Products pass through successive heating and cooling legs under nearly constant conditions, resulting in high energy efficiency and minimal pressure shocks on containers. Adoption is limited to very high-volume, reasonably standardized items due to their high capital cost.

Plant scale, container-type, and product rheology all influence the choice of operating mode. In steam or water spray batch retorts, where conduction predominates and cycle periods are rather long, emulsified canned meats in rigid cans are frequently processed. Particulate meals in pouches or trays, as well as meat-in-sauce or gravy, benefit from agitation or rotational systems that promote convective heating and more even temperature distributions, which lessen overcooking at the outer layers. For flexible containers, overpressure retorts (water spray or water immersion with compressed air) are required to counteract internal vapor pressure to avoid panel distortion or seal rupture (Adepoju *et al.*, 2017; Jimenez *et al.*, 2024; Mugale *et al.*, 2018).

24.6.4 Heat Penetration Studies and Process Validation

The foundation for developing secure and cost-effective thermal methods for canned meats is heat-penetration testing. In order to compute F_0, heating (f_h) and cooling (f_c) rate indices and lag factors, representative containers are instrumented with thermocouples at anticipated cold spots, processed at suggested retort settings, and product and retort temperature histories are recorded. The cold spot in conduction-heated cans is often close to the geometric center; in convection-heated liquids, it may be offset, necessitating empirical identification (Adepoju *et al.*, 2017; Etzel *et al.*, 2015; Jimenez *et al.*, 2024; Mugale *et al.*, 2018).

Research on canned fish, meat stews, and traditional meat dishes processed in cans and pouches demonstrates how filling procedures (headspace, orientation), pretreatments (precooking, blanching), and product composition (viscosity, fat content, particles) affect f_h, F_0, and cook value. For example, when the optimization of the time required for processing was attained based on specific details regarding the curve for the heat penetration, the mini chevon, which was packaged in retort pouches, needed an optimization that results in an F_0 value around 6 minutes, while excessive exposure to processing, beyond this mark, is a waste, especially where textural hardness is a concern. In a similar fashion, various trials that evaluate steam–air retorts, water immersion, for fish in an oily mixture compared to dry pack retorts, have shown less time is required for the products, thereby enhancing its usage on products that are susceptible to quality changes, e.g., steam–air retorts (Adepoju *et al.*, 2017; Mugale *et al.*, 2018; Shah *et al.*, 2017).

Integration of these data with microbiological challenge investigations and, increasingly, quantitative microbial risk assessment through process validation shows that conservative heat resistance parameters are required and safety margins must be incorporated into process design. The need to employ conservative heat resistance parameters and incorporate safety margins in process design is highlighted by recent work that has shown significant heterogeneity in reported D- and z-values for important spore formers across strains, matrices, and experimental procedures. Scheduled processes must be created by certified process authorities, recorded, and routinely revalidated in accordance with regulatory requirements for low-acid canned foods. This is especially important when formulation, container, filling weight, or retort equipment changes (Soni *et al.*, 2022).

24.6.5 Advances in Thermal and Retort Technologies

Alternative and hybrid sterilization technologies have developed quickly during the past ten years with the goal of lowering energy usage and quality losses while preserving or improving safety. Systems for

pure microwave in-container sterilization and microwave-assisted thermal sterilization (MATS) provide volumetric heating that can significantly reduce setup and holding periods. Research on fake crab meat, fish, and poultry products has revealed 48–72% shorter processing times when compared to traditional retorts at equivalent F_0, along with better water-holding capacity, texture, color, and retention of unsaturated fatty acids. Ensuring consistent energy distribution and creating package materials and geometries that are compatible with microwave penetration and retort overpressure continue to be major issues (Bhunia *et al.*, 2024; Guo *et al.*, 2017; Xue *et al.*, 2023; Zhang *et al.*, 2016).

In order to inactivate vegetative cells and, at higher pressures and temperatures, spores, high-pressure processing (HPP) and pressure-assisted thermal processing (PATP) combine high hydrostatic pressure (100–600 MPa) with moderate temperatures (30–90 °C). Although pressure levels must be carefully adjusted to prevent textural problems, pressure-assisted heating at 300–400 MPa and 65 °C increased water-holding capacity and microstructure in meat batters while achieving significant microbial inactivation. From a canning standpoint, PATP offers the possibility of decreased heat load at a given lethality, but it necessitates specialized vessel technology and pressure-resistant containers; its practical application to fully shelf-stable canned meats is still in its early stages (Akhtar and Abrha, 2022; Silva Paz *et al.*, 2025; Zheng *et al.*, 2018).

Ohmic heating, radiofrequency heating, and superheated steam (SHS) are being investigated as substitutes or supplements to traditional retorts. Because quick surface heating combined with controlled inside heating minimizes overcooking and mass transfer losses, SHS systems have been shown to preserve superior sensory qualities in shelf-stable ready-to-eat meat dishes at similar microbiological safety. For electrically conductive meals, ohmic and radiofrequency heating offer quick, volumetric heating that may shorten processing times and prevent fouling in thick meat sauces. In order to balance nutritional quality, safety, and energy efficiency in the production of canned meat, hybrid systems that incorporate agitation, sophisticated heat exchangers, and optimized F_0 objectives are being employed (Ahn *et al.*, 2024; Bhunia *et al.*, 2024; Guo *et al.*, 2017; Jimenez *et al.*, 2024; Zhang *et al.*, 2016).

24.7 Post-Processing Operations

The post-processing step in the manufacture of canned meat plays a crucial role in the retention of safety, quality, and integrity of the final product even after the thermal sterilization step. Post-processing involves controlled cooling processes, effective prevention of contamination, as well as proper packaging and storage methods.

24.7.1 Cooling Protocols

Cooling is the immediately succeeding and most fundamental processing step after heat sterilization (retorting) in the technology of canned meat products. The foremost purposes of cooling are to instantly stop further cooking, to suppress excessive denaturation of proteins, to establish the desired product texture, and to maintain packaging integrity. Cooling is also helpful in creating a vacuum inside the container, which is essential for its strength and shelf life.

In general, industrial cooling is a two-step process. First, there is a rapid drop in can surface temperature through immersion systems or sprays of chilled potable water. Next comes a controlled equilibration where the product's internal temperature is gradually reduced toward ambient conditions. The aim is to bring down the temperature of cans below approximately 40 °C without causing thermal shock, which might distort seams or lead to container failure (FAO and Codex, 2025; Agriculture Institute, 2025). Because pressure differentials during cooling may draw external liquids into micro-leaks, only potable water should be used, and any recirculated water must be disinfected to maintain at least 2 ppm free chlorine after adequate contact time (FAO and Codex, 2025).

Cooling is directly related to product quality. Insufficient cooling causes overprocessing, which promotes rapid decay of the meat's structure, including its nutritional content, while too rapid cooling to suboptimal temperatures may contribute to the occurrence of condensation in the seams, causing rust. Rapid cooling of the sterilized meat in the can is required to quickly bring the core temperature

below 40 °C, thus curing the risk of bacterial growth. The storage conditions for canned meat include temperatures between 1 °C and 5 °C with relative humidity below 75%. These storage conditions are linked to the preservation of meat quality.

In canned meat processing, the post-retort cooling process is most preferably done with cold water sprays or immersion cooling. This will help in reducing the internal pressure of the can, prevent its deformation, and make the process of handling the cans safe. Ineffective cooling of the products may result in the growth of heat-loving microbes, hence the optimal temperature in the cooling process should be about 35 °C (Toldrá, 2023). The cooling velocity needs adjustment based upon the pack and corresponding F_0 values because it could lead to overcooked and oxidative spoilage (Kusumaningrum *et al*., 2022; Taze *et al*., 2019; Vasilev, Klun and Uzelac, 2025). The sterilization cycle comprising CUT (come-up time), Pt (holding time), and CDT (come-down time) relies heavily on well-designed cooling protocols to maintain package integrity and product quality (Mosna and Vignali, 2015). Continuous checking of the quality of the cooling water is, therefore, very imperative in removing the risk of post-process contamination (Abinotami Williams, Puanoni and Ebuete, 2023).

The accelerated aging studies only confirm that temperature control after canning is important. Storage simulation at +37 °C strongly enhances oxidative and hydrolytic reactions, leading to a fast deterioration of the quality, thereby demonstrating the dependence of shelf life and quality retention of canned meat products on the efficiency of post-process cooling and subsequent storage temperature (Soldatova and Korzunov, 2022).

24.7.2 Prevention of Post-Process Contaminations

Post-process contamination renders ineffective the sterilizing functionality of a retort process and thus constitutes one of the most dangerous sources in canned meat processing. Methods used in controlling this risk relate to sanitary design, sanitation practices, and zoning in processing areas.

A fundamental control measure is the use of sanitized cooling water. Only potable and disinfected water should be applied during cooling, in view of the fact that microscopic seam imperfections may allow for water ingress during pressure equilibration (FAO and Codex, 2025). Hygienic handling procedures are also of importance; cans should not be handled by hand while still hot or wet, considering the risk of microbial transfer. Conveyors, transfer belts, and contact surfaces should be kept clean and in good condition to avoid contamination (Arokiyaraj, Dinakarkumar and Shin, 2024; FAO, 2025). Environmental hygiene further depends on strict facility sanitation schedules, personal hygiene requirements, and physical separation between raw material areas and post-sterilization zones (Inbaraj, Lai and Chen, 2025). Ecological quality systems also incorporate regular environmental monitoring and random incubation of sample batches as a means of detecting latent spoilage before product release (FAO and Codex, 2025).

Factors that could cause post-processing contamination include faulty seam seals, cooling water contamination, leakage of cooling gases, or unsound practices of sanitation. When there is low water activity and low levels of available oxygen, microorganisms that cause contamination like *L. monocytogenes*, *Enterococcus faecium*, and spores of *Bacillus* species have an elevated capacity to proliferate and result in increased levels of spoilage and safety failure (Gómez *et al*., 2020). Chilling rooms and equipment have to run to validated levels of HACCP and GMP programs.

Personnel hygiene is a significant factor. Controlled staff movement, training, and maintenance of cutting and packaging rooms at a temperature near 10 °C are all critical in minimizing the risk of contamination. Food contaminants have remained a major public health concern globally. *Escherichia coli*, *Salmonella*, *Listeria*, and *Staphylococcus aureus* have often been implicated as a cause of foodborne diseases. In the case of low-acid canned meats, the spores of the thermally resistant bacterium *C. botulinum* are a particular concern as a contaminant after sterilization. It signifies the need for strict personal hygiene measures after sterilization with the aid of sanitized tools and clothing (Kusumaningrum *et al*., 2022; Taze *et al*., 2019).

Lastly, appropriate vacuuming and air exclusion will prevent the growth of microorganisms, although defects in the sealing process or pinholes will allow water and/or microorganisms to enter and cause spoilage and/or “can blowing”. Clean and sanitary cooling water is needed throughout (Toldrá, 2023).

Accelerated aging tests proceed on the presumption of perfect post-processing cleanliness, emphasizing the crucial importance of contamination control in being able to ascribe changes in storage due to nothing but natural aging and not to contamination from external sources (Ebuete, Puanoni and Ebuete, 2023; Soldatova and Korzunov, 2022).

24.7.3 Labeling, Coding, and Storage Requirements

Labeling and coding are integral components of canned meat technology, serving regulatory, informational, and traceability functions throughout the supply chain. Product labels must clearly indicate the product identity (type of meat), net weight and ingredient list, batch or lot number, production and expiry dates, storage instructions, and allergen declarations. Labeling plays an important role in the traceability of the product, which is critical as a way to quickly identify the origins of a product as well as to easily manage product recalls or quality failures (Agriculture Institute, 2023). Batch codes, date markings, as well as digital traceability technologies, such as barcodes and QR codes, are becoming increasingly important as part of ERP system integration in the management of inventory and quality.

After labeling, meat products are packed into cool, dry, and well-ventilated storage spaces, typically kept below 30 °C with controlled relative humidity to limit corrosion, ensure the integrity of the containers, and prolong the shelf life of the product. High temperatures and condensation accelerate the oxidation of lipids, thus inducing modification in the composition and enhancing the physical properties of meat, leading to reduced product quality (Aldeewan, 2023; Agriculture Institute, 2023). Further, proper storage is also carried out following the first-in, first-out (FIFO) rotation.

The batch coding systems in the production date, sterilization batch number, and period for expiry will ensure full traceability. Canned meats are best stored in a cool, dark, and dry environment to avoid corrosion, oxidation, and loss of sensory attributes. Consume within one year for the best quality (Rahman *et al.*, 2023). Package materials should be impermeable to oxygen and resistant to mechanical damage to prevent microbial entry and quality deterioration.

Storage arrangement also plays a significant role in product shelf life. Cans should be packed in small blocks in well-ventilated areas in order to easily achieve temperature equalization to room temperature conditions as soon as possible, considering that storage conditions strongly influence storage shelf life and safety (Toldrá, 2023). For canned quail meat, the recommended storage temperature was determined to be 2–4 °C, though storage at 18–20 °C does not result in significant quality loss either (Macari, Rotaru and Alexandruc, 2022). The general storage product shelf life is determined by the effect of various internal and external storage conditions, especially temperature and humidity, and thus requires continuous monitoring (Riabovol and Bal-Prylypko, 2021; Umaraw *et al.*, 2020).

As a consequence, labeling must include the expiry date, batch number, nutritional information, and storage conditions for traceability and consumer safety reasons (Rašeta *et al.*, 2018). Shelf life depends on legislation, specifically (TR CU 021/2011), regulations, and validation, whereby accelerated aging techniques can provide seven to eight years of the expiry dating of the products (Kusumaningrum *et al.*, 2022; Soldatova and Korzunov, 2022). Therefore, precise labeling together with storage conditions is the key for the long-term quality, safety, and marketability of canned meat products.

24.8 Quality and Safety Attributes

The achievement of quality and safety in canned meat is considered very important for the acceptance of the product and for meeting the requirements of the relevant legislation and the demands for public health. Attributes regarding quality and safety include physical and chemical properties (e.g., texture- and nutrient-level preservation), sensory qualities, and the screening and management of potential risks.

24.8.1 Texture, Flavor, and Nutrient Retention

Texture and flavor are the major sensory factors determining consumer acceptability of meat products packed in cans. Thermal sterilization causes changes in muscle proteins, mainly myofibrillar proteins

and tissue proteins that either improve texture or result in oversoaking and dehydration of meat proteins. High temperatures promote denaturation of proteins and solubilization of collagen; on the other hand, lipid oxidation due to high temperatures causes the formation of aldehydes and ketonic compounds contributing to off-flavors and lowered sensory properties of meat products. Current research work on modified meat products with low nitrite concentrations using lactic acid bacteria supernatants indicates that processing factors play critical roles in determining color stability, texture properties, and developments of product palatability and shelf stability (Kęska *et al.*, 2025).

Nutrient retention will also be closely linked with the severity of the thermal processing. In general, proteins and minerals are stable, but heat-labile vitamins, specifically thiamine (vitamin B_1) and other B-complex vitamins, progressively degrade during long heat treatments at high temperatures, reducing nutritional value (Beriain *et al.*, 2018; Gómez *et al.*, 2020).

Generally, the quality of canned meat products can be defined in terms of texture, taste, moisture content, fat retention, water-holding capacity, nutrient retention, or a combination of the aforementioned factors. For canned meat products such as paté, an ideal emulsion in the product helps in the development of ideal gels to facilitate better "spreadability", along with the stabilizing effects on the systems comprising fat and water in the product, thus promoting better "organoleptic" quality in the product in the end (Ebuete, Puanoni and Ebuete, 2023; Toldrá, 2023). Thermal processing at temperatures of at least 70 °C, but preferably at temperatures close to 80 °C, helps in the destruction of microorganisms and conserves quality. It is prudent to rapidly cool the product to avoid condensation effects that would reduce shelf life.

The packing environment further enhances the stability of the meat's flavors as well as texture. Vacuum and modified atmosphere packaging with CO_2 levels of 20–30% and N_2 at 70–80% promote the growth of lactic acid bacteria that cause slower oxidation and produce less offensive odor rather than those caused by putrefactive flora. Also, inadequate cooling results in moisture accumulation on the meat's surfaces.

Methods of formulation, including the incorporation of dietary fibers, can greatly affect the level of color and texture, and modifying the color values L^*, a^*, b^*, C^*, and h^* due to added barley, wheat, and oat fibers with the values of 3–6%. Barley fiber BG 300 causes darkening and yellowing, whereas wheat and oat fibers cause lightening of the samples (Słowiński *et al.*, 2021). The objective measurement of textures can include compression tests and penetration tests (Hadi *et al.*, 2024). Time-variable retorting temperature conditions have been demonstrated to retain nutritional values near equal to the constant retorting process but in less time.

There are constant physicochemical and biochemical processes in processing and storage, which cause partial destruction of nutritional and hygienic properties. The corrosion of cans, changes in color, development of metallic tastes, and bitterness associated with storage (Khidhir *et al.*, 2021; Stojanović *et al.*, 2022) can occur in canned foods when stored for longer periods. Increased storage temperature accelerates fat oxidation in higher pH, free fatty acids, and thiobarbituric acid (TBA) values in unsaturated fatty acids, as in quails (Şayin Sert and Coşkun, 2022).

Although canned meat is a rich source of high-quality protein, B-vitamins, and bioavailable minerals, sensitive nutrients may be degraded by conventional thermal processing and may favor the formation of undesirable compounds in this matrix (Leroy *et al.*, 2023; Vasilev, Klun and Uzelac, 2025). Accelerated aging studies have demonstrated that under optimized conditions, all the physicochemical spoilage markers remain within acceptable limits and only slight dryness and crumbliness have been noticed during advanced shelf life stages; thus, optimized processing preserves texture, flavor, and nutritional quality over an extended shelf life (Kusumaningrum *et al.*, 2022; Soldatova and Korzunov, 2022; Taze *et al.*, 2019).

24.8.2 Sensory Evaluation of Canned Meat

Sensory analysis is one of the main pillars of quality evaluation of canned meat products, delivering direct information on consumer-relevant attributes like appearance, color, aroma, flavor, texture, juiciness, and overall acceptability. The analysis is usually conducted by trained sensory panels that use descriptive analysis techniques or hedonic scaling techniques based on a 9-point scale for the measurement of palatability, mouthfeel, or preference, which are often linked with physicochemical information for final product formulation optimization.

Descriptive sensory analysis has been particularly helpful in unraveling exactly how ingredient formulation, different thermal processing profiles, and preservative systems impact sensory characteristics. This is important for new product introductions that are positioned as clean label or health because the reductions in nitrite and/or salt can alter flavor and textural expectations.

Intensity, composition, and type of preservatives are the factors that prominently influence functional properties. Comparison among natural preservatives shows that Kaloira oil, *Nigella sativa*, proves effective in increasing the organoleptic properties and quality, as far as canned beef is concerned, when contrasted with the use of $NaNO_2$ and NaCl (Roy *et al.*, 2024). Further improved functional properties are ensured with storage and aging, where the recommended storage period for canned pate is around three months to have the finest organoleptic properties (Toldrá, 2023). Organoleptic assessment, including attributes of appearance, color, odor, and texture, plays a crucial role in developing consumer acceptability (Ebuete, Puanoni and Ebuete, 2023).

Research proves that the sensory properties of canned meats are within the acceptance level under various storage conditions and temperatures. For example, quail meat stored in cans for 12 months showed acceptable sensory properties regardless of the storage temperature (Macari, Rotaru and Alexandruc, 2022). On the contrary, nutritional modifications like the addition of dietary fibers, especially barley BG300, could result in the darkening of color, which could be detrimental to consumer acceptance (Słowiński *et al.*, 2021). Sensory assessment based on the hedonic scale produces consistent results on the usefulness of texture and appearance.

The process of extended storage can cause an observable deviation in the senses, for instance, darkening, odors of metals, and bitter tastes (Khidhir *et al.*, 2021; Stojanović *et al.*, 2022). However, accelerated aging tests, performed for a fictitious period of eight years of storage, show that taste and smell can still be accepted while the processing and storing conditions are properly managed (Soldatova and Korzunov, 2022).

24.8.3 Microbial, Chemical, and Physical Hazards

To preserve consumer safety throughout the shelf life, it is necessary for canned meat products that they attain and sustain commercial sterility. The hazards for such products are widely categorized into microbial, chemical, and physical hazards, each demanding distinct types of measures to manage them in the process stream.

24.8.3.1 Microbial Hazards

C. botulinum represents the most critical biological hazard for low-acid canned meats. It can resist thermal processing since its spores are highly heat-resistant and can produce botulinum toxin under anaerobic conditions. Other important pathogens are *Clostridium perfringens*, *Bacillus stearothermophilus*, *Salmonella* spp., *S. aureus*, *Campylobacter* spp., and coliform bacteria (Toldrá, 2023). Meat and poultry products are among the major vehicles of foodborne illness, with *Salmonella* reported as the most frequent pathogen. The parameters, such as the pH value, water activity, oxygen tension, formulation, and storage temperatures, therefore constitute an intrinsic and extrinsic factor that influences risk. From such an account, therefore, it is clearly critical that the come-up, holding, and cooling phases are regulated through a validated retort schedule aimed at the total destruction of the cells and the spores.

24.8.3.2 Chemical Hazards

The chemical risks come from both the ingredients and the processing environments. These include residues of veterinary drugs, hormones, pesticides, and heavy metals, plus migrants from packaging such as iron, tin, and bisphenols (Khidhir *et al.*, 2021). The curing process, using nitrites, may also result in nitrosamines. Poor storage conditions accelerate the oxidative degradation of lipids and the formation of thiobarbituric acid (TBA)-reactive substances responsible for rancidity and off-flavors. Temperature abuse has also been linked to high levels of histamine in canned fish products, making strict control over temperature essential along the supply chain (Abuhlega *et al.*, 2025). It is apparent that traditional

foods usually have below-limit heavy metal residues when good manufacturing practices are applied (Kusumaningrum *et al*., 2022). Accelerated aging experiments, carried out undercontrolled conditions, confirm that the chemical indicators of spoilage remain within recommended ranges (Soldatova and Korzunov, 2022).

24.8.3.3 Physical Hazards

Physical contamination could include the presence of metal fragments, glass pieces, bone particles, and Seam defects caused by slaughtering, slicing, inspection, can seaming, and packaging activities. These contaminants are direct harm-causing factors for consumers and are removed through activities such as maintaining equipment, use of metal detectors and X-ray machines, and visual inspections of packaged cans.

24.8.3.4 Control Frameworks

FSSAI and the USDA have the task of testing the canned meat products in the laboratory for the presence of harmful microbes, chemicals, and physical contaminants (FSSAI, 2024). A robust mitigation process is adopted through the implementation of strict GMP and HACCP protocols, sanitary plant design, validated retort processing, and temperature profile monitoring, seam examination, and the absence of spoilage and safety indicators in the finished products. This approach is the cornerstone of the technology used in the production and processing of canned meat products and is adopted for the prevention and reduction of microbes, chemicals, and physical hazards.

24.8.4 HACCP Applications and Critical Control Points

The Hazard Analysis and Critical Control Points (HACCP) approach is therefore the model designed to guarantee food safety, assess, and prevent hazards from receipt of raw materials to the point of distribution. HACCP is recognized globally by the European Codex Alimentarius Commission and the National Advisory Committee on Microbiological Criteria for Foods (NACMCF) guidelines, thus establishing the cornerstone for food processing, specifically for meat products in tin containers (MOFPI, 2024).

HACCP application is based on seven principles: (i) hazard analysis, (ii) identification of CCPs, (iii) establishment of critical limits, (iv) monitoring procedures, (v) corrective actions, (vi) verification activities, and (vii) documentation and recordkeeping. These principles are supported by prerequisite programs such as GMP, SSOPs, personnel training, and strong management commitment in the course of canned meat processing.

24.8.4.1 Critical Control Points in Canned Meat Production

The most important CCPs are reception of raw material, scalding and evisceration, chilling, slicing, filling and sealing, thermal sterilization processes, and cooling sanitation and storage. Of these, thermal processes have the highest importance. Those canning industries approved by government agencies use validated schedule processes according to target values of F_0 for the destruction of heat-resistant spores of *C. botulinum* bacteria, resulting in commercial sterility and shelf stability. This results in commercial sterility and shelf stability (Obeid *et al*., 2019).

Seam integrity and air exhausting are also designated CCPs, as defective closures can permit post-process contamination and lead to spoilage or “can blowing”. Cooling must be carried out using sanitized potable water to prevent microbial ingress through microleaks. Storage temperature and warehouse hygiene are further CCPs, as temperature abuse can accelerate chemical spoilage and microbial recovery.

24.8.4.2 Monitoring and Verification

The effectiveness of HACCP depends upon continuous monitoring of the “time–temperature profiles, can filling volumes, vacuums, seam sizes, and cooling water quality”. Physicochemical parameters like “peroxide value, thiobarbituric acid (TBA) number, and amino-ammonia nitrogen” can be employed as

verification procedures for assessing shelf life statements (Soldatova and Korzunov, 2022). Whenever there are deviations in critical limits, "predefined corrective actions would be necessary", like segregation, reprocessing, or disposal.

Overall, HACCP provides a structured framework that integrates hazard prevention, process control, and documentation to assure the microbial safety, nutritional quality, and regulatory compliance of canned meat products across the entire production continuum (Taze *et al.*, 2019).

24.9 Innovations and Emerging Technologies

The packaged meat sector, which has conventionally revolved around thermal sterilization and retort processes, is presently witnessing a radical shift because of sustainability objectives, consumer demands for lightly processed foods, and developments in digital and nonthermal technology. The new developments include innovations related to energy conservation, automation, hybrid processing, and clean-label/nutrition-oriented solutions.

24.9.1 Energy-Efficient Processing Technologies

Continuous retort systems give enormous benefits to the processing industry compared to the earlier retorts. This technology reduces labor costs, energy consumption, and machine withdrawal. Advanced retorts and improved heat transfer processes and continuous processes ensure effective microbial destruction and shorter processing times (Ebuete, Puanoni and Ebuete, 2023; Toldrá, 2023). The continuous processes are Sterilmatic™, Orbitort™, Hydrostatic™, and Hydrolock™, which ensure improved heat transfer and shorter processing times.

A standardized pressure-assisted thermal process, depending upon controlled temperature and pressure, is a novel trend in the direction of more energy-efficient preservation systems for packaged meats (Roy *et al.*, 2024). Conventional intense heat processing may result in the use of excess amounts of energy, which, in turn, increases production costs, and gentle heat with nonheat processing can minimize the production costs and pollution (Arokiyaraj, Dinakarkumar and Shin, 2024).

Optimization of heat treatment based on F_0 value calculations is of great importance. Although $F_0 \geq 3$ leads to microbial safety, oversterilization ($F_0 > 8–10$) leads to unnecessary nutrient breakdown and enhanced energy usage (Vasilev, Klun and Uzelac, 2025). Changing lethality goals can ensure nutritional safety and minimize energy use (Rašeta *et al.*, 2018). Other accelerated aging methods include methods that predict shelf life quickly, conserving both time and energy compared to the shelf life test (Soldatova and Korzunov, 2022).

More advanced methods for meat processing involving mild thermal processing, HPP, and sous vide processing improve the power efficiency of meat processing (Gil *et al.*, 2022; Yadav *et al.*, 2025). Hybrid sterilization equipment, agitating retorts, and continuous retorts are designed to increase the rate of heat transfer, thereby cutting down the processing time by as much as 80% and ensuring enhanced energy use. Moreover, advanced heating processes such as microwave, ohmic, and radiofrequency delivery mechanisms result in improved and rapid heat transfer, hence increasing the use of energy and ensuring the preservation of quality through the avoidance of temperature hot spots. Microwave-combined retorts, merging electromagnetic and conventional heat, simultaneously increase quality and processing rate (Coronel, 2023).

Overall, the integration of continuous processing, advanced heat transfer, and mild thermal and nonthermal technologies represent a significant advancement in energy-efficient canned meat production, supporting sustainability, product quality, and safety objectives.

24.9.2 Automation and Intelligent Processing Systems

Automation and digitalization are transforming the industry of canned meats because of the improvements they bring to process control and efficiency, as well as safety and quality. The incorporation of intelligent sensors and AI-enabled process control enables real-time changes in processing variables (Ebuete, Puanoni and Ebuete, 2023).

Robotic preserving processes such as filling, vacuum exhausting, and robotic carcass processing could increase more even heating, increased rates, and improved sanitary conditions. The flexibility of batch retorts to handle various types of packages exists, and crateless retorts are considered effective automated batch processing (Teixeira, 2019).

Advanced quality and safety integrated HACCP with ISO 9000 quality management systems, a next-generation approach to food safety. The trend of European regulations is to focus increasingly on the concepts of Integrated Quality Control (IQC) and Longitudinally Integrated Safety Assurance (LISA), for instance, in order to harmonize process monitoring and product compliance.

Industry 4.0 technologies such as predictive maintenance, automatic control of temperature and pressure, and digital safety management systems improve product uniformity and minimize errors after the process. Automated quality control systems are able to process real-time analysis of physicochemical indicators so that predictive changes can be made toward achieving desired quality parameters after the canning process (Soldatova and Korzunov, 2022).

Robotic and AI-enabled systems extend to seam inspection, packaging defect detection, and foreign-object monitoring. Machine learning models can predict equipment behavior, identify deviations in product quality, and adjust process parameters dynamically, improving yield, safety, and operational efficiency (KOMETOS, 2023; Palanisamy, Kadirvel and Ganesan, 2025).

Therefore, we can conclude that canning beef or canned meats are undergoing a new change with automation or intelligent processing technologies that are improving precision, reliability, and traceability in all steps involved in the process.

24.9.3 Hybrid Preservation Technologies

Hybrid preservation techniques use traditional thermal approaches in combination with nonthermal or "biological" preservation techniques, which result in a synergistic effect that maximizes microbial inactivation while retaining desired attributes such as sensory properties, flavor, color, and nutrients in the foodstuff, which are considered essential for commercial sterility.

The concepts of hurdles in technology include combining preservation hurdles with heat, curing salts, antioxidants, hydrocolloids, modified atmospheres, pH control, and biopreservation. These complex methods lead to longer shelf life and stability of products without requiring severe heat application (Toldrá, 2023). Pressure-assisted canning in thermal canning using 115.6 °C/240 °F heat for 90 minutes under 10 lb pressure combines heat and chemicals in synergy (Roy *et al.*, 2025).

Although the importance of the role performed by thermal sterilization in commercial sterility cannot be overemphasized, the emergence and use of hybrid systems have come to symbolize the move to the concept of "integrated preservation", and in a bid to meet the needs of modern consumers who are looking to consume those types of products that are processed, safe to consume, and of good quality, this method not only reduces the stress put on the products in terms of temperature, hence the meaning of sustainability, but also does not in any way compromise the quality and nutritional value obtained in canned meat products (Tavakkoli, 2025).

24.9.4 Clean-Label and Nutrition-Focused Innovations

The demand for less processed products has increased among the consumer segment, leading to innovations in the production of canned meat products based on clean labels and the level of nutrition. More sustainable principles for production have been achieved based on environmental packaging, lower use of chemical components, and environment-friendly components in production. Quality life cycle assessment methods have been adopted recently as solutions to products based on incorporating various components in the production plan, including occupational, environmental, and quality (Pacana *et al.*, 2024).

Plant-based ingredients such as plant-based reformulation, bioactive compounds, and fat substitutes enable the clean label strategy without compromising the texture, spreadability, or general quality of the product (Blanco-Gutiérrez, Varela-Ortega and Manners, 2020). Protein–polysaccharide cogelling systems exhibit improvements in hydration, sliceability, and yield of the product in healthier forms without

compromising sensory characteristics. Concluding the traditional preservative reduction approaches involving ingredients such as nitrites and salt are compensated for through the addition of essential oil ingredient technology and bioprotective cultures with the achievement of microbial safety and product stability in the extent of the product's shelf life (Vasilev, Klun and Uzelac, 2025).

Increasing consumer demand for preservative-free and less-processed meats has led to the use of an increased level of less artificial bioactive ingredients. An example is Kalojira oil, which is obtained from *N. sativa* seeds and has the advantage of exhibiting both antimicrobial and antioxidant properties to control microbial growth effectively in beef-canning products without changes in physicochemical properties (Olvera-Aguirre *et al.*, 2023). There are also reformulations with omega-3 fatty acids and dietary fibers and banana flours.

New and emerging trends and advancements in precision fermentation and alternative protein technology hold the potential for the production of valuable proteins and micronutrients targeted for the production of clean-label canned meat products. Advances in packaging technology also complement current efforts, as intelligent and active packaging with the addition of sensors, time–temperature indication, and antimicrobial packaging materials ensure the quality and extend the shelf life of the products, besides offering "real-time" information to the consumer (Palanisamy, Kadirvel and Ganesan, 2025). The use of antimicrobial packaging with natural antimicrobial agents like essential oils also supports the removal or avoidance of artificial preservatives, ensuring safety and consumer confidence associated with the production of clean-label products.

24.10 Regulatory Framework, Consumer Trends, and Sustainability

Canned meats are at the crossroads of strict food safety laws, changing customer demands for sustainability, convenience, and health, and growing pressure to minimize environmental impacts in manufacturing and packaging.

24.10.1 International Standards and Regulatory Compliance

Commercial sterility, process validation, packaging integrity, and contamination limitations are the main topics of an integrated framework of national and international standards governing low-acid canned meats. With a specific focus on controlling *C. botulinum* and other spore formers in hermetically sealed containers, the Codex Code of Hygienic Practice for Low-Acid and Acidified Low-Acid Canned Foods offers internationally recognized guidelines on hygienic design, retort operation, cooling water quality, seam integrity, and process control. These generic regulations are supplemented by product-specific Codex standards for canned meats and fish (such as canned crab meat), which include requirements for composition and labeling.

Processors of thermally processed low-acid canned foods in the United States are subject to 21 CFR Part 113 and associated guidelines, which require plant registration, filing of scheduled processes for each product/container/retort combination, operator training, and meticulous documentation of time–temperature profiles, container closure assessments, and critical deviations. The European Union and numerous other countries have comparable regulatory frameworks that frequently incorporate Codex concepts into national legislation and mandate HACCP-based food safety management systems that specifically identify container closing and thermal processing as essential control points.

Regulations define limit levels for process pollutants, including furan and its derivatives in canned foods, as well as heavy metals like tin, lead, cadmium, and mercury, in addition to microbiological safety. Heavy metal concentrations and chemical spoilage markers typically stay below regulatory limits under good manufacturing practices, according to systematic surveillance of canned meats in various countries. However, caution is required where enamel failures or improper storage conditions favor corrosion and migration. In order to prove cold-chain integrity for semi-preserved goods, compliance with these guidelines is becoming more closely associated with digital traceability, incorporating batch coding, electronic process records, and, in certain situations, intelligent packaging indicators (Khodaei *et al.*, 2023; McMillin, 2025; Tsao, Chen and Kao, 2022).

24.10.2 Consumer Preferences and Convenience-Driven Trends

Regulations define limit levels for process pollutants including furan and its derivatives in canned foods, as well as heavy metals like tin, lead, cadmium, and mercury, in addition to microbiological safety. Heavy metal concentrations and chemical spoilage markers typically stay below regulatory limits under good manufacturing practices, according to systematic surveillance of canned meats in various countries. However, caution is required where enamel failures or improper storage conditions favor corrosion and migration. In order to prove cold-chain integrity for semi-preserved goods, compliance with these guidelines is becoming more closely associated with digital traceability, incorporating batch coding, electronic process records, and, in certain situations, intelligent packaging indicators (Kenny *et al*., 2023; Llauger *et al*., 2021).

A number of canned meat product and packaging trends are being driven by these attitudes. Although it must be weighed against safety and shelf life restrictions in low-acid, ambient-stable goods, clean-label reformulation—which lowers nitrite and phosphate levels, lowers salt, and incorporates plant-based antioxidants—aligns with customer aspirations for "natural" ingredients. Convenience and portion control are supported for smaller homes by packaging formats that indicate freshness and quality, such as transparent or windowed retortable trays, smaller single-serve cans, and easy-open ends. Additionally, there is growing interest in using digital labeling and QR codes to convey information about sourcing, animal welfare, and the environment. This is indicative of a larger trend in animal-source goods toward transparency (Deshwal, Kr. and Panjagari, 2020; Li *et al*., 2022; McMillin, 2025; Msogoya *et al*., 2025).

24.10.3 Sustainable and Recyclable Packaging Solutions

Because steel and aluminum can be recycled endlessly without significantly losing quality, metal cans have excellent intrinsic sustainability credentials. Recent life cycle assessments (LCAs) of aluminum beverage and food cans in North America and Europe reveal high-average recycled content (about 70–80%) and end-of-life recycling rates above 50%. Each unit of recycled aluminum can save up to 95% of the energy needed for primary manufacture. Steel food cans are among the most recycled packaging shapes in Europe, with recycling rates topping 80–85%, according to research. When compared to various other preservation and packaging methods, the overall carbon footprint of canned meats is positively impacted by these high recycling rates as well as comparatively minimal product loss because of the durability and extended shelf life of canned goods (Stotz *et al*., 2017).

However, due to the relative low mass fraction of such wastes in mixed streams and the difficulty of separating polymer and aluminum layers, multilayer flexible laminates used in retort pouches and lidding films present substantial hurdles for mechanical recycling. While multilayer laminates require advancements in design for recyclability, chemical recycling technologies, or take-back schemes to achieve comparable circularity, LCAs comparing steel cans, glass jars, and carton-based systems for shelf-stable foods indicate that material light-weighting and increased recycling rates can significantly reduce impacts for metal packaging. In response, research is concentrating on bio-based polyesters and coatings, mono-material high-barrier polymers, and simpler laminate architectures that can preserve retort performance while enhancing end-of-life possibilities (Stotz *et al*., 2017; Yousef and Stasiulaitiene, 2024).

Practical sustainability strategies for canned meats include secondary and tertiary packaging optimization to minimize transport impacts; maximizing post-consumer recycled content within limits compatible with food-contact standards; reduction of can gauge thickness where seam integrity permits; and promotion of consumer participation in recycling programs through clear labeling and deposit-return schemes. Such interventions support process-side strategies like waste heat recovery and energy-efficient retorts covered under developing technologies in the sections below.

24.10.4 Environmental Impact Mitigation and Future Perspectives

Therefore, a holistic approach to the sourcing, processing, packaging, and distribution of raw materials is essential for the reduction of the environmental impact of canned meat production. In relation

to processing, the employment of better energy efficiency in retort technologies such as agitated batch retorts, continuous hydrostatic systems, MATS, and PATP hybrids can reduce the quantity of steam and water applied per unit of fuel delivered; improved process control can reduce overprocessing and product waste. Water management also greatly enhances environmental performance and compliance with regulations. This includes recirculation and cooling and sterilizing water treatment (Soni *et al*., 2020; Yousef and Stasiulaitiene, 2024).

Highest priority from the perspective of the packaging industry is the leveraging of the high recyclability of metals while also addressing the issue of the rising usage of complex laminated structures. The preference is given to mono materials or easily separable materials as compared to composite materials through European and North American industry initiatives promoting the use of "design to recycle" concepts, "producer responsivity", and quantitative recycling targets. This can lead to the continuation of the dominance of steel cans in the market, particularly from the perspective of canned meat products, while targeting retort pouches/trays when the associated superior benefits to the consumer or the marketer of the contemplated canning formats merit override of the potential recycling problems noted.

Further, sustainability-related conversations involving longer-term canned meats evolution appear to be integrating with more general debates regarding the role of meats derived from animals as a foundation for sustainable diets. Strong, although differentiated, expectations appear in a range of assessments of feedback regarding the purchase of sustainable diets, along with the sustainability of meats. For instance, particularly in areas where there is a scarcity of infrastructure for the storage of perishable products at reduced temperatures, the role of the generally more accessible canned meats, particularly those reformulated for greater nutritional superiority as well as sources of the products derived from animals more sensitive to welfare, the environment, as well as labels, might ensure the reduction of food losses and the assurance of protein availability. Nonetheless, their acceptability in the future remains reliant on the continuous attempt toward the partial mitigation of processing intensity, as well as the increased process of the circular economy.

24.11 Conclusion

Canning of meat products is an example of well-established but continuously evolving preservation technology that integrates high-quality raw materials, carefully designed formulations, controlled preprocessing, accurate filling and packaging, and scientifically established thermal sterilization into a single, dependable value chain. Throughout the chapter, it becomes clear that retort process design–time–temperature profiles represented as F_0 values as well as hermetic, mechanically robust packing and stringent post-process handling are the important factors determining commercial sterility in low-acid canned meats. Processors can successfully control *C. botulinum* and spoilage microorganisms while preserving desired texture, flavor, color, and nutritional qualities when the aforementioned factors are optimized together.

Within the realm of canned meat, the reader can find the paradigm of an evolutionary yet well-understood method of preservation wherein the marriage of high-quality materials, well-thought-out formulations, preprocessing controls, and the science of filling and packing, joined with the science of thermal sterilization, form the backbone of an assured value chain associated with the preservation of the food stuff. Throughout the entire chapter, the reader will find the definiens of retort process conditions in the form of F_0, as related to "time–temperature profile", as well as the science of "hermetic packing" coupled with the science of post-processing handling being the key parameters of commercial sterility as associated with low-acid canned meats. With these key areas being the backbone of the preservation of food stuff, the science of controlling *C. botulinum* as well as other spoilage organisms on one hand, and texture, taste, appearance, apart from other food, on one other hand, is achievable.

At the same time, regulatory frameworks, consumer expectations, and sustainability pressures are resetting innovation priorities. Stringent international and national regulations for low-acid canned foods anchor food safety, while consumers increasingly demand convenient, affordable protein options that also align with health, transparency, and environmental values. The high recyclability and robustness of

metal cans, together with evolving designs for more recyclable high-barrier laminates, position canned meats to play a meaningful role in the security of food supplies and waste reduction in a resource-constrained world. Further advances will depend on holistic approaches that link process and package improvements to cleaner formulations, digital traceability, and circular economy principles that ensure that canned meat products will remain safe, of high quality, and sustainable for global markets of diverse character.

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25

Cultured Meat: Driving Innovation, Overcoming Challenges, and Shaping the Future of Sustainable Meat

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25.1 Introduction

Cultured meat, which is also known as cultivated, cell-based, or lab-grown meat, refers to the actual meat, that is actually tissue, from the muscles of animals that has been grown in vitro by using animal cells in well-controlled experimental conditions. In practical terms, this is achieved by the multiplication and differentiation of cells (Lee, Loh and Wan, 2021). In most cases, they are stem or satellite cells grown in the host and end up as muscle and fat tissue. The resultant product has the exact biochemical properties of conventional meat and thus offers an ethically preferable, potentially more sustainable alternative to traditional livestock farming (Al-Anbari, 2024). This is part of a broader field of cellular agriculture, where cell culture techniques are used to produce animal products without animal growth or slaughter. Cultured meat is supposed to have similar nutritional value, flavor, and texture to farmed meat, while it is different in production from live animals and conventional farming. It has emerged from decades of advances in cell biology, tissue engineering, and bioprocessing. It is now pursued by hundreds of companies and research labs worldwide that use regenerative technologies to recreate food.

This is an innovation in the context of rising meat demand worldwide and dire sustainability challenges. Global meat production has grown more than threefold since the 1960s, and the continuity of population and income beyond the middle of the century is bound to add another nearly 50% (Falcon, Naylor and Shankar, 2022). Such growth is not sustainable. Livestock agriculture takes up some 80% of all agricultural land on Earth (including pasture and feed crops) and yet yields just 38% of the protein humans eat (Mehrabi *et al*., 2020). An example of such inefficiency is cattle meat; beef requires 20 times as much land and generates 20 times as many greenhouse gases per gram of protein as plant foods like beans and lentils (Xu *et al*., 2021). Aggregate food systems, like meat and dairy food systems in particular, are estimated to be responsible for about a third of anthropogenic greenhouse gas emissions and also cause deforestation, biodiversity loss, and water-use conflicts (Crippa *et al*., 2021). All of these environmental and ethical effects (including animal welfare and zoonotic risks) have led to a call to transform the animal protein production and consumption system radically.

Such attempts have quickly focused on cultured meat. Since the first presentation of a prototype of what would later be called a burger in 2013, dozens of start-ups have entered the industry. The cultivated-meat industry in 2024 had more than 175 companies operating on six continents and had more than US$3.1 billion in investment. This rapid growth suggests that cultured meat is viewed as a disruptive technology. This technology may usher in a fundamental paradigm shift in the food system by disaggregating meat production and animal rearing. Analysts note that cultured meat on a larger scale could dramatically reduce greenhouse gas emissions from livestock and free vast quantities of land that is already under forest or farmland for animal production (Munteanu *et al*., 2021). Theoretically,

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cellular meat would allow the world to obtain pure animal meat without harming the environment, international health, or food security. In other words, cultured meat will provide the same taste and nutritional experience as traditional meat, using fewer resources and killing no animals (Bryant and Barnett, 2020).

Cultured meat is at a particular point in the intersection of biotechnology and food engineering within the broader context of sustainable meat technology. It is based on decades of experience in cell culture and fermentation. It will need to employ innovations in cell line development, serum-free cell culture, bioreceptor design, and food-safe scaffolds to scale up muscle tissue production. In real-life applications, cultured meat reinvents meat production as an artificial process, one that can be programmed to be both efficient and nutritious from stable to fork. Life cycle tests have suggested that, once optimized, huge margins might reduce the land and water required to produce cultivated products compared to those required for animals in conventional methods, yet this will only be possible through the use of renewable energy sources and further technological advances.

In conclusion, cultured meat is one of the manifestations of the intersection of biology and engineering/food science—a sustainable protein engineering case study. This has placed it among the key subjects of interest to researchers and industry in their hunt for a more sustainable and humane meat source. The remaining sections of this chapter cover the science and technology behind cultured meat—how innovation has managed to rectify its issues and how the new solution can shape the future of sustainable meat.

25.2 Scientific and Technological Basis of Cultured Meat Production

25.2.1 Principles of Cellular Agriculture

Cellular agriculture is an interdisciplinary field that uses principles of biotechnology, tissue engineering, and cell biology to produce animal products through in vitro cell culture rather than through animal husbandry. In cellular agriculture, cells are cultured in controlled bioprocesses to produce final products such as cultured meat, cell-based egg proteins, and synthetic dairy proteins (Ercili-Cura and Barth, 2021). The processes are based on the principles of cell growth, differentiation, and metabolic control. By leveraging the self-assembly and biosynthetic properties of animal cells, this method should recreate the texture, flavor, and nutritional content of meat, milk, and eggs. It may reduce the environmental footprint and eliminate the need to slaughter animals.

Cell sourcing is the primary component of any cellular agriculture process. Usually, cell sources of bacterial, yeast, or eukaryotic origin are used, such as the primary cells of animals (like muscle satellite cells, myoblasts, etc.), embryonic or induced pluripotent stem cells (iPSCs) derived from livestock, and immortalized cell lines specifically adapted to industrial cultivation (Goswami *et al.*, 2024; Weeratunga, Harman and Van de Walle, 2023). The desired cell sources are characterized by high proliferative capacity, genetic stability, and the ability to differentiate into the desired cell types (in meat, mainly muscle and fat cells). Others involve the use of primary muscle stem cells obtained by animal biopsy, and others involve pluripotent stem cell lines, which can be endlessly expanded. Genetically engineered cells are being explored in research to improve growth rates or customize nutritional properties, although any genetic engineering must be strictly subject to safety and regulatory standards.

After achieving a good cell population, the other principle to observe is extensive cell proliferation. The step entails culturing cells in a nutrient-rich medium containing amino acids, sugars, lipids, vitamins, minerals, and growth factors (Okamoto *et al.*, 2022). Recipes used in the media are conventional tissue culture recipes that typically contain animal serum. However, recent methods favor serum-free or plant-based versions to enhance scalability and cost-effectiveness. Specific growth factors, such as fibroblast growth factor (FGF) or insulin-like growth factor (IGF), can be introduced to maintain cells in a growth state (Ahmad *et al.*, 2023).

The best physical conditions are maintained to promote optimal temperature, pH, oxygen tension, and nutrient levels. This is usually done by using specific control mechanisms in bioreactors to regulate environmental conditions. The objective of the proliferation phase is to scale up the number of cells

while maintaining cell health and potency. Once adequate quantities of cells have been obtained, the cells should be instructed to develop into fully-fledged tissue components. Differentiation is induced by cultural conditions, which can be altered to recapitulate developmental cues in vivo. In muscle cell production, this can be achieved by decreasing mitogenic signals in the muscle (e.g., by reducing or enhancing certain growth factors) and by providing components that enhance myogenic fusion and maturation (Jung *et al*., 2025; Lee, Loh and Wan, 2021). Introducing adipogenic cues can also induce cells to develop into fat cells.

Precursor cells can be induced to fuse and differentiate into myotubes (muscle fibers) or adipocytes (fat droplets) by biochemical signals, for example, hormones or small molecules. It also includes physical stimuli like mechanical tension, cyclic stretching, or electrical pulses. They may stimulate the alignment and maturation of muscle fibers. Finally, controlled differentiation redefines the gene expression programs (such as myogenic regulatory factors) and the extracellular cues that regulate the mature development and fat deposition of muscle in nature.

Scaffolds provide the three-dimensional structure upon which cultured meat will be based, in terms of both structure and qualities. These scaffolds are usually biocompatible and edible, and are modeled after the extracellular matrix in tissues. Some of them are natural polymers (including collagen, gelatin, or alginate), natural tissue matrices (including decellularized leaf tissue or fruit tissue), or synthetic hydrogels. An appropriate scaffold supports cell adhesion and tissue architecture while allowing the passage of oxygen and nutrients throughout the matrix (Seah *et al*., 2022). It also provides mechanical strength, so the growing tissue can maintain its shape and be handled. The properties of scaffolds, in terms of porosity, stiffness, and geometry, can be optimized to affect cell growth, cell alignment, and cell differentiation. In practice, cells can be cultured on or within a scaffold, or on microcarrier beads, to develop layers of muscle and fat cells (Bodiou, Moutsatsou and Post, 2020). These approaches aim to form thick, structured tissues that mimic the appearance and mouthfeel of conventional meat.

Cellular agriculture is based on industrial-scale cell culture, with bioreactor systems as its backbone. A bioreactor is a closed system designed to control temperature, pH, dissolved gases, and mixing (Pajčin *et al*., 2022). The most frequently used designs are stir-tank (mechanically stirred), fixed-bed (cells attached to a fixed or immobile framework), and perfusion (cells renewed constantly with new media and old cells washed away) bioreactors (Porto de Souza Vandenberghe *et al*., 2024). Bioreactors in scaffold-based cultures can use perfusion flow through the scaffold or specialized stirring to ensure that all cells are adequately supplied with nutrients and oxygen.

There is an engineering challenge in scaling these systems from the laboratory to the industrial level. Agitation, oxygenation, heat removal, and hydrodynamic shear should be well controlled to retain cell viability and function (de Carvalho *et al*., 2024). In modern bioreactors, sensors and feedback controls are incorporated to measure pH, oxygen, nutrient levels, and, as a result, the flow of gases, agitation, and feeding rate may be automatically adjusted. Collectively, these bioprocess technologies allow the growth of millions to billions of cells required for commercial production. There must be process control and monitoring to ensure that the cultured products are replicated and of high quality. Real-time sensing technologies are used to measure important bioprocess parameters, including cell density, metabolite concentration, pH, and dissolved oxygen, and the resulting data streams are run through advanced control algorithms to control inputs such as media feed rates or gas composition (Chen *et al*., 2022). Subsequent scale-up is performed in bioreactor systems, followed by directed cell differentiation and spatial assembly on a structural scaffold, resulting in the final product. These steps are supported by molecular-level processes, including the gene expression programs that induce the formation of muscle and fat cells.

These values apply to various cellular agricultural products. For example, milk proteins (e.g., casein) or egg white proteins can be produced at scale using mammalian cell cultures or genetically engineered microbes (Manzoki *et al*., 2025). The sensory properties are always the same; cells can be controlled to develop a desired animal product in a controlled and sustainable manner. Cellular agriculture can therefore be scientifically defined as the synergy of cell biology, biomaterials, and bioprocess engineering. The entire cultured meat system for end-to-end cultured meat production is shown in Figure 25.1.

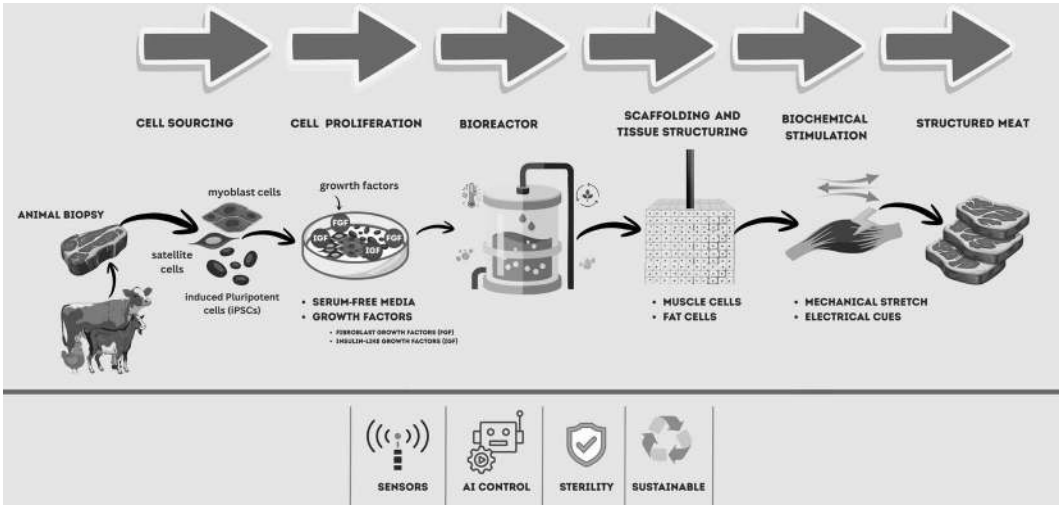

FIGURE 25.1 Cultured meat system for end-to-end cultured meat production.

25.2.2 Selection and Isolation of Satellite Cells, Myoblasts, and Stem Cells

The primary cell types to be studied as sources for cultured meat are satellite cells, myoblasts, embryonic stem cells, and induced pluripotent stem cells, due to their abundance and differentiation potential. Satellite cells are muscle stem cells within the tissue that reside underneath the basal lamina of muscle fibers and are activated in response to injury in skeletal muscle or as a signal for growth (Kaczmarek *et al.*, 2021). Upon activation, they divide to form myoblasts, which are mononucleated, myogenic-lineage cells that then go on to differentiate and fuse to form multinucleated myotubes. Myogenic regulatory factors, including Pax7, MyoD, and myogenin, are expressed by myoblasts and are popular because they have an innate capacity to generate contractile muscle fibers (Azhar, Wardhani and Renesteen, 2022; Hoseini, Hoseini and Kamangar, 2025). On the other hand, embryonic stem cells, which represent the inner mass of the blastocyst, and induced pluripotent stem cells, which are created through the reprogramming of somatic cells using specified transcription factors, also exhibit increased lineage properties. These pluripotent cells can be differentiated into myogenic, adipogenic, or connective lineages, allowing the biomanufacturing of complex, structured cultured meat comprising both muscle and fat tissue components.

Cell type selection is based on biological performance and industrial scalability. Myoblasts and satellite cells have proved beneficial due to their natural myogenic properties and comparatively simple differentiation protocols, and are thus a good choice for pure muscle tissue engineering (Yu *et al.*, 2021). However, they are limited in terms of a finite replicative lifespan and by drift in phenotypes over long passages. Pluripotent stem cells, such as iPSCs, have no limit to their lifespan and can be multiplied indefinitely, making them suitable for long-term manufacturing (Liu *et al.*, 2020). To ensure that their given lineages are preserved, their differentiation therefore requires strictly regulated conditions for signaling to occur, so that the presence of undifferentiated cells may not pose a safety hazard. Another factor to consider when selecting the best types of cells for the mass production of food is genetic stability, lack of tumorigenesis or transformation, and compatibility with regulatory systems.

Satellite cells and myoblasts are isolated by enzymatic digestion of skeletal muscle tissue, followed by pre-plating to eliminate fibroblast contamination, and enrichment using fluorescence-activated or magnetic-activated cell sorting by surface markers (Kim, Qiu and Kuang, 2020; Lee *et al.*, 2024a). These markers are CD56, integrin-alpha7, and VCAM-1. iPSCs are generated by introducing reprogramming factors usually Oct4, Sox2, Klf4, and c-Myc into donor somatic cells (Ray *et al.*, 2021). The colonies produced are confirmed by expressing pluripotency markers and propagated under specified conditions. Compared to satellite cells, which are tissue-specific and plasticity-restricted, pluripotent stem cells are a more versatile option for fabricating multi-lineage cultured meat. Each of them, however,

entails particular difficulties in terms of bioprocessing, differentiation control, regulatory approval, and, therefore, requires careful pairing with the desired product design and production model.

25.2.3 Scaffold Materials and Biomimetic Microenvironments

Scaffold materials and biomimetic microenvironments play an important role in determining the organization, maturation, and physicochemical characteristics of cultured meat tissues. In native skeletal muscle, the extracellular matrix is responsible for structural integrity, transduction of mechanical cues, and biochemical signaling (Csapo, Gumpenberger and Wessner, 2020). It then plays a key role in myogenesis, alignment, and function of myofibers. Discovering a proper scaffold system that favors the propagation of these properties is a key tool for scientists. A proper balance of nutrients and oxygen is needed. It is assisted by natural biopolymers. These include gelatin, collagen, alginate, etc. (Table 25.1).

The advantage is due to their biochemical properties, which are very similar to those of native tissues and confer bioactivity. Collagen and fibrin are most suitable for inducing the myoblast orientation and fusion (Samolyk *et al*., 2024). Alginate and chitosan can be used to scale up the process to an industrial level. Meanwhile, in factory-made category, synthetic polymers are available for the said task. They include poly lactic and co-glycolic acid, polycaprolactone, and polyethylene glycol. They have the advantage of greater control over mechanical strength, breakdown processes, and formulation stability. In addition, better adhesion is also reported, which ultimately enhances cellular interactions and promises additional benefits.

While designing a suitable environment, the choice of material is not enough; it requires a combination of structural topology with a specific mechanical design. Ideal scaffolds have better topography and anisotropy. These properties are required for guiding myotube formation. This tube is ultimately beneficial for recapitulating the design and contractile activity of native muscle tissue. Different categories, such as electrospun fibers, 3D-printed lattices, microgroove-driven hydrogels, and aligned fibrils, are available on the market. They enable myofiber extension, elongation, and growth dynamics (Volpi *et al*., 2022). One of the desired characteristics is mechanical stiffness. It is essential because it is an important determinant of signaling pathways that control cytoskeletal supply tension, cellular differentiation, and cellular fusion (De Belly, Paluch and Chalut, 2022). It is matched to the modulus of natural muscle. Other factors influencing the direction of lineage specification and the modulation of maturation in engineered tissues are the organization of biochemical gradients, growth factors, and immobilized peptides within the scaffold matrix (Li *et al*., 2021). For the best tissue-grade muscle, the combined effect of these biochemical signals with structural/mechanical parameters provides a powerful microenvironment.

Another challenge is addressing functional performance and regulatory compliance criteria. Food safety, toxicity, and compliance are underlined without compromising the end product. Recent research has led to the practice of innovative approaches in which edible scaffolds are developed from plant proteins and cellulose, and mycelium (Maseko *et al*., 2025; Srivastava *et al*., 2025). These are designed to

TABLE 25.1

Properties of Scaffold Materials for Cultured Meat

Scaffold Material	Mechanical Properties (kPa)	Biodegradability	Impact on Texture	Cell Adhesion	References
Collagen (animal-derived)	10–50	High	High (soft, natural)	High	Guzmán-Soria *et al.*, 2023
Gelatin (plant/animal-derived)	5–25	High	Moderate (soft)	Moderate	Kim *et al.*, 2021
Alginate	20–100	Moderate	Low–Moderate (gel-like)	Low–moderate	Iranmanesh *et al.*, 2021
Chitosan	30–150	Moderate	Moderate (firm)	Moderate	Lazăr *et al.*, 2025
Plant protein-based (pea, soy)	15–80	High	Moderate (fibrous)	Moderate	Jing *et al.*, 2020; Marszalik *et al.*, 2025

provide structural integrity directly in the finished meat product. These systems, in addition to providing mechanical support, also enhance the system's sensory characteristics, such as firmness and fiber directionality. Advances in microenvironment engineering increasingly focus on the implementation of vascular-mimetic channels for improved nutrient diffusion through thicker constructs (Casanova *et al.*, 2024), and on the coculture of muscle with adipogenic and CT cells for the production of more complex, multi-tissue architectures. As scaffold materials and artificial microenvironments develop, they form a basis for a technological platform that allows cultured meat to finally approach the structural, sensory, and functional characteristics of traditional meat, while maintaining the possibility of scalability and sustainability.

25.2.4 Bioreactor Engineering: Types, Scale-Up, and Process Control

Bioreactor engineering plays a key role in the development of cultured meat constructs from lab scale to industrial-scale production, enabling consistent, high-quality biomass. Bioreactors can provide a controlled environment for cell expansion, differentiation, and tissue maturation; mass transfer; control of the hydrodynamic environment; nutrient delivery; and removal of metabolic wastes (Castro *et al.*, 2020). Several bioreactor setups are used depending on cell requirements and product structure. Stirred-tank bioreactors are widely used for the proliferation of myoblast and pluripotent stem cells due to efficient mixing, a scalable and amenable shape, and compatibility with microcarriers that increase the surface area of adherent cells (Borys *et al.*, 2021). Fixed- and packed-bed systems support high-density cultures, resulting in lower shear stress. Perfusion bioreactors support three-dimensional tissue constructs, enabling proper nutrient flow and enhancing oxygenation (Felder *et al.*, 2020). Researchers have provided an equation (Equation 25.1) for complete modeling of proliferation in perfusion bioreactors. It is given as follows:

$$\mu = \mu_{\max} * \frac{S}{K\,s + S} - D \tag{25.1}$$

where

μ is the specific growth rate of cells,
$\mu_{\max}$ is the maximum specific growth rate,
S is the limiting substrate concentration,
K_s is the Monod constant, and
D is the dilution rate in perfusion.

For the structured formation of meat, scaffold-based bioreactors with perfusion, cyclic strain, or electrical stimulation are used to promote myofiber alignment and improve functional maturation. Scaling up the production of cultured meat will require optimization of cell density, liquid turnover, oxygen transfer coefficients, and limits on shear stress to preserve phenotypic stability and viability across large volumes. As bioreactor size increases, problems arise in homogeneous mixing, and oxygen and heat dissipation, leading to the use of advanced impeller designs, controlled microcarrier suspension, and high surface area gas exchange systems (Palladino *et al.*, 2024). Computational fluid dynamics models are encountering growing challenges in predicting flow patterns, shear zones, and nutrient gradients to design large-scale systems with intact cell functionality rationally. Modular and parallelized bioreactor configurations offer alternative techniques for scaling and avoiding the complexity of operating huge single units.

25.2.5 Serum-Free and Cost-Optimized Approaches

Optimal cell density is also maintained in the production process. Nutrient efficiency is also maintained through recirculation and perfusion-based feeding strategies. This also removes metabolites, thus preventing waste accumulation. Contemporary strategies particularly exploit new sources of amino acids and proteins (botanical, algal, and food-by-product hydrolysates), which are cheap and edible; however, the natural compositional variance requires strict specification requirements. The optimization of downstream processing is attracting significant attention, with media constituents produced to meet regulatory

TABLE 25.2

Key Components of Serum-Free Media

Component	Function in Cell Growth/Differentiation	Typical Concentration	Source	Reference
Amino acids	Protein synthesis, cell proliferation	2–10 mM	Synthetic/microbial	Cedeno, Olubiyo and Ferreira, 2025
Glucose	Energy source, metabolic flux	1–5 g/L	Synthetic	Djisalov *et al.*, 2021
Lipids	Membrane synthesis, adipogenesis	50–200 µM	Plant/microbial	Sugii *et al.*, 2023
Growth factors (FGF-2, IGF-1)	Proliferation and differentiation signaling	ng–µg/mL	Recombinant	Venkatesan *et al.*, 2022
Trace minerals (Fe, Zn, Se)	Enzyme activity, cell metabolism	µM–mM range	Synthetic/microbial	Lee *et al.*, 2024b

requirements for food-grade production. As a system, the serum-free, cost-efficient media formulations constitute an initial technological platform to support the proposed scalable, ethically responsible, and cost-effective cultured meat product, controlling cell growth and meeting sustainability and safety standards (Table 25.2).

25.2.6 Role of Growth Factors, Nutrients, and Signaling Pathways

During the production of cultured meat, growth factors, nutrients, and intracellular signaling pathways interact synergistically to regulate cellular proliferation, differentiation, and maturation. Growth factors are necessary extracellular cues that affect the lineage characteristics of somatic cells. An example is fibroblast growth factor, which promotes proliferation and inhibits premature differentiation of myogenic progenitors, such as satellite cells and myoblasts. In comparison, insulin-like growth factor-1 stimulates downstream ERK signal transduction networks like PI3K-Akt and MAP kinase to stimulate protein synthesis, induce incipient tube thickening, and myoblast fusion (Lesort and Johnson, 2000). Few cells are stimulated by c-Met. C-Met has better hepatocyte growth factor. TGF-beta plays a crucial role in this case, allowing balanced proliferation and differentiation.

Intracellular signaling pathways mediate biochemical stimuli to generate integrated cell responses. The mammalian target of rapamycin (mTOR) plays a pivotal role in the regulation of the anabolic growth and the maturation of myogenic processes (Khalil *et al.*, 2023). The Wnt and Notch signaling cascades mediate the maintenance of stemness as well as lineage commitment and self-renewal of satellite cells (Tsivitse, 2010). Energy status and metabolic adjustment in high-density cultures are mediated by AMP-activated protein kinase (AMPK). Precise modulation of these pathways requires minute control over media composition and the controlled delivery of growth factors to achieve physiologically relevant tissue formation at appropriate dosages. By combining superior external signaling quality and nutrient-optimized conditions, it is possible to design cultured meat systems that allow robust proliferation and produce living, structured, and functional biomass at scale.

25.3 Process Engineering and Quality Optimization

25.3.1 Tissue Structuring: Myofiber Alignment and Vascularization Strategies

Tissue structuring has a key role in the formation of cultured meat products with anisotropic design, mechanical properties, and functional characteristics similar to those in live muscle tissue. Achieving this organization in vitro depends on biophysical and biochemical cues that drive myogenic cell elongation and alignment. Aligned scaffolds produced by electrospinning, microgrooving, or 3D printing favor parenchymal scaffolds and substrates with variable stiffness (Do *et al.*, 2015). As they are adjusted to

physiological values, they favor cytoskeletal structuring and myotube fusion. Mechanical stimulation, like cyclic stretch, tension activates mechanical transduction pathways that include integrins, focal adhesion kinases, and yes-associated protein (YAP) and transcriptional coactivator with PDZ-binding motif (TAZ) signaling (Zhao *et al*., 2022). They lead to better assembly of the sarcomeres and maturation of the fibers. Electrical stimulation can also enhance myofiber contractility and metabolic competition, advancing toward more physiologically relevant muscle tissue.

Vascularization approaches address one of the key challenges in the fabrication of thick or structured cultured meat that is impaired oxygen and nutrient diffusion. In native muscle, the capillaries are near the connecting fibers because of the high metabolic requirement. To recreate the above, engineered tissues use artificial perfusable microchannels, sacrificial templating, or bioprinted vascular-like networks to promote mass transport. Coculturing of myogenic cells with endothelial cells enables the self-organization of microvascular structures in response to stimuli from angiogenic signaling pathways, such as the vascular endothelial growth factor (VEGF)–vascular endothelial growth factor receptor (VEGFR) and notch-delta-like protein 4 (Dll4) pathways (Kim and Kim, 2023). Perfusion bioreactors are a complementary approach that allows nutrients and waste to flow in a controlled manner, eliminating hypoxic zones and making thicker structures more feasible. Emerging edible biomaterials and tissue assembly methods based on vascular structures are also targeted to integrate vascular channels into the final integrated product. Together, myofiber alignment and vascularization strategies can be combined to create the structure and physiology needed to develop cultured meat optimized for texture, functionality, and scalability, bringing the realization of routine cultured meat production one step closer to the routine production of conventional animal tissue (Gu *et al*., 2025).

25.3.2 Texture and Palatability Engineering through Biomechanical Stimulation

Texture and palatability engineering through biomechanical stimulation is directed at reproducing the mechanical, structural, and sensory properties of conventional meat by modulating cellular behaviour and tissue maturation during the fabrication of cultured meat. Skeletal muscle development in vivo is affected by mechanical loading in real time, and recreating these cues in in vitro systems activates mechanotransducive pathways, leading to increased myofiber organization, sarcomere formation, and extracellular matrix deposition. Cyclic stretching, tension loading, and controlled compression stimulate the activation of signaling pathways mediated by integrins such as focal adhesion kinase, RhoA-ROCK, and YAP/TAZ (Cai, Wang and Meng, 2021). RhoA-ROCK and YAP/TAZ contribute to cytoskeletal alignment, enhanced protein accretion, and enhanced contractile functionality (Baiyao *et al*., 2012). The use of biomechanical cues significantly enhances the development of denser, more mature myotubes. Consequently, it endows the developed muscle in culture with greater tensile strength—an effect which explains the firmness and fibrousness always seen in animal-derived muscle tissues.

Adjusting the microarchitectural structure of muscle fat is accomplished by biophysical stimulation. Mechanical loading gives advantages of better synthesis of extracellular matrix, modulates the kinetics of collagen cross-linking, maintains the water-binding capacity of tissues, and controls indispensable sensory properties. Scientists can make an environment inhabited by cocultures. Introducing dynamic strain helps the arrangement of deposition of intramuscular fat in an ordered manner, which is necessary for the release of components giving good sensory appeal. The interaction of mechanical and electrical components also facilitates better sensory properties. Overall, biomechanical stimulation offers an important engineering approach for producing cultured meat with the desired texture and sensory quality by enabling tissue maturation under controlled, reproducible conditions.

25.3.3 Nutritional Profile Modulation via Metabolic Engineering

Pharmaceutical modulation of cells is used to improve the health value and functional characteristics of cultured meat by precisely controlling cellular metabolic pathways and biochemical constituents. Muscle and adipose cells can be manipulated to achieve ideal amino acid levels, lipid profiles, micronutrient levels, and bioactive components that may improve both the nutritional quality and the health of consumers (Song, Lv and Guo, 2025). Modulation of critical regulators of protein synthesis, including mTOR

and autophagy regulators such as RNA-directed protein kinase (AMPK), can enhance the deposition of essential amino acids and overall protein synthesis. Pathways involved in adipogenesis can be targeted, for example, by activating the peroxisome proliferator-activated receptors (PPAR genes) and SREBP1 (Wu, Puigserver and Spiegelman, 1999). They can increase only those types of fatty acids that are desirable, for example, omega-3 and omega-6 fatty acids, polyunsaturated fat, as well as decrease the accumulation of saturated fat. These modifications can result in healthier fat compositions than those in conventional meat, with only slight alterations to sensory characteristics. The biomass growth yield equation (Equation 25.2) quantifies how metabolic processes affect nutrient utilization. The equation is given as follows:

$$Y_{X/S} = \frac{\Delta X}{\Delta S} \tag{25.2}$$

where

$Y_{X/S}$ is the biomass yield coefficient,

ΔS is the substrate consumed, and

ΔX is the increase in cell mass.

25.3.4 Integration of Fat Cells and Marbling for Organoleptic Quality

Integrating adipocytes that successfully altered is not only an option for recreating the conventional meat, but also a primary prerequisite for reproducing the organoleptic attributes of the product, flavor release, juiciness and tenderness, as well as overall mouthfeel. The phenomenon of intramuscular fat deposition stems from the topological structure of the lipid-laden cells interspersed among muscle cell fibers. In the desired cultured meat, it is essential to carefully coordinate the developmental trajectories of the myogenic and adipogenic lineages, as they form the skeleton of the myriads of structural and functional units that comprise this synthetic tissue. Adipogenic differentiation can be induced from mesenchymal stem cells or induced pluripotent stem cells by activating PPPA and C-enhancer-binding protein alpha (C/EBPα) signaling pathways (Muruganandan, Roman and Sinal, 2009). These pathways are involved in the formation of stable intramuscular adipose reserves with characteristics of mature muscle fat stores.

The engineering of marbling further requires precise control over adipocyte morphology, lipid composition, and their integration with the surrounding myofibers. Scaffold designs that spatially control the level and the distribution of various growth factors, and are engineered to contain concentration gradients, can enable the patterning of adipocyte distribution in these aligned muscle constructs, allowing the generation of discrete marbling objectives. Moreover, advances in bioprinting technologies offer an opportunity to align adipogenic and myogenic bioinks in space with high precision, thereby enabling organoleptic refinement of the final product. The biochemical environment that includes selection of precursors of lipids and fatty acid supplementation can be tailored for the modulation of the saturation profile and the promotion of the formation of precursors for flavor compounds, and simultaneously for oxidative stability (Musakhanian, Rodier and Dave, 2022). Coculture systems help harness cross-linking between muscle and fat cells in cellular culture. At the same time, adipokines and myokines exert a synergistic effect on maturation at both ends, helping to define the appropriate sequence of structures needed to achieve real tissue texture (de Oliveira dos Santos *et al.*, 2021).

The physiological relevance of the engineered marbling has significantly improved sensory desirability by reducing toughness (due to lipid lubrication), juiciness (due to controlled fat melting during thermal processing), and flavor (due to increased volatile compound generation). Consequently, the efficient integration of fat tissue into cultured muscle is one of the most important technological advancements in cultured meat production, enabling it to match or exceed the organoleptic properties of traditional meat cuts.

25.3.5 Process Monitoring: Real-Time Sensors, AI, and Automation

Using more advanced sensor technologies, continuous, noninvasive measurement of important physicochemical and biological parameters is now available, including dissolved oxygen concentration, pH, temperature, glucose concentration, lactate or ammonia concentration, and biomass concentration.

Optical and electrochemical probes, when combined with dielectric spectroscopy, provide high-resolution information on viability, metabolic states, and media composition without disturbing the culture environment (Downey *et al.*, 2014).

Artificial intelligence (AI) is used to support process supervision by interpreting complex multivariate data streams generated during bioreactor operation. Machine learning (ML) can assist with the most suitable growth paths and problems associated with initial cellular development. It further facilitates adjustments that are required over time. Predictive modeling frameworks are used to predict cellular responses that are made due to changes in the environment. These models help to make the best decision on feed rates, agitation, and oxygen transfer strategies. Real-time sensing assisted by AI-driven analytics in cultured meat production is a classic example of such research in the market, incorporating predictive modeling (Todhunter *et al.*, 2024). Automatic systems, mechanical or electrical stimulation, also allow control of gas. It serves an advantage to reduce human variability and improve consistency. Other factors facilitating higher production are advanced cell-line management, scaffold-handling technology, and input analysis modules.

25.4 Environmental and Sustainability Assessment

25.4.1 Life Cycle Assessment (LCA) of Cultured Meat Production

This evaluation considers all the key life cycle steps, including the acquisition of cellular feedstocks, media formulations, the preparatory phase, through the bioreactor operations, which are the heart of the manufacturing step, downstream processing and recovery, etc. (Kumar and Verma, 2021). The most important key performance indicators, such as energy requirement, greenhouse gas emission, water usage, land usage, and resource intensity, are assessed and compared to the livestock production systems that systematically follow conventional production methods. The comparison analysis in Table 25.3 shows that the most important environmental hotspots are critical, and that it is necessary to develop specific mitigation measures to reduce the ecological footprint of cultured meat. Carbon footprints per unit of generated protein are calculated in Equation 25.3.

Carbon footprints per unit of protein-standard metric in LCA studies:

$$\mathrm{CF} = \frac{i\left(Ei * GWPi\right)}{P} \tag{25.3}$$

where

E_i is energy or material input,

$GWPi$ is the global warming potential, and

P is the mass of protein produced.

TABLE 25.3

Environmental Impact of Cultured versus Conventional Meat

Protein Source	GHG Emissions (kg CO_2-equiv/kg Protein)	Water Footprint (L/kg Protein)	Land Use (m^2/kg Protein)	Energy Consumption (MJ/kg Protein)	References
Cultured meat (lab-scale)	10–30	1,000–3,000	1–3	50–150	Raihan, 2023
Beef	60–120	15,000–20,000	20–50	60–120	Ouatahar *et al.*, 2021
Pork	7–15	5,000–6,000	4–6	30–50	Jeong and Kim, 2023
Poultry	4–6	4,000–5,000	3–5	20–40	Kang *et al.*, 2025; Vergé *et al.*, 2009

Cultured meat systems generally show substantial reductions in potential land use and eutrophication due to the lack of feed crops, grazing, and manure management, with more varied outcomes in terms of energy consumption due to the intensive requirements for bioreactors, media production, and process-controlled environments (Xie *et al.*, 2025).

A critical determinant of LCA outcomes is the formulation of growth media, since recombinant growth factors, amino acids, and nutrient concentrates can also impose substantial cumulative energy demand and greenhouse gas emissions if produced by energy-intensive biotechnological processes. Optimization of media composition, the use of components from food-grade or agricultural by-products, and large-scale recombinant production platforms can significantly lessen this burden. Bioreactor operation is another significant factor, due to electricity consumption for temperature control, agitation, aeration, and perfusion; hence, the LCA results are not susceptible to the carbon intensity of regional energy grids or to the costs of bioprocess design efficiency. LCA is a very important tool that paves science by focusing on maximum sustainability. It provides quantitative standards to confirm that cultured meat has the potential to deliver on its claim as a lower-impact alternative to traditional meat production.

25.4.2 Energy, Water, and Land Footprint Compared to Conventional Meat

The energy, water, and land footprint of cultured meat differs significantly from that of conventional animal agriculture because biological growth cycles are replaced with controlled bioprocessing systems. Land use is significantly reduced, as in the production of cultured meat; there are no grazing areas, no feed crops, and no manure management infrastructure required (Karlsson and Röös, 2019). This avoids large-scale deforestation and habitat conversion associated with livestock systems and concentrates production in compact, vertically integrated facilities with minimal spatial requirements. Water use is also far lower, as the production of cultured meat avoids the need to irrigate crops and use drinking water, and instead relies primarily on process water for media preparation and equipment cleaning. In cases of sourcing media components from plant hydrolysates or food by-products, water intensity is lower than for inputs based, for example, on livestock or high-resource feed crops (Figure 25.2).

The picture of energy use is more complicated. While cultured meat is exempt from the energy-intensive stages of feed production, animal husbandry, slaughter, and the cold-chain transport of the carcass, culturing the meat introduces new requirements for bioreactor operation, temperature and oxygen level control, sterile processing, and the production of defined media constituents. These energy demands can be as great as those of poultry or pork if systems are inefficient or require high levels of recombinant growth factors produced through risky fermentation that consumes a lot of energy. However, energy intensity is expected to decline significantly through scale-up, process intensification, and the integration of renewable energy sources. Efficient bioreactor designs, enhanced oxygen transfer, heat recovery systems, and cost-optimized media can help reduce the differences between cultured meat and conventional meat, particularly compared with ruminant livestock, which have high GHG emissions and low feed conversion efficiency.

25.4.3 Waste Valorization and Circular Bioeconomy Integration

Waste valorization and integration into a circular bioeconomy are becoming increasingly important for improving the sustainability of cultured meat production by minimizing resource losses and converting process by-products into valuable inputs. Cultured meat systems generate waste streams from wasted growth media, cellular metabolites, and scaffold residues, mostly during equipment cleaning steps. These outputs include organic compounds, amino acids, salts, and small amounts of biomass that can be recovered from the mixture using filtration, membrane separation, or classical chromatography methods for use in upstream processes. Recycling media components, mainly amino acids and vitamins, reduces the environmental burden associated with de novo synthesis and lowers overall production costs (Tanaka *et al.*, 2024). Metabolic profiling of previously used media can aid in developing more targeted recovery strategies to support product recovery and to help identify chemically stable components that can be reused in subsequent culture passes.

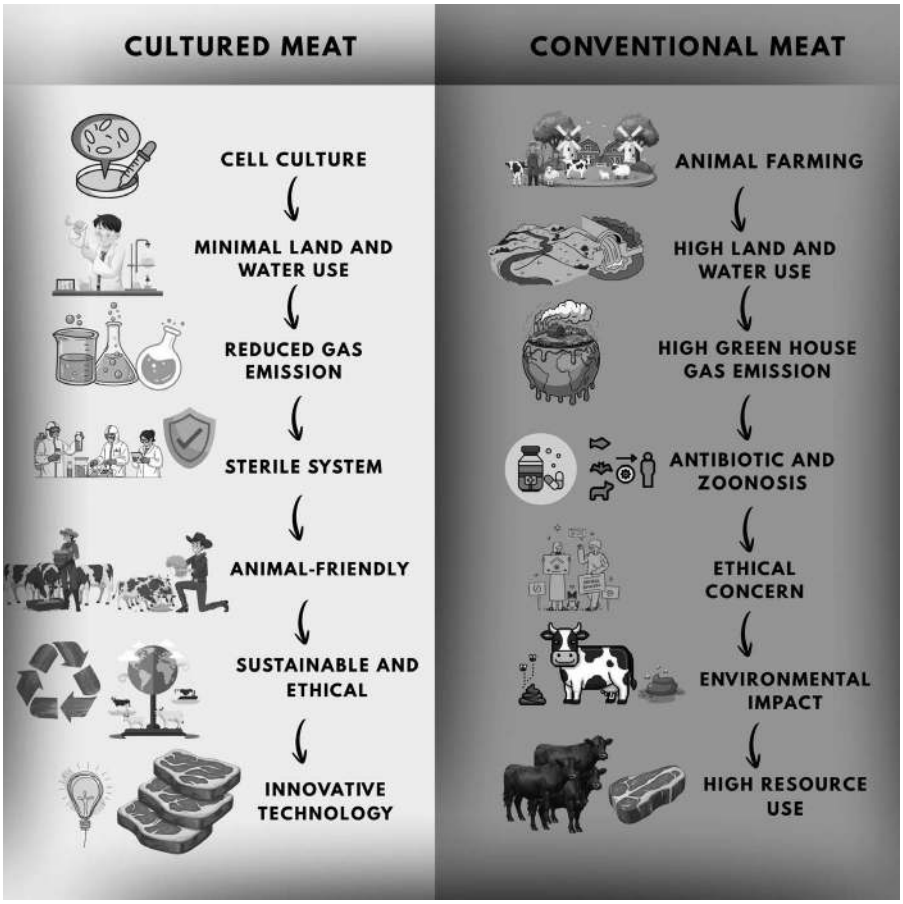

FIGURE 25.2 Cultured versus conventional meat.

Process residues are also a potential feedstock for other biotechnology sectors. Biomass-rich waste is directed to anaerobic digestion for biogas production, reducing the facility's energy requirements and enabling closed-loop energy use. Alternatively, these streams can serve as substrates for microbial fermentation processes to produce enzymes, pigments, or single-cell proteins, further strengthening the interconnectivity of bioindustrial platforms. Edible or biodegradable scaffold material made from plant, algal, or mycelial proteins also ensures high circularity, as nonrecoverable waste is minimized, and it allows compostability or reprocessing (Vargas-Ovalle and Demitri, 2025).

Integration into a wider circular bioeconomy involves designing cultured meat plants to fit within the industrial ecology principle, in which waste flows from one process to another. Colocation of solar, wind, bio, and other renewable energy sources, sites for nutrient cycling, allows for synergy in resource flows and transport-related emissions. With the right waste valorization and circular design, culture's meat production would shift from a linear resource-consuming production system to one that is more regenerative and as efficient as possible, with much less climate impact and a more sustainable system in the long term.

25.4.4 Carbon-Neutrality Pathways in Cultured Meat Systems

Achieving carbon neutrality for cultured meat systems requires a holistic approach that accounts for greenhouse gas emissions across the product's life cycle, from sourcing cells and producing media to

running the bioreactor and processing the final product. Most sources of carbon in bioprocessing rely on energy-intensive processes, including maintaining controlled bioreactor conditions, thermal control, aeration procedures, the manufacture of growth factors, and the development of specified media constituents. The mitigation policies include increasing energy efficiency through the use of advanced bioreactor platforms and the installation of low-shear agitation (LSA) systems, minimizing oxygen transfer, and reducing unnecessary metabolite release (Pajčin *et al.*, 2022). This is accomplished by replacing plant-based nutrient substrates and recycled reagents.

Incorporation of renewable energy systems, such as solar arrays powered by photovoltaic sources, wind systems, and bioproduct processing facilities that generate bioelectric energy, provides a feasible route to reducing the carbon emission of bio-processing facilities (Jahir *et al.*, 2023). Coupling energy-efficient systems with real-time monitoring/automated process control can dynamically adjust operating parameters to avoid excess energy use while maintaining optimal conditions for cellular growth and differentiation. Further contributions to net-zero carbon results are made by life cycle-level interventions, including the reuse of spent media, the valorization of biomass residuals for biogas or biofertilizers, and modular production architectures with minimized material and transport requirements.

Carbon neutrality is also possible through supporting carbon offset strategies: using regenerative agriculture, afforestation, or even onsite carbon capture and utilization technologies. By combining the potentials of energy optimization, renewable integration, waste valorization, and life cycle management, the dependence of a culled meat industry on these potentials can be redirected toward low-emission, climate-resilient protein systems that offer a low-volume option to the regular meat industry and can also underpin an Indo-European strategy.

25.5 Safety, Quality, and Regulatory Perspectives

25.5.1 Microbiological Safety and Contamination Control, and Compositional Characterization

Microbiological safety is critical in meat production, as the nutrient-rich, aqueous nature of cell culture allows pathogens to multiply rapidly if contaminants are present. Cultures are maintained in sterile conditions in closed bioreactor systems by closely monitoring the air, media, and equipment to prevent the intrusion of bacteria, fungi, and viruses (Cai *et al.*, 2024). Continuous monitoring provided by rapid microbial detection systems, combined with real-time pH, dissolved oxygen, and metabolic by-product monitors, enables early detection of deviations that may indicate contamination. Reduction of pathogens is crucial, and prevention is achieved by the combined use of aseptic processing, automated handling, and validated sterilization protocols.

25.5.2 Regulatory Frameworks: Global Landscape

The dual role played by USDA protects bioprocess integrity and ensures the superior quality of the product. Risk analysis is done with a key focus on cell line characterization, growth media formulations, microbial safety, and possible allergen risks (Boesenberg *et al.*, 2025). In this way, proper traceability and process control is achieved.

For countries following EU rules, they must comply with the "novel foods" category. Countries have to submit a dossier to the European Food Safety Authority (EFSA) on the safety of cultured meat (Authority *et al.*, 2024). Such a dossier includes compositional information, toxicological evaluation, Allergenicity profiles, extensive descriptions of the production procedures, issues of risk, consumer protection, and transparency. The Singapore Food Agency (SFA) has granted clearance for the commercial sale of cultivated meat (Johnson and Monaco, 2025; Liang and Lee, 2022). Before issuance clearance, safety standards, the food's amino acid composition, production process, and nutritional profile were tested several times. Other countries are also in line for global harmonization of safety assessment, labeling, and quality standards.

25.5.3 Standardization of Analytical and Quality Parameters

Many challenges surround the need to standardize analytical and quality parameters. They must be standardized to comply with industry standards, ensure consumer safety, and secure market acceptance of cultured meat. Researchers obtain results through consistent measurements of nutritional and functional quality properties. Monitoring of these parameters ultimately influences texture, marbling, and palatability. Microbial screening, sterility assays, and allergenicity tests form the foundation of an adequate safety evaluation framework. Regulatory approval is another objective after which the industries run. Regulatory compliance requires validation, which ensures product uniformity across disparate production sites. Standardization of the process enables optimization of variables related to process control, bioreactor performance, and media composition. In this way, targeted results are achieved and expressed in terms of process reliability, product quality, and consumer confidence. Collectively, analytical and quality standards prove to be a source of reliable, reproducible, and safe production of cultural meat products.

25.6 Economic Viability and Market Integration

25.6.1 Cost Drivers and Economies with Supply Chain Engineering for Cultured Meat Ingredients

Cost drivers in cultured meat production are mainly related to sourcing cells, growth medium components, bioreactor operation, scaffold materials, and downstream processing. Growth media, particularly recombinant growth factors, amino acids, and serum-free supplements, account for a high percentage of production costs (Quek *et al*., 2024). In contrast, energy costs for bioreactor temperature control, oxygenation, and agitation of the growth media also add to operational costs (Humbird, 2021). As with structured products, scaffold manufacturing and quality control testing are additional economic burdens. All of these variables agree to become the baseline cost profile for cultured meat and scale-down strategies.

However, economies of scale up can enable significant reductions in per unit production costs through higher cell density, bioreactor design, and continuous or perfusion-based culture systems, thereby maximizing nutrient use and minimizing media turnover (Wang *et al*., 2025). High-density cultures and modular, parallelized arrays of bioreactors can be scaled up to a larger production volume, enabling process intensification capabilities (e.g., automated feeding, in-line monitoring, and controlled differentiation processes) for enhanced efficiency and reproducibility. Media optimization can be employed to optimize ingredient costs further while still preserving the cellular performance using either hydrolysates of plant-based proteins or growth factors from microorganisms (Hadi and Brightwell, 2021).

Supply chain engineering integrates the sourcing of raw materials, logistics, and waste valorization to create a more cost-effective and sustainable supply chain. The centralized production of recombinant growth factors, the separation of nutrient streams from plants, and the colocation with renewable energy or biomass processing hubs minimize transport and energy costs. New concept of recycling of used media and the valorization of by-products ensures economic feasibility and sustainability. These strategies facilitate acceptance of cultured meat by highlighting the quality, safety, and sustainability of the products.

25.6.2 Market Adoption Scenarios and Consumer Perception

Technological maturity of manufacturing networks, cost-competitive economics, strong regulatory alignment, and alignment with consumer values are key factors kept in mind to facilitate the commercial uptake of cultured meat to commercial uptake. These factors ensure sustainability, animal welfare, and food safety. The initial effort to make cultured meat more acceptable is to upscale a few segments by supplementing with premium cultured bovine and fish products. Customers then willingly pay for perceived premium attributes. To further increase production lines, it is best to cut costs through media utilization, process intensification, elimination of unjustified sourcing channels, and the strict preservation of product quality. Current market price analysis shows that cultured meat is more expensive than traditional meat (Garrison, Biermacher and Brorsen, 2022).

Customer perception is very important for the acceptability of cultured meat. This trust of the customer is influenced by awareness, trust, and reading frameworks. Customers also face problems with production technology, labeling, safety, and the nutritional profile of meat. It is a general finding of several surveys that familiarity with the need for cultured meat, used culture, and perceived naturalness play a significant role in shaping consumer acceptance. Customers who are more environmentally conscious, younger, and inhabitants of urban areas exhibit higher acceptance rates toward cultured meat. If a product is regulated, customers may be ready to consume it.

25.6.3 Positioning Cultured Meat in Sustainable Meat Markets

Cultured meat is more sustainable than traditional meat. It offers a better environmental footprint, mitigating ecological harms and meeting contemporary societal pressures regarding ethics and welfare (Hedberg, 2022; Rodríguez Escobar *et al.*, 2021). Cultured meat is better in terms of land usage, water efficiency, and reductions in greenhouse gas emissions (Alexander *et al.*, 2017). It also addresses animal welfare, the spread of zoonotic diseases, and the use of antimicrobials. All of these factors influence customers to buy cultured meat.

Functional and nutritional parameters of cultured meat represent variability. The ability to alter fatty acid profiles, increase micronutrient content, and engineer texture properties of cultured meat enables customers to buy a product that is healthy, has better sensory properties, and enforces the concept of sustainability. Integration into modern supply chains that provide sustainable meat requires compliance with distribution, labeling, and marketing requirements, the most relevant of which is the need to demonstrate environmental and ethical advantages without sacrificing sensory properties (Post *et al.*, 2020). By highlighting both the environmental virtues and the equality, or in some ways, the excellence of cultured meat in comparison with traditional options, a particular niche will be cut in sustainable protein collections, thus leading to consumer acceptance and stimulating the long-term market development.

25.7 Societal and Ethical Considerations

25.7.1 Ethical Implications, Animal Welfare, Public Trust, Cultural Acceptance, and Religious Perspectives

Cultured meat has significant ethical benefits, as it will reduce the scale of animal slaughter to obtain food (Chriki, Ellies-Oury and Hocquette, 2022). The pain and stress suffered by donor animals due to the sourcing of satellite cells and stem cell lines through minimally invasive and nonlethal biopsies is significantly reduced, and the removal of intensive mainstream farming puts a heavy burden on the environment and the welfare of animals. In turn, cultured meat is a more ethical option that aligns with the principles of humane and sustainable food systems.

The development of meat-like products presupposes the consideration of numerous factors before they can receive universal cultural approval and the trust of the community. Transparency is a term used in the manufacturing process. It is essential to conduct safety verification and show the nutritional and sensory profile of cultured meat (Ong *et al.*, 2021). Transparency is thus useful for customers. Acceptance is also affected by sensory attributes and the culinary applications of meat. For reducing skepticism and increasing acceptance, it is essential to give education, better sensory properties, and proper labeling.

Cultured meat also faces market incursion because of religious and ethical dogmas (Bryant, 2020). Cellular matrix determines the status of kosher, halal, and vegetarian. High care is taken to select the cellular source and the composition of the culture medium. Heterogeneity of faiths underscores the need for a certification mechanism for global acceptability of cultured meat.

25.7.2 Equity in Access: Cultured Meat for Food Security

In this world full of different meat sources, cultured meat provides an opportunity to grow. In cultured meat, it is possible to produce animal protein in a scalable, tightly controled, and highly efficient way;

the positive impacts induced are reducing the land, water, and other ancillary resources (Risner *et al.*, 2025). Traditional meat is totally the inverse of this type of meat. It is very useful in areas with severely restricted protein intake, extremely high urban population density, or climates unfavorable to traditional animal husbandry. By reducing dependence on climate, cultured meat is helping reliability in the food supply chain (Stephens *et al.* (2018). This helps to ensure protein availability.

As the technology is still in laboratory scale, its cost is high. It is projected to fall as unit cost declines. Its decline is influenced by protocol optimization, economies of scale, and the development of cost-saving media formulations. Relevant research, focused investment, and continuous optimization pathways may play a role in reducing cost. By partnering with locals, offer opportunities to overcome significant logistical and infrastructural barriers. Decentralized production designs and modular bioreactors are other points at which collaboration could be done.

Nutritionally, cultured meat can be designed to meet the dietary needs of a local area, for example, by enhancing essential amino acids, micronutrients, or favorable fatty acid ratios to improve health (Demarquoy, 2025; Kardas, Staśkiewicz-Bartecka and Kołodziejczyk, 2025). When executed within proper, transparent regulatory frameworks, ethical sourcing procedures, and culturally appropriate product development, cultured meat can be a valuable tool for protecting protein security, promoting equitable nutrition, and advancing sustainable food systems around the world.

25.8 Challenges and Future Research Directions

25.8.1 Technical Barriers in Large-Scale Production and Innovations in Cell Line Engineering and Genome Editing

Large-scale manufacturing of cultivated meat is still confronted with several technical challenges related to cell proliferation, tissue differentiation, and tissue maturation at industrial-scale production volumes. Key issues include stable maintenance of phenotypes and genetic features over extended periods of culture, successful delivery of nutrients and oxygen to dense three-dimensional constructs, and prevention of contamination in high-volume bioreactors (Jaime-Rodríguez *et al.*, 2023; Rahman *et al.*, 2025). Scaffold fabrication and microenvironment control, however, become outpaced as tissue thickness and structural fidelity increase; this, coupled with the high cost and scarcity of growth factors and defined medium, brings scaling to a standstill. Process monitoring, automation, and bioreactor design must be carefully engineered to ensure reproducible culture conditions from batch to batch in large-scale operations.

Innovations in cell line engineering help overcome some of these needs by developing cells with improved proliferative potential, longevity, and stable differentiation. Immortalized satellite cells/myoblasts result from manipulation of stem cell biology. Keeping telomerase expression under control or the cell cycle regulated leads to a minimization of animal biopsies and an increase in production efficiency. Genome-editing technologies, including recombinant Cas9 nuclease and guide RNA sequences, provide the possibility to fine-tune metabolic pathways, growth factor dependence, and to optimize nutrient usage, thus allowing cellular growth at low cost, serum-free culture conditions (Tavakoli *et al.*, 2021). These strategies also allow adjustment of nutritional characteristics, fat accumulation, and structural protein production, thereby improving the scalability and quality of the products.

Advancements in cell line engineering and genome editing constitute a foundation for moving beyond the challenges in biological and engineering processes to achieve production of cultured meats at large scales, so that ultimately reliable, reproducible, and economically viable production processes could be developed, without compromising safety, nutritional value, or taste of the product.

25.8.2 Role in Future Hybrid Meat Systems and Personalized Nutrition

Precision fermentation is a process that can be employed to manufacture important proteins cost-effectively, such as recombinant albumin, growth-promoting, and functional biomolecules between structural proteins, with less dependence on expensive animal-derived media components, thereby maximizing the scale and scope of studies. These bio-produced ingredients can be optimally designed to support cell proliferation, differentiation, and tissue maturation.

3D bioprinting provides spatial control over tissue architecture, enabling the deposition of myogenic, adipogenic, and stromal cells within edible scaffolds to recreate muscle fiber alignment, marbling, and organoleptic structure (Zo *et al*., 2025). Layer-by-layer bioprinting enables the creation of complex geometries, loading of vascular-like conduits, and precise spatial organization of heterogeneous cellular aggregates. Precision fermentation and 3D bioprinting are beneficial for augmenting operational efficiency and resource optimization (Pereira *et al*., 2025). These may also produce viable, scalable, and consumer-accepted protein sources. By incorporating bioactive compounds in tissue construct engineering, scientists can achieve commercial-scale, high-quality protein.

25.9 Conclusion

Cultured meat has emerged as a sustainable source of meat. It combines cellular agriculture, bioreactor design, scaffolds, and metabolic engineering. These techniques help to produce high-quality meat. Traditional meat faces challenges of cellular agriculture, bioreactor design, scaffolds, and metabolic engineering. In this case, cultured meat proves an option to customize nutritional profiles and ultimately integrate into hybrid and personalized dietary systems.

Although a lot of research is done on cultured meat, it is facing difficulty in scaling up the technology due to technical, economic, and legislative challenges. High cost is also a problem, especially the high cost of culture media. Societal apprehension is also inhibiting market penetration. To move forward, research in domains like cell lines, genome editing, controlled fermentation, and three-dimensional bioprinting is required.

Overall, cultured meat is a technological innovation providing alternate meat source which advocates sustainability, changing ethics, and customer demands. To make cultured meat more acceptable, technology, the regulatory framework, and existing attitudes must be changed. This may allow cultured meat to make space in the existing meat market.

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26

Meat By-Products: Utilization, Value Addition, and Sustainability

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26.1 Introduction

Meat by-products, often referred to as the "fifth quarter" in the context of red meat processing, encompass all edible and inedible parts of a slaughtered animal other than the dressed carcass (Toldrá *et al*., 2012). The classification of these materials is generally dichotomized into edible and inedible categories, a distinction heavily influenced by cultural norms, regulatory frameworks, and processing capabilities. Edible by-products typically include organs such as the liver, heart, kidneys, tongue, and stomach (tripe), as well as blood and certain fats (Irshad and Sharma, 2015). Conversely, inedible by-products comprise hides, skins, hair, horns, hooves, teeth, and contents of the gastrointestinal tract. However, the boundary between these categories is fluid; advancements in processing technology increasingly allow for the recovery of edible proteins and functional compounds from materials previously deemed inedible waste (Mora, Reig and Toldrá, 2014).

The volume of by-products generated is substantial, often constituting between 60% and 70% of the slaughtered animal's weight depending on the species (Irshad and Sharma, 2015). For instance, in bovine processing, the dressed carcass yield is approximately 50–60%, leaving nearly half of the animal's mass as potential by-product material. This immense volume represents a critical reservoir of biological material that, if mismanaged, becomes a significant environmental liability rather than an economic asset.

The economic implications of by-product utilization are profound. While the primary economic driver of the meat industry remains the sale of muscle meat, the profitability of slaughterhouse operations frequently hinges on the efficient recovery and sale of by-products (Toldrá, Mora and Reig, 2016).The value of the by-products can account for 10–20% of the total value of a beef animal, and even higher proportions in poultry and pork production systems. Failure to valorize these components results in lost revenue and increased disposal costs, which can significantly erode profit margins in an industry characterized by high volumes and low margins.

Environmentally, the meat industry is under increasing scrutiny regarding its ecological footprint, particularly concerning greenhouse gas emissions, water usage, and waste generation (Skunca *et al*., 2018). The disposal of meat processing waste via landfilling or incineration contributes to environmental degradation through the release of methane, a potent greenhouse gas, and the potential leaching of organic pollutants into groundwater systems. Conversely, the conversion of by-products into value-added goods aligns with principles of industrial ecology, reducing the net environmental impact per unit of meat produced (Asem-Hiablie *et al*., 2018).

Sustainability in meat processing is no longer an optional add-on but a fundamental operational imperative. The "circular bioeconomy" framework advocates for the retention of value within the economic cycle for as long as possible, minimizing waste and resource extraction (Maina, Kachrimanidou and Koutinas, 2017). In this context, sustainable meat processing involves optimizing the slaughter process to maximize the recovery of high-quality by-products and employing energy-efficient technologies

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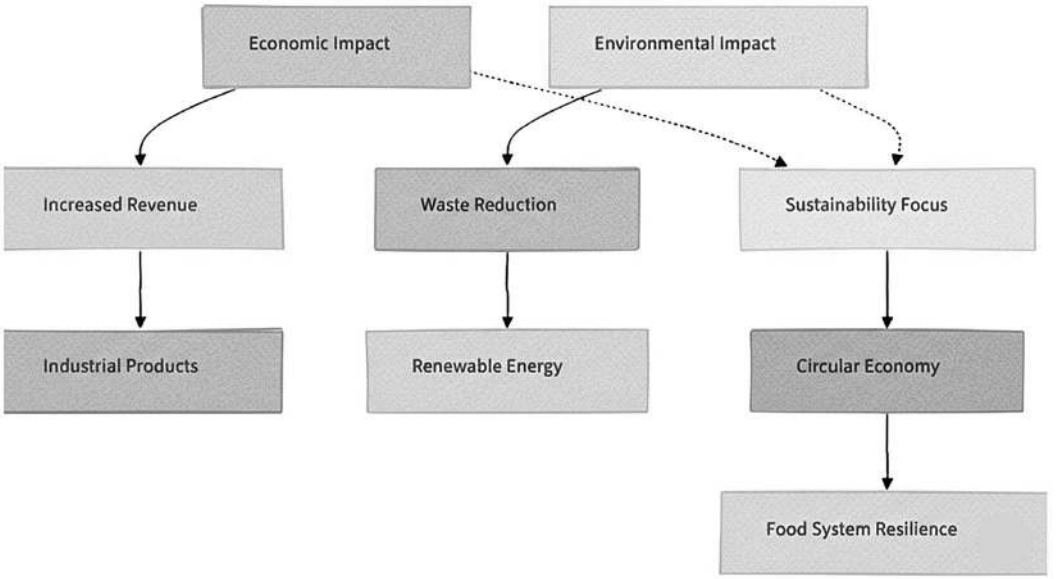

FIGURE 26.1 This flowchart illustrates the key aspects of meat by-product management, showing economic, environmental, and sustainability impacts and their interconnections.

to transform these materials. Integrated sustainability strategies must address not only the environmental metrics but also social dimensions, such as food security—by recovering nutrient-dense edible offal—and economic resilience for producers.

Sustainable practices in meat processing are crucial, aligning with circular economy principles that transform waste into value-added products like fertilizers, biofuels, and bioactive compounds, thereby mitigating environmental impacts and supporting organic farming (Irshad and Sharma, 2015; Jurgilevich *et al*., 2016).

This chapter provides a comprehensive review of meat by-product types from bovine, porcine, and poultry sources, analyzes current utilization practices such as rendering and feed production, and explores emerging technologies like enzymatic hydrolysis for bioactive peptides (Irshad and Sharma, 2015; Verma *et al*., 2025). It further discusses integrating sustainability into the by-product value chain, emphasizing life cycle assessments (LCAs) and closed-loop systems to foster economic viability and ecological balance (Figure 26.1) (Jurgilevich *et al*., 2016; Rao, Bast and de Boer, 2021; Sadhukhan *et al*., 2020).

26.2 Types and Sources of Meat By-Products

Conversion of livestock into meat in abattoirs generates substantial quantities of by-products representing approximately 10–15% of the total value of the live animal in developed countries, although these by-products account for nearly two-thirds of the animal after slaughter (Alao *et al*., 2017). Meat by-products are defined as the non-meat portions of the dressed carcass, also known as "fifth quarter" (Latoch, Stasiak and Siczek, 2024).

26.2.1 Edible By-Products

Meat by-products are classified, based on edibility, into edible and inedible categories, with edible by-products intended for human consumption, whereas inedible by-products are not consumed as food and include all parts of dead animals or condemned meat and organs (Irshad and Sharma, 2015). Depending on cultures and countries, edible by-products may be regarded as delicacies with high market value, or rejected and discarded (Toldrá *et al*., 2012).

From a biological standpoint, most of the non-carcass parts are edible if they are cleaned, handled, and processed properly; however, in developing nations, meat is often maligned as a food for the wealthy due to the low purchasing power of consumers; consequently, most of the soft tissues are utilized for human consumption (Irshad and Sharma, 2015).

Edible by-products, also known as "offal meats", "variety meats", or "organ meats" include the liver, lungs, heart, brain, kidneys, and other organs (Table 26.1) (Latoch, Stasiak and Siczek, 2024). The yield of edible offal depends on several factors, such as sex, species, age, and live weight, ranging from 10% to 30% in cattle, pigs, and lambs and from 5% to 6% in chickens (Toldrá *et al*., 2012). Edible offal is further categorized, based on color, into red offal, comprising the liver, kidneys, spleen, testicles, and heart; white offal, comprising the stomach, lung, sweetbread (thymus or pancreas), intestine, and brain; and dark (or black) offal, which includes the head, neck, feet, trotters, shanks, and oxtail (Latoch, Stasiak and Siczek, 2024).

The nervous system, spinal cord, and brain are not subjected to industrial processing but rather are used directly for human consumption. To maintain the textural properties, they are blanched before cooking. Heart meat is prepared for consumption in two ways: either as a whole heart that is roasted or braised or as sliced heart that is grilled or braised. Kidneys are also prepared, either whole or sliced, after the removal of the ureter and blood vessels, and then grilled or braised. The most widely consumed edible organ is the liver, which is used in the preparation of liver paste, liver sausage, and other processed meat products. Liver can be prepared by boiling, braising, and grilling. Calf, lamb, and pig livers are used in the preparation of processed meat products as stuffed sausages. Veal calves, young cattle, and lamb livers are also popular in Europe and the United States due to their unique texture and flavor (Rahman, Sahar and Khan, 2014).

TABLE 26.1

Potential Application, Storage, and Preparation of Meat By-Products

Meat Kind	Preparation and Storage	How It is Used
Kidney	Ground, sliced, or whole Refrigerated or fresh	Cooked in liquid, broiled, braised, in soup, in stew, grilled
Liver	Fresh, refrigerated, or frozen	Fried, broiled, in loaf, braised, patty, sausage
Heart	Sliced, whole Fresh, refrigerated, or frozen	Patty, loaf, luncheon, cooked in liquid, braised
Tongue	Whole Fresh, refrigerated, or frozen	Cured, cooked in liquid, sausage casing, sausage ingredient
Brains	Whole or sliced	Braised, broiled, cooked in liquid, poached, scrambled, sausage ingredient
Stomach	Fresh, refrigerated, smoked, and pickled	Sausage ingredient, sausage casing, cooked in liquid, broiled
Tail	Fresh, refrigerated, or frozen	Cooked in salty liquid
Spleen	Fresh, refrigerated, and precooked	Fried, in pies, in blood sausage
Intestines (small and large)	Whole, fresh, refrigerated, or frozen Remove fecal matter, soak, wash and add salt before use	Sausage casing
Head and cheek trimmings	Fresh, refrigerated, or frozen	Cooked sausage
Skin	Fresh or refrigerated	Gelatin
Ear		Smoked and salted, stewed with feet
Feet	Fresh, refrigerated or frozen	Jelly, pickled, cooked in liquid, boiled, fried
Fat	Fresh, refrigerated, or frozen	Shortening, lard, tallow
Bone	Fresh, refrigerated, or frozen	Soup, gelatin, rendered shortening, mechanically deboned tissue, jellied products
Blood	Refrigerated or frozen	Black pudding, sausage, blood and barley loaf

Intestines are used in the preparation of different products after being boiled as fertilizers, tallow, meat meals, and pet food, but their primary use remains as sausage casings. Intestines are very delicate and heavily contaminated when removed from the carcass. For us in sausage production, they are cleaned immediately after slaughter and separation from the carcass. During processing, the ruffle fat is removed, and the fecal matter is thoroughly eliminated. Although this practice is not commonly applied today, fermentation was traditionally used. All blood vessels and fibrous tissues are removed, and the inner mucous membrane is separated from the casing. Finally, the intestines are soaked in salt and packaged (Jayathilakan *et al*., 2011).

Consumption levels and consumer preferences for edible by-products have been widely investigated; however, the results remain inconclusive and fragmented. Economic, cultural, social, and religious. These factors play a crucial role in shaping consumer behavior in each region. In some parts of the world, edible by-products are considered gourmet items, whereas in other regions they are considered inedible. The use of edible offal for nutritive purposes is unstable and has a strong impact on the status of the livestock sector. Consequently, the range of offal products is much narrower compared to that of meat products (Latoch, Stasiak and Siczek, 2024).

There is a remarkable diversity in the global consumption of edible by-products, and which is influenced by the growing demand for ready-to-use products, dietary changes, health concerns, the accumulation of heavy metals, societal and demographic factors, dietary neophobia, and the availability of raw materials. While health, sensory, and nutritional characteristics represent primary criteria in food selection, economic and cultural factors such as norms, societal traditions, and customs together with social influences, including consumer attitudes and beliefs, also play a significant role in shaping decisions related to offal consumption. Offal tends to have a negative image, that can influence consumers' emotions and behavior. Furthermore, food neophobia can directly affect consumers' willingness to consume offal and has been reported to have negative impact on the intention to eat them (Latoch, Stasiak and Siczek, 2024).

Offal is highly popular and has a long history of culinary use in Asia. Traditional dishes in countries such as Vietnam, China, and Thailand often incorporate offal with widespread consumer acceptance fostered by cultural appreciation. The growing urbanization and expanding middle-class population in Asia have increased the demand for value-added and processed products derived from by-products, such as gelatin and collagen, particularly for the health and beauty industries (Bou *et al*., 2025).

In Europe, there has been a shift in societal preferences toward meat cuts, leading to a decline in offal consumption over the years. Nevertheless, offal continues to hold culinary value in traditional dishes, such as foie gras in France, haggis in Scotland, and pork feet and tripe dishes in Italy and Spain. In recent years, due to the growing focus on food waste reduction and sustainability, there has been a renewed interest in offal, particularly among younger consumers who embrace "nose-to-tail" eating as an integral part of sustainable gastronomy (Bou *et al*., 2025).

Despite its bitter aftertaste, mildly metallic taste, and soft texture, which may be unpalatable to some consumers, liver remains a staple in many European diets, with the poultry liver being the most consumed type, largely due to the popularity of pâté (Latoch, Stasiak and Siczek, 2024).

In Africa, due to its affordability and availability, offal plays a significant role in daily diets. Offal, such as kidneys, liver, and intestines, is considered a delicacy and is widely consumed in many regions. Cultural practices prioritize resourcefulness, emphasizing the minimal waste of animal products. Nevertheless, limitations in processing and storage capacities in many regions may limit their broader use (Bou *et al*., 2025).

In Americas, there is diversity in consumption trends. In Latin America, countries such as Brazil and Mexico have long-standing traditions of offal consumption, with dishes such as feijoada (a stew that includes pork offal) and tacos de lengua (tongue tacos). Conversely, in North America, particularly Canada and The United States, has largely shifted away from regular offal consumption, except within ethnic communities and niche markets. Nevertheless, the expanding global shift toward sustainable eating and high-protein diets has driven demand for these products among health-conscious consumer groups (Bou *et al*., 2025).

In Western countries, there has been an overall decline in offal consumption, which may be attributed to several factors, including dietary shifts, regulatory constraints, increasing demand for convenient

products, and its association with low-income consumers. Furthermore, concerns regarding sustainability and the potential health risks associated with meat and meat products have reinforced these trends, amid prevailing negative perceptions that are amplified by investors and the media. Consequently, offal has become progressively scarce in retail markets, resulting in limited consumer familiarity with these products (Bou *et al*., 2025).

26.2.2 Inedible By-Products

In prehistoric times, long before the advent of the meat industry, inedible by-products played a significant role. Since meat was obtained mainly by hunting, during the preparation of animals for food, the inedible portions were used for clothing, as structural component for housing, as fuel, or left for disposal by nature, as well as for other life-support roles, thereby supporting the animal's function as a primary source of nutrition. The main inedible by-products are skin or hide, wool, horns, hooves, bones, blood, manure, and trimmings. Furthermore, dead animals, whether due to natural causes or death at the slaughterhouse prior to slaughter, as well as animals unfit for human consumption, may be processed in economically viable manner, unless disposal by alternative methods is necessary (Irshad and Sharma, 2015).

Inedible by-products, as mentioned earlier, are discards that are unfit for human consumption and are either rejected as waste or recycled into secondary products. Inedible by-products can be further classified into primary and secondary products. Primary products are collected directly from animals after slaughter, including bones, blood, hides, and skin while secondary products are obtained as derivatives from the primary products, including bone meals, insulin, button, gelatine (Alao *et al*., 2017).

26.2.3 Species-specific By-Products

By-products vary by species: bovine yields large bones and hides for gelatin, porcine provides blood and casings for sausages, and poultry generates feathers and feet for feed (Fan and Wu, 2022; Irshad and Sharma, 2015; Jayathilakan *et al*., 2011). Poultry by-products, like spent hens, are rich in proteins suitable for functional foods, while fishery discards (though not strictly meat) offer parallels in PUFA-rich lipids (Caruso *et al*., 2020; Venugopal, 2021). Unique characteristics include higher collagen in bovine sources for biomaterials and antimicrobial peptides from porcine blood (Verma *et al*., 2025). Potential uses leverage these traits, such as poultry waste for biofuels or bovine bones for nano-composites (Rao, Bast and de Boer, 2021; Zioga *et al*., 2022).

Meat by-products are also utilized for various medical purposes in countries like China, Japan, and India. Hormones that regulate body metabolism are secreted by endocrine glands, including the liver, lung, thyroid, parathyroid, corpus luteum, follicle, ovaries, pituitary, and adrenal glands. These glands are preserved by freezing to prevent their degradation by microbial activity. Initially, they are cleansed, and connective tissue and fats are removed; they are then packed in waxed paper and stored at –18 °C. In the pharmaceutical industry, the glands are examined, sliced, and mixed with appropriate solutions for hormone extraction. Ethylene, light petroleum solvents, acetone, or gasoline are used for fat removal when glands have a high fat content. Following defatting and drying, the material is milled into a fine powder for capsule production and subsequently evaluated for safety and potency before sale (Rahman, Sahar and Khan, 2014).

26.3 Current Practices in Meat By-Product Utilization

Historically, the incorporation of edible by-products into processed meat items has been a standard practice in many cultures. Sausages, pâtés, and blood puddings utilize organs like liver, heart, and lungs, as well as blood. These ingredients not only reduce raw material costs but also impart distinct flavors and textures prized in traditional cuisines (Toldrá *et al*., 2012). Liver, for example, is a key ingredient in liverwurst and braunschweiger, contributing high levels of iron and Vitamin A. However, the use of these ingredients is often limited by consumer acceptance and the intense flavors they can impart.

Meat by-products, comprising 50-60% of the live animal weight, are increasingly utilized through traditional and nonfood avenues to maximize economic value and minimize environmental harm (Irshad and Sharma, 2015). In regions like India, where annual slaughter yields 6.3 million tons of meat and substantial by-product loads, efficient practices prevent aesthetic and health issues while generating revenue comparable to meat sales (Irshad and Sharma, 2015). These practices encompass food processing, industrial applications, and waste management, aligning with broader sustainability goals in the meat sector (Gregg *et al*., 2020; Jayathilakan *et al*., 2011).

26.3.1 Traditional Uses in Food Industry

Traditional food industry applications leverage edible and semi-edible by-products to enhance product nutrition and functionality. Processed meat products, such as sausages, hot dogs, and burgers, commonly incorporate offal like liver, heart, and trimmings to improve texture, flavor, and protein content, reducing reliance on prime cuts and lowering production costs (Irshad and Sharma, 2015; Jayathilakan *et al*., 2011). For instance, in poultry and meat processing, by-products like heads, feet, and organs are blended into emulsified products, contributing up to 20–30% of the formulation while providing essential nutrients (Jayathilakan *et al*., 2011).

The extraction of collagen and its hydrolyzed derivative, gelatin, represents one of the most established value-addition pathways for meat by-products. Bovine bones and porcine skins are subjected to acid or alkaline pretreatment followed by thermal extraction to yield gelatin (Glimåker *et al*., 2023). This versatile hydrocolloid is ubiquitous in the food industry, serving as a gelling agent in desserts, a stabilizer in dairy products, and a texture modifier in low-fat foods. The global market for gelatin is immense, driven by its unique melting characteristics which mimic the mouthfeel of fat.

These materials undergo hydrolysis to extract gelatin, used in confectionery, dairy products, and pharmaceuticals, with global production exceeding 400,000 tons annually (Irshad and Sharma, 2015; Jayathilakan et al., 2011). Collagen, derived similarly, serves as a functional ingredient in meat analogues and health supplements, offering gelling and emulsifying properties (Gregg *et al*., 2020). In sustainable contexts, these processes recover value from otherwise discarded materials, supporting circular bioeconomy principles (Gregg *et al*., 2020).

Rendering is perhaps the oldest method of recycling meat by-products. It involves the thermal processing of fatty tissues and bones to separate water, fat (tallow or lard), and protein solids (meat and bone meal [MBM]) (Meeker, 2009).

Rendering processes extract fats from adipose tissues, skins, and organs through heating and separation, yielding tallow or lard for food uses like shortenings and frying oils (Jayathilakan *et al*., 2011). This method processes over 90% of inedible fats in many countries, preventing waste while producing high-quality lipids (Irshad and Sharma, 2015). Overall, these traditional uses transform by-products into viable food components, enhancing industry profitability and reducing disposal burdens (Irshad and Sharma, 2015; Jayathilakan *et al*., 2011).

The protein meal fraction serves as a high-protein ingredient in animal feed, although regulations in many regions now restrict its use in ruminant feed to prevent the transmission of bovine spongiform encephalopathy (BSE) (Woodgate, 2023).

26.3.2 Nonfood Applications

Nonfood applications extend by-product utility beyond human consumption, focusing on industrial and agricultural sectors to foster resource efficiency. The pet food industry is a primary consumer of meat by-products that are not utilized for human consumption. Organs, trimmings, and rendered meals provide essential proteins, fats, and micronutrients for canine and feline diets (Meeker, 2009). High-quality by-products are often marketed as premium ingredients in pet nutrition, emphasizing the ancestral dietary patterns of carnivorous pets. Furthermore, rendered meals are critical components in aquaculture feeds, replacing wild-caught fish meal and enhancing the sustainability of fish farming (Stevens *et al*., 2018).

In livestock feed, hydrolyzed by-products like MBM serve as cost-effective protein sources, although regulations limit their use in ruminant feeds to prevent diseases like BSE (Jayathilakan *et al*., 2011).

TABLE 26.2

Current Practices in Meat By-Product Utilization

Practice Category	Key Methods and Examples	Economic/ Environmental Benefits	Challenges	References
Traditional food uses	Sausages with offal, gelatin from bones, rendering for fats	Revenue from value addition, nutrient recovery	Health concerns, market decline	Irshad and Sharma, 2015; Jayathilakan *et al.*, 2011
Nonfood applications	Pet feed from proteins, fertilizers/ biofuels from waste, leather from hides	Renewable energy, reduced fertilizer use	Regulatory restrictions on feeds	Gregg *et al.*, 2020; Irshad and Sharma, 2015; Jayathilakan *et al.*, 2011; Sadhukhan *et al.*, 2020
Waste management/ disposal	Rendering/ composting, landfilling	Emission reductions via valorization	Pollution from improper methods	Socas-Rodríguez *et al.*, 2021; Irshad and Sharma, 2015; Jurgilevich *et al.*, 2016

Low-quality by-products and processing wastes that are unsuitable for feed are increasingly directed toward energy and agricultural applications. MBM is rich in nitrogen, phosphorus, and calcium, making it an effective organic fertilizer. Fertilizer production utilizes blood, bone, and manure from processing waste, yielding organic amendments rich in nitrogen, phosphorus, and potassium, which support sustainable agriculture and reduce synthetic fertilizer dependency (Gregg *et al.*, 2020; Irshad and Sharma, 2015).

In the energy sector, animal fats (tallow) are a feedstock for biodiesel production through transesterification. Biofuel generation from rendered fats and organic wastes via anaerobic digestion or transesterification produces biodiesel and biogas, offering renewable energy alternatives and cutting greenhouse gas emissions by up to 80% compared to fossil fuels (Gregg *et al.*, 2020; Irshad and Sharma, 2015; Sadhukhan *et al.*, 2020). For example, in integrated systems, meat waste biorefineries convert discards into platform chemicals and energy, aligning with circular economy models (Sadhukhan *et al.*, 2020). Additionally, anaerobic digestion of slaughterhouse wastewater and soft tissue waste generates biogas (methane), which can be captured and used to power processing facilities, thereby closing the energy loop (Rao *et al.*, 2010).

Hides and skins are among the most valuable nonfood by-products. The tanning industry converts putrescible raw hides into durable leather, a material essential for footwear, apparel, upholstery, and automotive interiors, with the global leather industry relying on 2.5 billion animal hides annually (Jayathilakan *et al.*, 2011). Despite the rise of synthetic alternatives, natural leather remains prized for its breathability and durability. However, the tanning process itself faces environmental challenges due to the use of chromium and other chemicals, driving research into eco-friendly enzymatic tanning methods (Meeker, 2009). Additional applications include adhesives from collagen and lubricants from fats, further diversifying economic returns (Irshad and Sharma, 2015; Jayathilakan *et al.*, 2011). These nonfood pathways not only valorize by-products but also promote industrial symbiosis, where waste from one sector becomes input for another (Table 26.2) (Gregg *et al.*, 2020; Sadhukhan *et al.*, 2020).

26.3.3 Waste Management and Disposal Methods

Current waste management practices for meat by-products emphasize rendering, composting, and incineration to handle the high volumes generated, particularly from small-scale abattoirs where utilization lags (Irshad and Sharma, 2015; Jayathilakan *et al.*, 2011). Rendering remains dominant, processing 70–80% of inedible materials into marketable products like feed and fuels, while composting converts organic wastes into soil enhancers (Jayathilakan *et al.*, 2011; Socas-Rodríguez *et al.*, 2021). In developing regions, open dumping or landfilling persists due to infrastructure gaps, affecting 20–30% of by-products (Irshad and Sharma, 2015).

Improper disposal, such as untreated landfilling or effluent discharge, leads to severe environmental impacts, including groundwater contamination from high biochemical oxygen demand (BOD) levels—up to 5,000 mg/L in meat processing wastewater—and methane emissions contributing to climate change (Irshad and Sharma, 2015; Jayathilakan *et al.*, 2011; Socas-Rodríguez *et al.*, 2021). These practices

TABLE 26.3

Environmental Impacts of Disposal versus Utilization

Aspect	Improper Disposal	Utilization Practices	References
Emissions	High methane and BOD pollution	Up to 80% GHG reduction	Gregg *et al.*, 2020; Sadhukhan *et al.*, 2020; Irshad and Sharma, 2015; Jurgilevich *et al.*, 2016
Resource recovery	Minimal, leads to nutrient loss	High, generates energy and materials	Irshad and Sharma, 2015; Jayathilakan *et al.*, 2011; Socas-Rodríguez *et al.*, 2021
Regulatory compliance	Often violates safety standards	Aligns with EU/US frameworks	Jayathilakan *et al.*, 2011; Socas-Rodríguez *et al.*, 2021

exacerbate pollution, nutrient runoff causing eutrophication, and health risks from pathogen spread, with global meat industry waste accounting for 5–10% of agricultural emissions (Jurgilevich *et al.*, 2016; Sadhukhan *et al.*, 2020). Transitioning to valorization reduces these impacts, as seen in circular models where waste is repurposed rather than discarded (Gregg *et al.*, 2020; Jurgilevich *et al.*, 2016).

Regulatory frameworks govern by-product management to ensure safety and sustainability. In the EU, Category 1–3 classifications under Regulation (EC) No. 1069/2009 mandate risk-based handling, prohibiting high-risk materials in feed while promoting rendering (Socas-Rodríguez *et al.*, 2021). The US FDA and USDA enforce similar standards via the Federal Meat Inspection Act, emphasizing pathogen control and traceability (Jayathilakan *et al.*, 2011). In India, FSSAI guidelines focus on hygienic processing to prevent adulteration, although enforcement challenges persist (Irshad and Sharma, 2015). Internationally, Codex Alimentarius standards harmonize practices, encouraging valorization to minimize environmental footprints (Jayathilakan *et al.*, 2011; Socas-Rodríguez *et al.*, 2021). These regulations drive adoption of sustainable methods, balancing economic viability with ecological protection (Table 26.3) (Gregg *et al.*, 2020; Socas-Rodríguez *et al.*, 2021).

26.4 Emerging Technologies for By-Product Valorization

Emerging technologies are pivotal in transforming meat by-products from waste streams into high-value resources, addressing sustainability challenges in the meat industry where by-products constitute 50–60% of animal biomass (Jayathilakan *et al.*, 2011; Verma *et al.*, 2025). These innovations, including enzymatic hydrolysis and biotechnological fermentations, enable the extraction of bioactive peptides, lipids, and other compounds, reducing environmental impacts while creating economic opportunities in food, pharmaceuticals, and materials (Caruso *et al.*, 2020; Venugopal, 2021; Verma *et al.*, 2025). By integrating biorefinery approaches, these technologies support circular economy principles, converting discards into functional ingredients like antioxidants and antimicrobials (Gregg *et al.*, 2020; Lange *et al.*, 2021; Sadhukhan *et al.*, 2020)

26.4.1 Advanced Extraction and Processing Techniques

Advanced extraction methods enhance the recovery of valuable components from meat by-products, such as proteins and lipids, with minimal environmental footprint compared to traditional chemical processes (Caruso *et al.*, 2020; Verma *et al.*, 2025).

To move beyond traditional rendering and gelatin production, the industry is adopting sophisticated extraction technologies. Enzymatic hydrolysis uses specific proteases (e.g., papain, alcalase, pepsin) to break down proteins from bones, blood, and trimmings into functional hydrolysates (Mora, Reig and Toldrá, 2014). Unlike harsh chemical hydrolysis, enzymatic methods are milder, preserving the nutritional quality of amino acids and generating products with specific functionalities such as high solubility or emulsifying capacity.

Enzymatic extraction utilizes proteases and lipases to hydrolyze proteins and fats from bones, skin, and organs, yielding bioactive peptides with antioxidant and antihypertensive properties (Jayathilakan *et al*., 2011; Verma *et al*., 2025). This method is eco-friendly, operating under mild conditions (e.g., 40–60 °C, pH 7–8), and improves yield by 20–50% over acid hydrolysis, as seen in porcine blood and poultry waste processing (Jayathilakan *et al*., 2011; Verma *et al*., 2025). Chemical extraction, involving solvents like ethanol or acetone, targets lipids and carotenoids but requires optimization to avoid toxicity, often combined with enzymatic steps for higher purity (Caruso *et al*., 2020; Osorio, Flórez-López and Grande-Tovar, 2021).

Membrane filtration technologies, including ultrafiltration (UF) and nanofiltration (NF), are being employed to fractionate and concentrate proteins and bioactive peptides from dilute process streams, such as blood plasma or wash waters (Alibhai *et al*., 2006). These nonthermal separation processes minimize protein denaturation, retaining biological activity. For instance, ultrafiltration can concentrate plasma proteins for use as binders in meat products, effectively replacing synthetic additives.

Membrane technology, including ultrafiltration and nanofiltration, isolates proteins and bioactive compounds from hydrolysates and effluents, achieving 80–95% recovery rates while separating contaminants (Caruso *et al*., 2020; Venugopal, 2021; Verma *et al*., 2025). In meat processing, it concentrates whey-like proteins from blood and offal, producing isolates for nutraceuticals, and is scalable for industrial use with low energy consumption (Jayathilakan *et al*., 2011; Venugopal, 2021).

Supercritical fluid extraction (SFE), typically using carbon dioxide (CO_2), offers a green alternative for extracting high-value lipids and bioactive compounds from meat by-products. SFE operates at moderate temperatures and leaves no solvent residues, making it ideal for isolating sensitive compounds like omega-3 fatty acids from fish waste or cholesterol-free fats from bone marrow (Villacís-Chiriboga *et al*., 2021).

Supercritical fluid extraction (SFE) employs CO_2 under supercritical conditions (31 °C, 73 bar) to extract high-value components like polyunsaturated fatty acids (PUFAs) from fish and meat fats, offering solvent-free, high-purity yields (up to 90%) without degrading heat-sensitive bioactives (Caruso *et al*., 2020; Venugopal, 2021). Applied to fishery discards analogous to meat by-products, SFE recovers omega-3 oils efficiently, supporting applications in functional foods (Caruso *et al*., 2020; Venugopal, 2021). These techniques collectively reduce waste volumes by 70% and enhance product quality, fostering sustainable valorization (Caruso *et al*., 2020; Sadhukhan *et al*., 2020; Verma *et al*., 2025).

26.4.2 Biotechnological Approaches

A major area of research is the generation of bioactive peptides—short amino acid sequences that exert physiological benefits beyond basic nutrition. These peptides, derived from the hydrolysis of meat proteins (collagen, myofibrillar proteins, blood proteins), have been shown to possess antihypertensive, antioxidant, antimicrobial, and immunomodulatory activities (Fu *et al*., 2019). They represent a high-value opportunity for the pharmaceutical and nutraceutical sectors.

Biotechnological methods leverage microbial and enzymatic actions to upgrade by-products into functional materials, aligning with bioeconomy goals for resource efficiency (Gregg *et al*., 2020; Lange *et al*., 2021; Sadhukhan *et al*., 2020; Verma *et al*., 2025).

Fermentation utilizes microorganisms to transform by-products into higher-value compounds. Lactic acid fermentation of blood or offal can preserve these materials and enhance their flavor profile for use in savory ingredients. Furthermore, solid-state fermentation of keratinous wastes (feathers, hair) by keratinolytic bacteria can produce highly digestible protein feed (Ojha, Bußler and Schlüter, 2020).

Fermentation processes transform by-products using bacteria (e.g., *Lactobacillus*) or yeasts to produce single-cell proteins, organic acids, and biofuels from organic wastes like blood and intestines (Caruso *et al*., 2020; Venugopal, 2021; Verma *et al*., 2025). In meat contexts, solid-state fermentation of poultry feathers yields keratin hydrolysates with antimicrobial activity, while submerged fermentation converts bone meal into biogas and fertilizers, improving digestibility and reducing pathogens (Venugopal, 2021; Verma *et al*., 2025). These processes achieve 60–80% conversion efficiency, mitigating landfill burdens (Caruso *et al*., 2020; Sadhukhan *et al*., 2020).

Enzyme technology enhances functionality by modifying proteins for better solubility and emulsification, using transglutaminases or alcalases on collagen from skins to create gels for food packaging (Jayathilakan *et al.*, 2011; Verma *et al.*, 2025). This improves by-product utility in meat analogues, increasing gel strength by 30–50% and enabling applications in hypoallergenic products (Jayathilakan *et al.*, 2011; Osorio, Flórez-López and Grande-Tovar, 2021).

Bioactive peptide production from meat proteins involves hydrolysis to generate sequences with health benefits, such as ACE-inhibitory peptides from bovine heart or porcine plasma, exhibiting 50–70% inhibition rates for blood pressure regulation (Jayathilakan *et al.*, 2011; Verma *et al.*, 2025). Microbial fermentation further refines these, enhancing bioavailability for nutraceutical use (Caruso *et al.*, 2020; Verma *et al.*, 2025).

These approaches promote closed-loop systems, turning by-products into high-value bioactives while supporting rural bioeconomies (Gregg *et al.*, 2020; Lange *et al.*, 2021).

26.4.3 Nanotechnology Applications

Nanotechnology is opening new frontiers in by-product valorization. Nanoencapsulation involves trapping bioactive compounds (e.g., peptides, antioxidants) within nanoscale carriers made from by-product-derived biopolymers like gelatin or chitosan. This improves the stability and bioavailability of sensitive nutraceuticals (Ramachandraiah, Han and Chin, 2015). Additionally, nanocomposites reinforced with nanofibrillated collagen or keratin are being developed for biodegradable packaging materials, offering a sustainable alternative to petroleum-based plastics in food packaging.

Nanotechnology innovates by-product valorization by structuring materials at the nanoscale for enhanced performance in delivery, reinforcement, and monitoring (Figure 26.2) (Lange *et al.*, 2021; Osorio, Flórez-López and Grande-Tovar, 2021; Sadhukhan *et al.*, 2020).

Nanoencapsulation entraps bioactive compounds from by-products, like peptides from offal or PUFAs from fats, using liposomes or chitosan nanoparticles to improve stability and bioavailability, extending shelf life in foods by two to three times (Del Rio Osorio, Flórez-López and Grande-Tovar, 2021; Venugopal, 2021; Verma *et al.*, 2025). In meat processing, encapsulating antioxidants from liver hydrolysates prevents oxidation in products, aligning with clean-label demands (Jayathilakan *et al.*, 2011; Verma *et al.*, 2025).

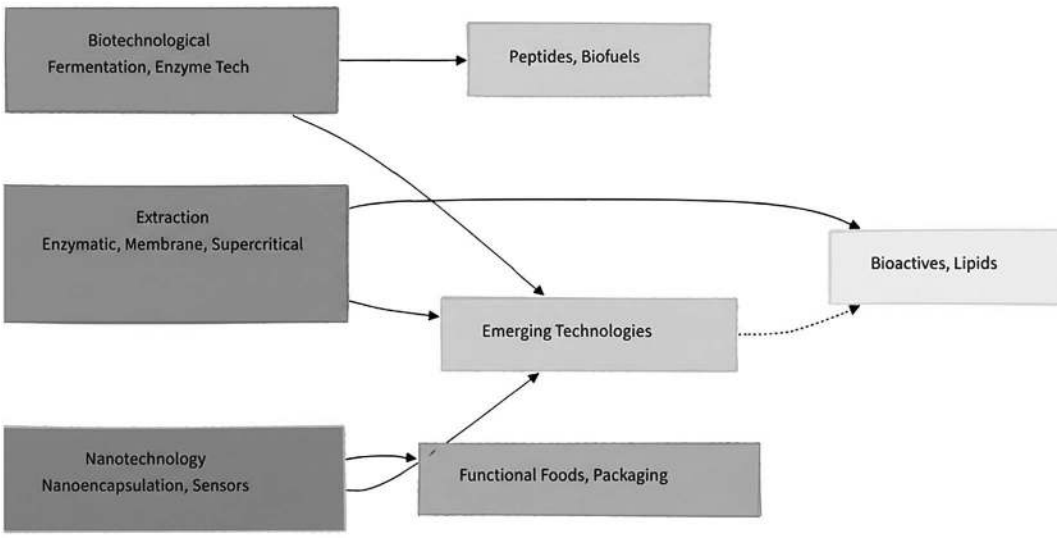

FIGURE 26.2 This diagram outlines emerging technologies for by-product valorization, categorizing extraction, biotechnological, and nanotechnology methods with their applications.

Nanocomposites incorporate meat-derived materials, such as collagen nanofibers from bones, into biopolymer matrices for packaging films with improved barrier properties and biodegradability (Gregg *et al*., 2020; Lange *et al*., 2021; Osorio, Flórez-López and Grande-Tovar, 2021). These reduce plastic use in food chains, offering antimicrobial coatings from peptide-loaded nanocomposites (Del Rio Osorio, Flórez-López and Grande-Tovar, 2021; Sadhukhan *et al*., 2020).

Nanosensors, utilizing gold or silica nanoparticles functionalized with by-product enzymes, enable real-time quality control in processing by detecting spoilage markers like biogenic amines with sensitivities down to 1 ppm (Osorio, Flórez-López and Grande-Tovar, 2021; Sadhukhan *et al*., 2020; Venugopal, 2021). In by-product streams, they monitor hydrolysis efficiency, ensuring contaminant-free outputs for pharmaceutical applications (Caruso *et al*., 2020; Lange *et al*., 2021).

Nanotech applications bridge by-products to high-tech sectors, driving circular innovation with minimal resource input (Gregg *et al*., 2020; Lange *et al*., 2021; Sadhukhan *et al*., 2020).

26.5 Nutritional and Functional Properties of Edible By-Products

Edible by-products, such as organs and trimmings from meat processing, are nutrient-dense alternatives to muscle meat, offering high-quality proteins, vitamins, and bioactive compounds that support health and sustainability (Rațu *et al*., 2023; Verma *et al*., 2025). These materials, often underutilized due to cultural preferences, can enhance food formulations by providing essential nutrients and functional attributes, aligning with circular economy principles to reduce waste and promote nutritional security (Osorio, Flórez-López and Grande-Tovar, 2021; Rațu *et al*., 2023). Their incorporation into products like fortified foods and nutraceuticals addresses global deficiencies while valorizing by-products from the meat industry (Osorio, Flórez-López and Grande-Tovar, 2021; Verma *et al*., 2025).

Meat by-products are claimed to contain many indispensable nutrients that can be used as medicinal ingredients and food, as they are comprised of fatty acids, essential amino acids, vitamins, minerals, and hormones (Rahman, Sahar and Khan, 2014). Meat by-products are characterized by higher moisture content compared to muscle tissue, including organs such as the lung, brain, kidney, tripe, and spleen (Jayathilakan *et al*., 2011). Also, higher carbohydrate content was observed, especially in organ meats such as the kidney and liver (Rahman, Sahar and Khan, 2014).

Animal organs and glands often have a high nutritive value and provide a diverse range of flavors and textures. They are considered delicacies in many parts of the world, particularly Southeast Asia. Those intended for human consumption include the liver, lung, heart, brain, kidney, and spleen. They also comprise the bovine pancreas and tongue; the stomach and uterus of pigs; the rumen, reticulum, omasum, and abomasum of cattle and sheep; as well as the thymus and testes of pigs and sheep (Jayathilakan *et al*., 2011).

26.5.1 Protein Quality and Amino Acid Profiles

Edible by-products are exceptional sources of high-quality protein. The essential amino acid profile of organs such as the liver and heart is comparable, and in some cases superior, to skeletal muscle meat. They are particularly rich in lysine, threonine, and valine, making them excellent candidates for protein fortification in diets based on cereals, which are typically deficient in these amino acids (Seong *et al*., 2014). Collagen-rich tissues, while deficient in tryptophan, provide high levels of glycine and proline, which are conditionally essential for wound-healing and connective tissue health.

According to Jayathilakan *et al*. (2011), the protein content of the cattle feet, ears, tail, and liver is very close to that of muscle tissue with a large amount of collagen observed in the ears and feet; whereas the lowest protein content was found in the fatty tissue, brain, and chitterlings; moreover, pork tail exhibits the highest fat content and the lowest moisture content among all meat by-products. Due to the large amount of connective tissue in meat by-products, the amino acid profile differs from that of muscle tissue, with substantial amounts of proline, hydroxyproline, and glycine and lower levels of tryptophan and tyrosine (Rahman, Sahar and Khan, 2014).

Edible by-products exhibit protein quality comparable to or exceeding muscle meat, with balanced amino acid profiles that meet human nutritional needs (Rațu *et al*., 2023; Verma *et al*., 2025). Liver and heart proteins contain high levels of essential amino acids (EAAs) like lysine and leucine, often surpassing muscle meat's 80–90% digestibility score, due to their complete profiles and lower connective tissue (Rațu *et al*., 2023; Verma *et al*., 2025). For instance, kidney proteins provide a PDCAAS (protein digestibility corrected amino acid score) of 0.9–1.0, similar to beef muscle, but with enriched branched-chain amino acids for muscle repair (Rațu *et al*., 2023).

The potential for protein fortification in food products is significant, as by-product proteins can be hydrolyzed into powders or isolates for incorporation into baked goods, beverages, and meat analogues, boosting protein content by 10–20% without altering sensory qualities (Del Rio Osorio, Flórez-López and Grande-Tovar, 2021; Rațu *et al*., 2023; Verma *et al*., 2025). In sustainable applications, spent egg-laying hen proteins from poultry by-products fortify plant-based products, enhancing nutritional value and reducing reliance on primary animal sources (Fan and Wu, 2022).

Bioavailability and digestibility considerations are favorable, with enzymatic treatments improving absorption rates to 95% for peptides from offal, although anti-nutritional factors like purines in organs may require processing to mitigate (Osorio, Flórez-López and Grande-Tovar, 2021; Verma *et al*., 2025). Compared to muscle meat, by-products often show higher in vitro digestibility (85–95%) due to softer textures, but bioavailability varies by cooking method, with steaming preserving more EAAs (Fan and Wu, 2022; Rațu *et al*., 2023).

26.5.2 Micronutrient Content

By-products are often termed "superfoods" due to their density of micronutrients. Various edible by-products are rich in vitamins and minerals, positioning them as superior sources compared to muscle meat (Osorio, Flórez-López and Grande-Tovar, 2021; Rațu *et al*., 2023; Verma *et al*., 2025). Liver is exceptionally high in vitamin A (up to 16,000 IU/100 g), B12 (50–100 µg/100 g), and iron (20–30 mg/100 g), while heart provides potassium (300 mg/100 g) and zinc (4–6 mg/100 g), and kidneys offer selenium (100–200 µg/100 g) and folate (Osorio, Flórez-López and Grande-Tovar, 2021; Rațu *et al*., 2023). These levels often exceed daily requirements, making by-products potent micronutrient reservoirs (Verma *et al*., 2025). Furthermore, heme iron found in spleen, liver, and blood is highly bioavailable compared to non-heme iron from plant sources, presenting a vital resource for combating global iron deficiency anemia (Toldrá *et al*., 2012).

Compared to muscle tissue, meat by-products contain higher amounts of vitamins as the liver and kidney contain riboflavin at levels five to ten times higher than those found in muscle tissue. Moreover, the liver is an excellent source of vitamin A, vitamin B complex, niacin, folacin, and ascorbic acid. In addition, the kidney also contains substantial amounts of vitamin B12, vitamin B6, and folacin. A 100 portion of pork or beef provides 450–1,100% of the recommended dietary allowance (RDA) of vitamin A, 37% of the RDA of ascorbic acid, 65% of the RDA of vitamin B6, and 3,700% of the RDA of vitamin B12. Lamb spleen, kidney, and liver are also deemed good sources of several vitamins and minerals (Jayathilakan *et al*., 2011).

Their potential for addressing micronutrient deficiencies is evident in populations with limited access to diverse diets; for example, incorporating liver into fortified meals can combat anemia and vitamin A deficiency, affecting 1.7 billion people globally (Osorio, Flórez-López and Grande-Tovar, 2021; Rațu *et al*., 2023). Poultry by-products like gizzards contribute copper and phosphorus, aiding in bone health and immune function (Fan and Wu, 2022).

Biofortification strategies using by-product-derived nutrients involve extraction and enrichment, such as adding liver extracts to cereals or beverages to increase iron bioavailability by 20–30%, or using enzymatic processes to create micronutrient-stable powders for functional foods (Del Rio Osorio, Flórez-López and Grande-Tovar, 2021; Rațu *et al*., 2023; Verma *et al*., 2025). These approaches enhance food security, particularly in developing regions, by repurposing waste into nutrient-dense additives (Fan and Wu, 2022; Osorio, Flórez-López and Grande-Tovar, 2021).

The highest amount of copper is also found in beef and lamb liver, providing 90–350% of the copper RDA. Moreover, the highest content of manganese is also found in the liver. In addition, sweetbread and

thymus contain the highest levels of potassium and phosphorus. Meat by-products contain nearly the same or lower amounts of sodium compared to muscle tissue (Rahman, Sahar and Khan, 2014).

Organ meats such as the brain, liver, chitterlings, lungs, heart, and kidneys contain higher levels of polyunsaturated fatty acids compared to muscle tissue. Moreover, it has been shown that meat by-products contain three to five times more cholesterol than lean meat. Furthermore, they contain high levels of phospholipids. Therefore, the US Department of Health and Human Services supports consumption of meat by-products in limited amounts. Additionally, there is a potential accumulation of drugs, pesticides, and toxic heavy metals (Rahman, Sahar and Khan, 2014).

Cholesterol is the raw material for vitamin D3 synthesis and is present in the brain and spinal cord. It is also used in cosmetics as an emulsifier. The hypothalamus in the brain is a source of other materials that can be used for similar purposes. Meltatonin, which is produced by the pineal gland, can be used in the treatment of various conditions such as mental retardation, schizophrenia, and insomnia. Bile, which is obtained from the gallbladder, is composed of various constituents, including pigments, acids, proteins, and cholesterol. It can be utilized in the treatment of bile duct disorders, indigestion, and constipation. In addition, it is used to promote hepatic secretory activity. Cattle and pig bile is commercially available in a liquid form or as a dry extract. Cortisone and prednisone can be isolated separately from bile and utilized for medical purposes. Gallstones are sold at a high price due to their aphrodisiac properties. Furthermore, they are used as decorative items in the production of pendants and necklaces (Jayathilakan *et al*., 2011).

Heparin can be obtained from the lining of the small intestine, liver, and lungs, and is used as an antithrombotic agent and blood thinner to delay clot formation and blood coagulation during organ transplantation (Rahman, Sahar and Khan, 2014).

Estrogen and progesterone can be isolated from pig ovaries and may be used in the treatment of women with reproductive disorders. Relaxin is often used during labor and is isolated from the ovaries of pregnant sows. Insulin is isolated from the pancreas and is used for the regulation of sugar metabolism and the treatment of diabetes. Glucagon is obtained from pancreatic cells and is used to increase blood sugar levels and in the treatment of insulin overdoses or hypoglycemia caused by alcoholism. Trypsin and chymotrypsin are also obtained from the pancreas and are used to enhance wound-healing after injury or surgery. Catgut can be manufactured from the intestines of sheep and calves and is used to make internal surgical sutures. While the intestines are being processed into casings, the lining of the small intestines of cattle and pig can be collected and either processed into a dry powder for distribution to heparin producers or preserved in a raw state (Jayathilakan *et al*., 2011).

26.5.3 Bioactive Compounds and Functional Properties

Beyond basic nutrients, meat by-products contain functional bioactive compounds. Carnosine and anserine, dipeptides found in high concentrations in muscle and brain tissue, exhibit potent antioxidant activity (Mora, Reig and Toldrá, 2014). Coenzyme Q10, vital for cellular energy production, is abundant in heart tissue. Chondroitin sulfate and glucosamine, extracted from cartilage and connective tissues, are widely used supplements for joint health. These functional attributes position meat by-products as valuable ingredients for the functional food and dietary supplement markets.

Edible by-products contain bioactive peptides, lipids, and other compounds derived from hydrolysis or natural occurrence, offering multifunctional benefits (Table 26.4) (Osorio, Flórez-López and Grande-Tovar, 2021; Verma *et al*., 2025). Peptides from heart and blood exhibit antihypertensive and anti-inflammatory effects, while lipids from organs provide omega-3 fatty acids and phospholipids for cardiovascular health (Rațu *et al*., 2023; Verma *et al*., 2025). Other compounds include carnosine in muscle trimmings and taurine in hearts, contributing to antioxidant defense (Del Rio Osorio, Flórez-López and Grande-Tovar, 2021).

These exhibit strong antioxidant properties, scavenging free radicals at rates two to five times higher than synthetic equivalents, as seen in liver-derived peptides that inhibit lipid peroxidation (Verma *et al*., 2025). Antimicrobial activities are notable, with peptides from poultry by-products disrupting bacterial membranes, effective against pathogens like *E. coli* (Fan and Wu, 2022).

TABLE 26.4

Nutritional Profiles of Key Edible By-Products

By-Product Type	Key Proteins/ Amino Acids	Micronutrients (per 100 g)	Bioactives and Properties	References
Liver	High lysine, leucine	Vitamin A (16,000 IU), Fe (25 mg), B12 (60 µg)	Antioxidant peptides, anti-anemia	Verma *et al.*, 2025; Rațu *et al.*, 2023; Osorio, Flórez-López and Grande-Tovar, 2021
Heart	Complete EAA profile	K (300 mg), Zn (5 mg), taurine	Antihypertensive, antimicrobial	Verma *et al.*, 2025; Osorio, Flórez-López and Grande-Tovar, 2021
Kidney	Balanced EAAs	Se (150 µg), folate (100 µg)	Anti-inflammatory lipids	Rațu *et al.*, 2023; Fan and Wu, 2022
Poultry offal	High digestibility	Cu (0.5 mg), P (200 mg)	Omega-3, gut health benefits	Verma *et al.*, 2025; Fan and Wu, 2022

Potential health benefits include reduced oxidative stress, improved gut health, and disease prevention, positioning by-products for nutraceutical applications like supplements and functional beverages (Rațu *et al.*, 2023; Verma *et al.*, 2025). For instance, hydrolysates from fish and meat by-products show promise in SARS-CoV-2 inhibition and bacterial treatments, supporting pharmaceutical uses (Osorio, Flórez-López and Grande-Tovar, 2021). Overall, these properties enhance food quality and promote sustainable health solutions (Figure 26.3) (Fan and Wu, 2022).

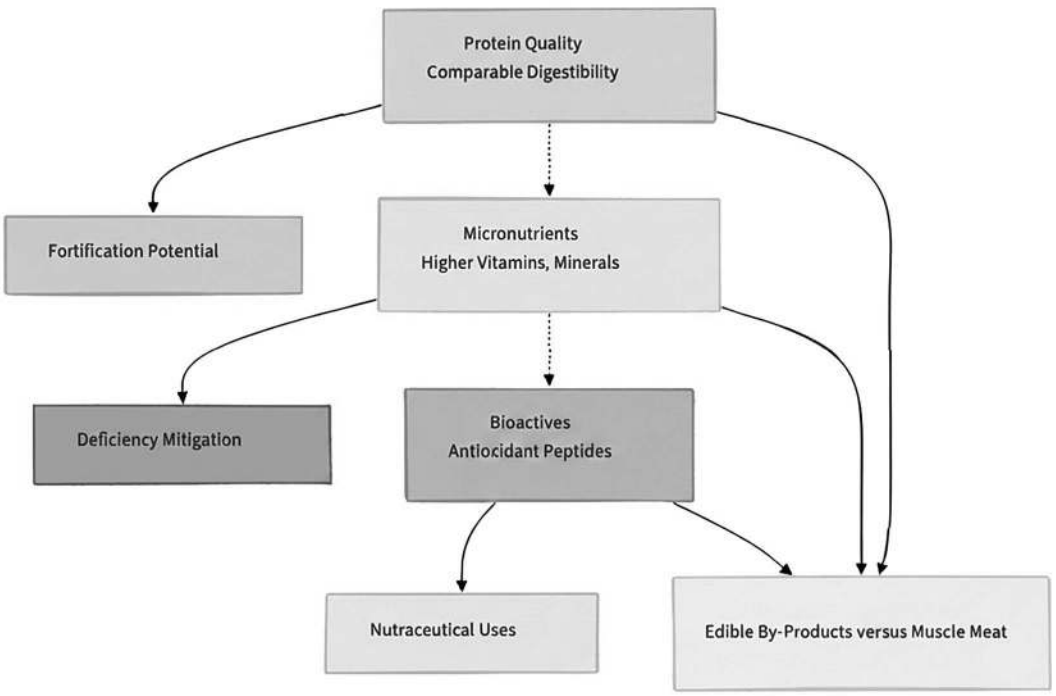

FIGURE 26.3 This flowchart compares the nutritional profiles of edible by-products to muscle meat, emphasizing protein quality, micronutrients, and bioactive compounds.

26.6 Sustainability and Circular Economy Models

26.6.1 LCA of By-Product Utilization

LCA provides a quantitative methodology to evaluate the environmental impacts of by-product utilization strategies. Studies consistently show that valorizing by-products significantly lowers the environmental burden allocated to the primary meat product. For example, rendering fats for biodiesel has a lower carbon footprint compared to fossil diesel and avoids the methane emissions associated with landfilling organic waste (Asem-Hiablie *et al.*, 2018). LCA identifies "hotspots" in the value chain—often energy consumption in drying or thermal processing—guiding engineers toward more efficient process designs.

LCA reveals that valorization reduces emissions by 20–50% compared to disposal, with hotspots in energy-intensive rendering (Rao, Bast and de Boer, 2021; Sadhukhan *et al.*, 2020). Strategies like biorefining minimize impacts, outperforming landfilling (Sadhukhan *et al.*, 2020).

26.6.2 Circular Economy Principles in Meat Processing

Adopting a circular economy model requires shifting from a linear "take–make–dispose" paradigm to a closed-loop system. In meat processing, this implies "industrial symbiosis," where the waste of one process becomes the feedstock for another. For instance, wastewater sludge can be digested to produce biogas (energy) and digestate (fertilizer) for crop production, which in turn feeds the livestock (Maina, Kachrimanidou and Koutinas, 2017). Integrated biorefineries located at slaughterhouses are the physical manifestation of this principle, capable of fractionating raw materials into a spectrum of fuel, chemical, and food products onsite. Closed-loop systems recycle by-products into feeds and energy, fostering symbiosis with agri-food sectors (Lange *et al.*, 2021). Economic benefits include cost-savings and new revenue streams (Irshad and Sharma, 2015; Lange *et al.*, 2021).

26.6.3 Energy and Resource Efficiency

Sustainable management also entails maximizing resource efficiency (Figure 26.4). Water recycling technologies, such as membrane filtration of process water, allow for the recovery of water for non-potable uses (cleaning, cooling), drastically reducing freshwater withdrawal. Waste-to-energy conversion,

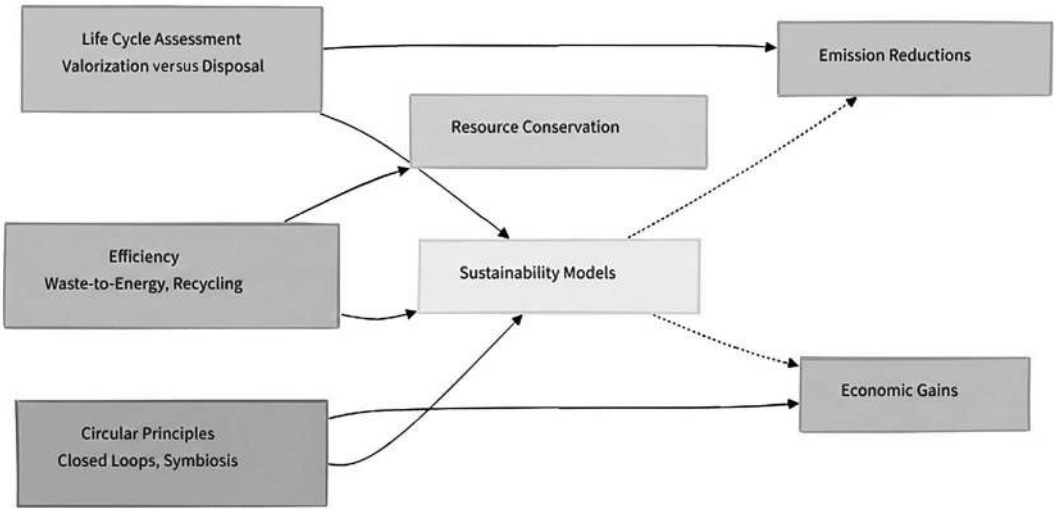

FIGURE 26.4 Sustainability metrics in meat by-product management, covering LCA, circular principles, and efficiency strategies.

particularly anaerobic digestion of soft tissues and high-strength wastewater, allows processing plants to offset significant portions of their fossil fuel consumption, enhancing energy security and reducing operational cost (Wang *et al.*, 2021). Waste-to-energy via biogas from effluents conserves resources, while water recycling in processing cuts usage by 30% (Venugopal, 2021). Packaging from by-product biopolymers enhances sustainability (Sadhukhan *et al.*, 2020).

26.7 Barriers to Adoption and Potential Solutions

26.7.1 Consumer Perception and Acceptance

A significant barrier to the utilization of edible by-products is consumer perception. In many Western cultures, offal is associated with poverty or viewed with disgust (neophobia). Research indicates that while "nose-to-tail" eating is gaining traction among culinary elites, mass consumer acceptance remains low (Henchion, McCarthy and O'Callaghan, 2016). Strategies to overcome this include "stealth incorporation"—processing by-products into neutral protein powders or functional ingredients that do not resemble the original organ—and education campaigns highlighting the sustainability and nutritional benefits of consuming the whole animal. Cultural biases limit offal consumption in Western markets, viewing it as waste (Fan and Wu, 2022; Irshad and Sharma, 2015). Education on nutritional benefits and marketing as "superfoods" can boost acceptance (Zioga *et al.*, 2022).

26.7.2 Regulatory Challenges

The regulatory landscape for meat by-products is complex and stringent, driven primarily by food safety concerns. Regulations regarding transmissible spongiform encephalopathies (TSEs) strictly control the use of certain ruminant tissues (Specified Risk Materials; Woodgate, 2023). Furthermore, the classification of a material as "waste" versus a "by-product" has profound legal implications for its transport and processing. Harmonizing international trade standards is crucial, as demand for offal is often high in regions like East Asia and Africa, while supply is surplus in the West. Safety concerns require contaminant testing, with EU laws lacking specificity for by-products (Caruso *et al.*, 2020). Harmonization efforts and private standards can bridge gaps (Lange *et al.*, 2021).

26.7.3 Technical and Economic Feasibility

While many valorization technologies (e.g., SFE, nanofiltration) are proven at the laboratory scale, scaling them up to industrial levels presents technical and economic challenges. The high capital investment required for advanced bioseparation equipment can be prohibitive for small-to-medium enterprises (SMEs). Cost-benefit analyses must demonstrate that the value of the recovered product exceeds the cost of extraction and purification. Developing modular, flexible processing units that can handle variable by-product streams may improve economic feasibility. Scale-up of hydrolysis is costly, but cost-benefit analyses show ROI via high-value peptides (Verma *et al.*, 2025). Investments in biorefineries yield long-term viability (Table 26.5) (Lange *et al.*, 2021).

TABLE 26.5

Barriers and Solutions

Barrier	Description	Solutions	References
Consumer perception	Cultural aversion	Awareness campaigns	Irshad and Sharma, 2015; Rațu *et al.*, 2023
Regulatory	Safety compliance gaps	Standards harmonization	Rao, Bast and de Boer, 2021; Socas-Rodríguez *et al.*, 2021
Technical/economic	High costs, scalability	Investment in tech	Verma *et al.*, 2025; Sadhukhan *et al.*, 2020

26.8 Future Trends and Opportunities

The future of by-product management lies in high-value niche markets. The biomedical sector offers immense potential, with collagen scaffolds for tissue engineering and xenotransplantation of organs becoming realities. Industry 4.0 technologies—digitalization, Internet of Things (IoT), and artificial intelligence (AI)—will optimize logistics and traceability. Smart sensors can monitor the quality of perishable by-products in real time, ensuring safety and maximizing yield (Ramachandraiah, Han and Chin, 2015).

Emerging markets for peptides in functional foods and cosmetics are expanding, driven by demand for natural ingredients (Verma *et al.*, 2025). Cross-industry partnerships, like meat–fishery biorefineries, enhance valorization (Venugopal, 2021). Digitalization via Industry 4.0 enables real-time monitoring for efficient by-product management (Figure 26.5) (Lange *et al.*, 2021).

26.9 Conclusion

The efficient utilization of meat by-products is a cornerstone of a sustainable and ethical global food system. This chapter has demonstrated that "waste" is merely a resource in the wrong place or form. Through the application of engineering innovations, biotechnological advances, and circular economy principles, the meat industry can transform the "fifth quarter" from a disposal burden into a diversified portfolio of high-value products. Key findings highlight that while traditional uses like rendering and gelatin production remain foundational, the future lies in fractionating specific bioactive molecules for health and wellness applications. Barriers such as consumer reluctance and regulatory complexity are significant but surmountable through education, innovation in product formulation, and science-based

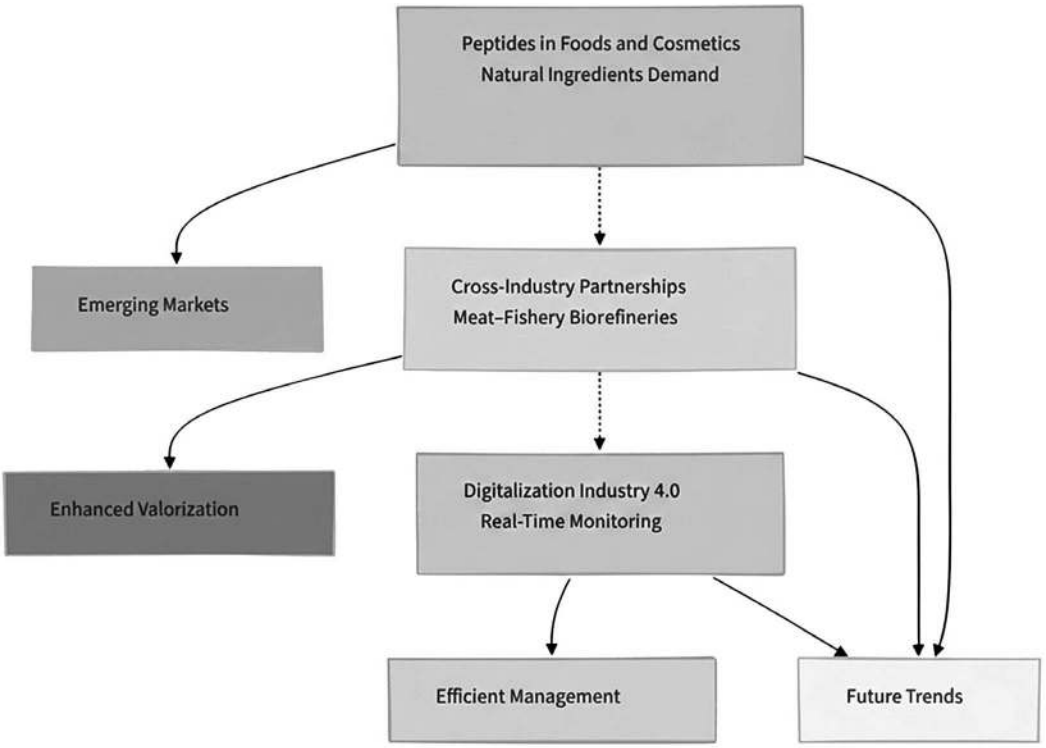

FIGURE 26.5 This flowchart illustrates future trends and opportunities in meat by-product utilization, including market expansion, partnerships, and digital advancements.

policymaking. The vision for the future is one of zero-waste meat processing, where every molecule of the animal is utilized to its highest potential—feeding people, nourishing pets, powering industry, or healing patients. Stakeholders—from processors and researchers to policymakers and consumers—must collaborate to realize this vision, ensuring that livestock production contributes positively to the nutritional and environmental security of future generations.

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27

Computer Vision Systems in Meat Science and Processing: Innovations and Applications

Abeera Moin and Theodoros Varzakas

27.1 Introduction

Meat is an excellent source of proteins followed by phosphorous (P), zinc (Zn), and iron (Fe). On the contrary, the high-protein meat replacers contain only 20–60% of the protein of meat products (Bohrer, 2017). Interestingly, the global meat industry holds a crucial importance in global food systems. It supplies high-density nutrition to billions of populations while supporting economies and global trade networks. According to Food Agricultural Organization of United Nations (FAO), the global meat production across all regions is expanding with robust consumption and strong demand. Approximately, 384 million tons (carcass weight equivalent) of meat is expected to be produced globally in 2025, showing 1.4% increment from 2024 (FAO, 2025). In addition, the meat industry plays a crucial role in many economies such as Australia's, providing employment to approximately 438,000 individuals, either directly or through associated businesses (Ruberg, 2021). It is essential to understand that complex biological and technological processes are involved in meat production and processing that must continuously adapt to the increases in demand, food safety and quality concerns, and added pressures to meet sustainability targets. Moreover, traditionally, meat processing, quality, and safety assessments involve labor-intensive and manual methods which are subjective, time-consuming, and unsuited to high-throughput requirement of modern processing facilities. This situation was troubling for meat processors and has led to the research on automated and data-driven technologies that can enhance the objectivity, consistency, and traceability across the meat production pipeline.

Computer vision systems (CVS), also known as machine vision technology, works in real-time, nondestructive, cost-effective, objective, and consistent methods, and is used extensively in the food industry, including meat production and its quality and safety inspection. The CVS is a subdomain of machine vision that leverages digital images and computational analysis to objectively quantify the visual attributes of biological materials (Chmiel *et al.*, 2016; Taheri-Garavand *et al.*, 2019). CVS fundamentally aims to replicate human visual perception and eliminates the human bias through electronic systems. The basic CSV process involves capturing the object images, translating that visual information into digital data, extracting appropriate features, and then making decisions based on specific characteristics such as color, conformation, size, marbling, and surface texture (Fernandes *et al.*, 2020). Many researchers have examined the application of machine vision techniques to the quality recognition of a variety of meats, including pork, lamb, beef, chicken, and fish.

The adoption of automation with CVS in the meat processing industries aligns with broader global trends of digital transformation and the advancing paradigm of Industry 4.0. This chapter details the ability of CVS for rapid, repeatable, and noninvasive assessment of carcass, primal cuts, and processed meat products that enables real-time decisions to support quality control, food safety, and good manufacturing monitoring and process optimization.

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27.2 Technological Foundations of CVS

Digital images, both macroscopic (Balage *et al*., 2018) and microscopic (Monteschio *et al*., 2019), can be employed to get acquisitions of information about meat and meat products using CVS. Digital cameras, smartphones (Meunier *et al*., 2020), ultrasound (US) methods (Fiore *et al*., 2020), nuclear magnetic resonance (NMR) (Lambe *et al*., 2021), along with computed tomography (CT) (Xiberta *et al*., 2018), dual energy X-ray absorptiometry (DXA) (López-Campos *et al*., 2018), and near infrared (NIR) spectroscopy and hyperspectral (HS) imaging (Balage *et al*., 2018; Ma and Sun, 2020) can be used to get images. External features of animal carcasses or meat product can arise from digital cameras and scanners, whereas internal characteristics of meat or products, not visible in the external appearance, can be acquired from US, NMR, CT, and DXA methods, as reported by Scholz *et al*. (2015). López-Campos *et al*. (2018) reported that DXA operates at lower levels of radiation than CT and is relatively inexpensive, of high reliability and ease of use and seems to be the most significant of all.

Image analysis is carried out in several stages, extracting information from the image as shown in Figure 27.1. Image preprocessing requires contrast enhancement, denoising, and other techniques in order to reach image processing and select the region of interest, detect the edge, etc.

Elements of an experimental platform, consisting of a device for image captures and a computer with image analysis software, are shown in the paper by Modzelewska-Kapituła and Jun (2022). The lighting conditions of samples are an important aspect affecting the quality of the images received. Several lighting resources are used for illumination of samples, including halogen, fluorescent (Arsalane *et al*., 2018), LED (Ruedt, Gibis and Weiss, 2020), or UV lamps (El Jabri *et al*., 2010; Teira *et al*., 2003). These depend on the sample characteristics and attributes to be measured. Color parameters affect the extraction of objects from the image (Arsalane *et al*., 2018; Caridade *et al*., 2020).

Classification can be used to get information on size, shape, color, and texture images, and this can be carried out by statistics, neural networks, and fuzzy logic (Jackman, Sun and Allen, 2009a, 2009b, 2000c; Jackman *et al*., 2009).

RGB images can be employed in computer vision and present versatility, robustness, and wide applicability in industrial settings, including food inspection (Hidalgo *et al*., 2025). CVS analyze visual cues related to meat freshness (Sánchez *et al*., 2023), such as color (Wu and Sun, 2013), marbling (Liao *et al*., 2025), and surface texture (Modzelewska-Kapituła and Jun, 2022) by leveraging advanced image

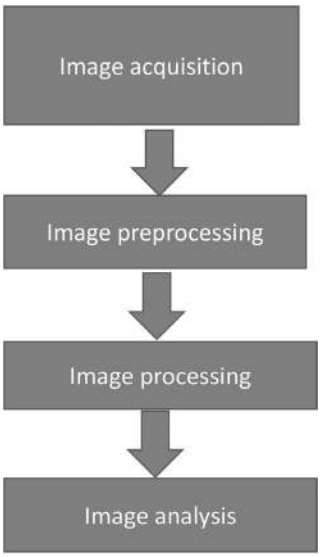

FIGURE 27.1 Typical workflow of a computer vision system in meat science, from image acquisition to decision-making. (Adapted from Modzelewska-Kapituła and Jun, 2022; Ruedt, Gibis and Weiss, 2020.)

TABLE 27.1

Comparison of Imaging Modalities and Traditional Algorithms and AI-Driven Algorithms Used in Meat Science

Food Detection	Perception Technology	Algorithm	Reference
Meat adulteration identification	E- tongue	LDA, PLSR	Zaukuu *et al.*, 2021
Meat adulteration identification	E-tongue	ELM	Lu *et al.*, 2021
Pork adulteration with beef quantification	E nose	1D CNN, RFR	Huang and Gu, 2022
Freshness detection of pork, beef, and mutton	E nose	DFA	Chen *et al.*, 2019
Meat freshness	Machine learning (ML) classifiers	Deep convolutional neural networks (DCNNs), followed by random encoding of aggregated deep activation maps (RADAM)	Hidalgo *et al.* 2025

Abbreviations: 1D CNN, one-dimensional convolutional neural network; DFA, discriminant factor analysis; ELM, extreme learning machine; LDA, linear discriminant analysis; PLSR, partial least squares regression; RFR, random forest regression.

Source: Adapted from Wei *et al.* (2026).

processing and machine learning techniques. This approach is scalable and nondestructive for real-time meat quality assessment (Kaushal *et al.*, 2024; Saha, Padhiary and Chandrakar, 2025).

Deep convolutional neural networks (DCNNs) have been used and applied in computer vision tasks, including object recognition, segmentation, and visual quality assessment (Kaushal *et al.*, 2024; Zhao *et al.*, 2025a, 2025b). It should be pointed out that the associated demands for training data and computational resources increase, making full model optimization costlier and time-consuming as network architectures become deeper and more complex (Lee *et al.*, 2022a, 2022b). Advances in hardware still rely on large, high-quality labeled datasets (Luo *et al.*, 2024; Rex, Annrose and Jenifer Jose, 2022; Saha, Padhiary and Chandrakar, 2025). This challenges applications in food quality monitoring, since collecting and labeling data is often labor-intensive, time-consuming, and costly (Luo *et al.*, 2024; Rex, Annrose and Jenifer Jose, 2022).

An alternative to training DCNNs is the random encoding of aggregated deep activation maps (RADAM), which leverages the rich texture information embedded in intermediate network layers and transforms it into a compact numerical vector suitable for traditional machine learning classifiers (Scabini *et al.*, 2023). This takes place without requiring additional training or fine-tuning (Filus and Domańska, 2023).

AI technologies are depicted in Table 27.1. They are differentiated into machine learning (supervised and unsupervised learning), including linear regression, logistic regression, support vector machine (SVM), decision tree, random forest (RF), etc. (supervised) and K-means clustering, hierarchical clustering, principal component analysis (PCA), autoencoder, etc. (unsupervised) (Liakos *et al.*, 2025; Zhao *et al.*, 2025b) and deep learning, including convolutional neural network (CNN), recurrent neural network (RNN), long short-term memory (LSTM), generative adversarial network (GAN), residual network (ResNet), etc. (Liu *et al.*, 2025a, 2025b; Wei *et al.*, 2026).

27.3 Applications in Meat Quality Assessment

The CVS has been extensively and efficiently explored as a meat quality assessment tool for automization of high-throughput food processing units. These systems capture visual characteristics of muscle foods such as color, shape, texture, and size to evaluate various quality parameters (Figure 27.2). The digital imaging sensors of CVS in combination with image processing algorithms and pattern recognition

model quantifies the visual attributes and make decision on the detected meat based on predescribed discrimination criteria (Xu *et al*., 2024). It means in the meat inspection system, the reference images and feature datasets that represent healthy, safe, and desired quality information are established within the system. During the operation, the real-time images are constantly compared with the predefined reference models, using image processing and pattern recognition algorithms. Any deviation from the set threshold indicates process inconsistency, quality defect, or a food-safe risk and is automatically flagged by the system in real time. The usual format of an image is RBG color model, which is converted into alternative representations such as CIE L^*, a^*, b^*, hyperspectral imaging (HSI), or grayscale texture matrices. Subsequently, CVS link visual cues of meat with internal physicochemical properties, thereby supporting nondestructive quality parameters evaluation and process optimization (Pinto *et al*., 2023).

Marbling refers to visible intramuscular fat (IMF), located between skeletal muscle fibers. According to Magalhã *et al*. (2016), marbling is considered as a critical quality parameter of meat as it is determinant of meat's juiciness, flavor, and tenderness. Moreover, it also influences consumer buying decision (Cheng *et al*., 2015). Traditional human vision–based process for categorizing IMF scores is susceptible to multiple factors, for instance, the evaluator's skills, preferences, and degree of fatigue. Therefore, the automation of marbling estimation processes is an opportunity to lessen misclassification by human intervention, and improve profitability through the accurate marketing destination of each carcass (Lee *et al*., 2022a, 2022b). The CVS-based algorithms are evaluating the quantity and distribution of IMF in meat by image processing. They identify and extract visuals such as the count densities and area densities of fat globules present in the muscle (Taheri-Garavand *et al*., 2019).

A group of researchers evaluated marbling patterns in Australian beef carcass using a camera-based imaging system and analyzing the digital images of the rib eye muscle. The calibration was done against expert marbling scores and chemically determined intramuscular fat. The system predicted moderate accuracy and showed 40–50% variation in intramuscular fat and 30–50% variation in visual marbling scores (Stewart *et al*., 2021). The CVS estimation of intramuscular fat in pork showed weak to moderate correlation with chemical crude fat with correlation coefficients $r = 0.34$ for the whole loin and $r =$ 0.38–0.39 for chops (Liu *et al*., 2019). In another study, waterwashed algorithm and artificial neural networks (ANN) were combined to predict the meat marbling grade for beef obtained from Chinese yellow cattle. Interestingly, the IMF was predicted with 86.84% accuracy (Meng *et al*., 2014). Similarly, Barbon *et al*. (2017) analyzed the beef images for IMF classification and the detection accuracy of the model was found 81.59%. The pictorial data was segmented using the Otsu procedure, followed by illumination normalization and contrast adjustment. Afterward, erosion technique was employed and IMF detection model was established by using *k*-nearest neighbor algorithm. Interestingly, a three-dimensional image analysis study of beef striploins suggested that marbling in a muscle is not composed of fat flakes but a single, interconnected, and intramuscular fat network (Bottema *et al*., 2020).

Appearance and texture are major aspects affecting the consumer acceptability of food commodities (Moin *et al*., 2024). CVS is used to evaluate the undesirable appearance of meat such as dark, firm, and dry meat (DFD). The DFD is considered as a meat quality defect and has higher pH and consequently darker color. Therefore, the CVS sensing of lightness or L^* value could be employed for discrimination (Shange *et al*., 2019). Color assessment of pork whole loin and individual chops was conducted by using CVS L^*, a^*, b^* values in comparison with hunter color measurement. The CVS color measurements were found consistent with instrumental evaluation showing a strong correlation ($r = 0.82$–0.84). This study by Liu *et al*. (2019) indicated that CVS provides an objective, nondestructive, and repeatable method for color assessment of pork muscles. Moreover, CVS also served as an objective, nondestructive, and rapid approach for monitoring meat freshness. The freshness of pork meat was evaluated by CVS using color region ratio (CRR) method. The findings showed higher correlation between CRR and meat freshness with 88% detection accuracy (Xiao *et al*., 2014). Weng *et al*. (2020) also employed CVS to evaluate the freshness of meat by observing color changes during refrigerated storage. The L^*, a^*, b^* values were evaluated from the images and correlated with conventional freshness indicators such as pH and storage time. Interestingly, the lightness and redness of meat was found strongly associated with loss of freshness.

In a study on lamb carcass grading using CVS, the lamb chop images were computed by combination of advance texture measure like spatial gray-level cooccurrence matrix (GLCM) and geometric features enabled ANN models. The classification efficiency of 96.9% was observed (Chandraratne *et al*., 2006).

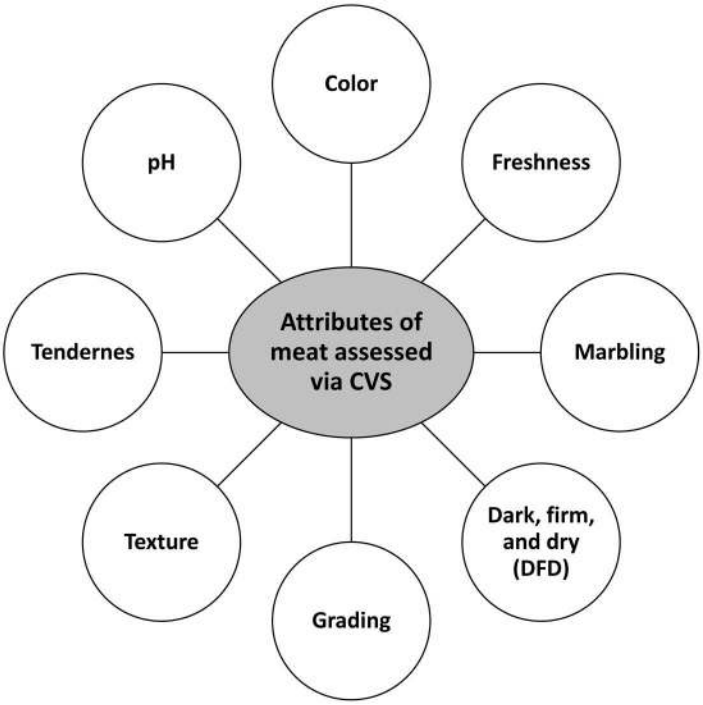

FIGURE 27.2 Examples of CVS applications in meat quality assessment.

Another interesting reported application of CVS was the discrimination among normal and woody chicken breast samples. The combination of image analysis and SVM models was employed to achieve a classification accuracy of 91.8% (Geronimo *et al*., 2019).

27.4 Applications in Meat Safety and Inspection

According to public health, global regulations, and science of food, the safety of a food is a prerequisite for food quality. Meat has higher moisture content consequently; it is a highly perishable food commodity. Many researchers have exploited CVS along with spectroscopic techniques, hyperspectral imaging (HSI), electronic nose (e-nose), and multispectral imaging (MSI) technologies as quick and nondestructive meat quality and safety evaluation methods (Khaled *et al*., 2021). These are useful for screening large volumes of meat and meat-based products at high speed. In the abattoirs, the foremost process-associated safety concern is the contamination of fecal material, stomach and gut content, bile, hairs, feathers, and blood. Computer vision and conventional spectroscopic techniques are integrated in hyperspectral imaging to obtain both spectral and spatial information simultaneously. This combination was found more effective than usual fluorescence imaging since all materials are not excited by fluoresce (Xiong *et al*., 2017). Park *et al.* (2006) evaluated performance of hyperspectral imaging with a 2-wavelength equation (I_{565}/I_{517}) band ratio to detect both ingesta and fecal contamination. This model performed with 96.4% accuracy. Park *et al.* (2011) reported 91% accuracy of feces contamination detection by hyperspectral imaging in a processing line. They reported the false positive at boundary, thigh, wing bone, and vent. A 100% surface contamination detection rate was observed in a study on chicken carcass by Wu *et al.* (2017) with negligible false positive (0.39%). They combined successive projections algorithm (SPA) and multivariable linear regression (MLR) with hyperspectral imaging.

Another challenge faced by meat processer is the physical hazard that occurs in terms of bone fragments in the boneless meat and poultry. Both transmittance and reflectance modalities of hyperspectral

imaging were employed to detect bone fragment in chicken breast fillets and promising accuracies were obtained (Yoon *et al.*, 2006, 2008). In addition, microbial count and detection of specific bacteria are also evaluated by using CVS. Traditionally, these detections are time-consuming and require skilled personal to perform the tasks with many precautions. However, many studies have reported real-time prediction of microbiological load. In a study, the total viable count (TVC) of bacteria was determined in chicken breast using near-infrared hyperspectral imaging and different spectroscopic transforms (Feng & Sun, 2013a). The determination of Enterobacteriaceae on chicken fillet with R^2 of 0.87 was conducted using near-infrared hyperspectral imaging and partial least square regression (Feng *et al.*, 2013). Feng and Sun (2013b) reported the detection of *Pseudomonas* loads in chicken fillets by employing near-infrared hyperspectral imaging with partial least squares regression and genetic algorithm.

The CVS seems indispensable due to its rapid, nondestructive, and complementary traits for high-throughput meat-processing plants. It could be used as a complementary detection tool in the meat inspection of poultry, pigs, and cattle according to revised European Union legislation (EU Commission, 2019; EU Parliament, 2017). Current legislation allows for the use of CVS in the inspection process for pigs and bovines (Klottrup, 2023; Sandberg *et al.*, 2023), while the inspection can be fully replaced by CVSs in poultry (Sandberg *et al.*, 2023). Table 27.2 presents applications of computer vision in meat quality and safety assessment.

TABLE 27.2

Applications of Computer Vision in Meat Quality and Safety Assessment

Attribute	Characterization	Meat Type	Technology and AI Method	Accuracy/ Outcome	Reference
Freshness	Total volatile basic nitrogen	Pork	Hyperspectral imaging and calorimetric sensor array with nonlinear data fusion	$R^2 = 0.9527$	Huang *et al.*, 2014
Freshness	Color	Pork	Color region ratio	88% accuracy	Xiao *et al.*, 2014
Freshness	Total volatile basic nitrogen	Beef and pork	Near-infrared spectroscopy with support vector regression (SVR) and partial least square model (PLS) models	SVR showed higher prediction accuracy	Leng *et al.*, 2021
Intramuscular fat	Spatial distribution and visible fat flecks	Beef	Structured-illumination reflectance imaging (SIRI) with deep learning classification	Up to 90.85% classification accuracy for marbling categories	Cai *et al.*, 2024
Intramuscular fat		Beef	Hyperspectral imaging (HSI) and partial least squares regression (PLSR)	PLSR model showed $R = 0.95$	Aredo *et al.*, 2017
Marbling	Degree and distribution of intramuscular fat	Beef	Structured image acquisition, improved YOLOv8x deep learning model with CBAM and SE attention mechanisms and ROI preprocessing	99.3% validation accuracy	Liu *et al.*, 2025a
Woody chicken breast	Texture	Poultry	Image analysis and support vector machine (SVM) models	91.8% accuracy	Geronimo *et al.*, 2019
Dark, firm, and dry (DFD)	Change in lightness	Pork	CVS L^*, a^*, b^* values	$R = 0.82$–0.84	Shange *et al.*, 2019

27.5 Process Automation and Robotics

Automation of operation in CVS software is one such innovation. The food industry will respond to market demands while reducing value-chain wastage with accurate and fast measurements of the quality and quantity of meat (Gardner *et al*., 2021). Chen and Qin (2008) and Du *et al*. (2008) created algorithms for automatic image segmentation in order to extract fat depots. A highly effective algorithm based on the thresholds of visual sensitivity was made by Chen and Qin (2008), whereas Du *et al*. (2008) applied an algorithm consisting of a three-stage image processing of steaks to determine marbling characteristics, such as intramuscular fat and its distribution. Automatic segmentation of beef images of *longissimus thoracis et lumborum* muscles was determined by an algorithm as reported by Jackman, Sun, and Allen (2009c).

In some New Zealand abattoirs, the VIAScan® system was introduced, based on CVS, to estimate the lean meat yield in lamb carcasses automatically. Breeding values for the weight of lean meat within the hindleg, loin, and shoulder primal cuts were estimated (Jopson, Newman and McEwan, 2009).

Kamruzzaman, Makino, and Oshita (2016) also developed a system for online monitoring of red meat (beef, lamb, and pork) color as a means of automation of CVS operations.

27.5.1 Validation

Validation of CVS can be carried out by multiple methodologies in order to establish a bona fide gold standard (Bonicelli *et al*., 2021; Trachtman *et al*., 2020), while others use Krippendorf's alpha or kappa as inter-observer agreement measures (Blömke, Volkmann and Kemper, 2019). A proper gold standard is lacking for the meat inspection, because meat inspector' judgment cannot be regarded as perfect (Alban *et al*., 2022; Denwood *et al*., 2015, 2024), hence missing accuracies of sensitivity (Se) and specificity (Sp) for CVS and getting just estimates (Dohoo, Martin and Stryhn, 2014; Lalkhen and McCluskey, 2008). Veldhuis *et al*. (2021) also pointed out the hindrance of the simple estimate of Se and Sp. Moreover, if a ground truth dataset were inspected retrospectively, the inspection routine would be altered significantly (Stärk *et al*., 2014). Bayesian latent class modeling enables an estimation of Se and Sp without knowledge of the true disease status (Hui and Walter, 1980; Lahuerta-Marin et al., 2018; Toft *et al*., 2005; Uno and Tango, 2024) using binomial data from multiple diagnostic tests and populations to estimate an unobserved or a latent variable, such as the presence of chronic pleurisy on the inspected pig carcass (Alban *et al*., 2021, 2022; Lund *et al*., 2026).

27.6 Challenges and Limitations

Challenges and limitations include the high cost of advanced imaging systems, data handling and processing bottlenecks, lack of standardized datasets and protocols, and environmental challenges in industrial settings (lighting, speed).

27.7 Future Trends and Opportunities

Future trends include edge AI and real-time inspection, multimodal sensing (CVS + spectroscopy + IoT), and explainable AI for regulatory trust.

Moreover, CVS is part of Industry 4.0 smart factories.

27.8 Conclusion

CVS acts as a driver of safer, more sustainable, and efficient meat processing.

New machine learning technologies such as RADAM, when combined with different pretrained DCNN and traditional machine learning classifiers, can achieve competitive classification performance offering simultaneously improved computational efficiency. Future potential might include a call for interdisciplinary collaboration.

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28

Artificial Intelligence and Cybersecurity Tools for Detecting Fraud in Meat and Meat Products

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28.1 Introduction

Global meat production in 2025 is projected to reach 384 million tons (carcass weight equivalent), representing an estimated 1.4% rise compared with 2024 levels (FAO, 2025a). In addition, the FAO indicates an increase in meat prices in 2025; this rise is largely driven by persistent global demand, which has pushed beef prices to record levels alongside modest upward movements in poultry prices (FAO, 2025b). As global demand and consumption of meat continue to climb, these economic pressures simultaneously heighten the vulnerability of supply chains to various forms of meat fraud. The combination of elevated market value, tightening supplies, and intensifying competition among producers and retailers creates incentives for dishonest practices such as species substitution, mislabeling of origin, dilution with lower-quality materials, or the sale of noncompliant products. Consequently, there is a pressing need for dependable analytical strategies capable of identifying adulterated meat products. A variety of methodologies have been employed for meat authenticity assessment, broadly categorized into biology-based, chemistry-based, and spectroscopy-based approaches. Biological techniques, such as multiplex polymerase chain reaction (PCR) (Zhao *et al.*, 2021), PCR-restriction fragment length polymorphism (PCR-RFLP) (Uddin *et al.*, 2021), loop-mediated isothermal amplification (LAMP) (Cai *et al.*, 2025), and enzyme-linked immunosorbent assay (ELISA) (Aprilia *et al.*, 2022), are recognized for their sensitivity and specificity. Nonetheless, these techniques often involve lengthy workflows, high operational costs, and sophisticated laboratory procedures that require trained specialists. Chemical analytical tools, including gas chromatography–mass spectrometry (GC-MS) and liquid chromatography–tandem mass spectrometry (LC-MS/MS), have demonstrated high accuracy for *halal* verification and species authentication (Quintanilla-Casas *et al.*, 2025). Despite their reliability, these instruments demand intricate extraction steps and extended analysis times, limiting their suitability for routine or large-scale screening. Spectroscopic techniques such as near-infrared spectroscopy (NIRS) (Cruz-Tirado *et al.*, 2024), Raman spectroscopy (RS) (Sun *et al.*, 2022), and hyperspectral imaging (HSI) (Cruz-Tirado *et al.*, 2024) have also proven effective for detecting adulteration, although the multidimensional datasets they generate require advanced expertise for proper interpretation. Considering the limitations associated with existing methods, there remains a clear need for rapid, precise, user-friendly, and cost-effective tools to support the reliable detection of meat adulteration.

In this context, artificial intelligence (AI) has emerged as a promising solution, offering advanced data-processing capabilities that enable the rapid, accurate, and nondestructive detection of meat adulteration. The integration of AI has emerged as a key approach for designing reliable detection systems. The growing interest in these data-driven solutions aligns closely with the broader shift toward rapid, eco-friendly analytical methodologies, a trend further supported by advances in portable analytical devices (Magdas *et al.*, 2025). Over the past few years, AI has demonstrated remarkable capability in processing massive datasets, uncovering subtle patterns, and producing robust assessments, enabling the development of dependable tools for evaluating meat authenticity from digital images,

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hyperspectral measurements, thermal profiles, and related inputs (Zhang, Ma and Ma, 2025). Machine learning (ML), a branch of AI, enables software to predict outcomes more accurately without being explicitly programmed. ML algorithms predict new output values using historical data. Deep learning (DL), a branch of ML, uses algorithms modeled based on biological neurons. In fact, ML algorithms, including artificial neural networks (ANNs), support vector machines (SVMs), and random forest (RF), offer powerful solutions for building robust predictive models from such datasets. Recent investigations centered on meat authenticity highlight the promise of AI as an emerging analytical tool for detecting meat fraud (Huang *et al.*, 2023). Additionally, previous studies have combined ML and DL with other spectroscopic methods for meat analysis (Dashti *et al.*, 2022; Parastar *et al.*, 2020; Zhang, Ma and Ma, 2025). For instance, a noninvasive HSI, when integrated with interpretable DL algorithms, has been particularly effective in identifying traces of lymphatic tissue and in determining the composition of mixed-species meat products (Liu *et al.*, 2026). This approach supports fast, in-line evaluation during processing and eliminates the need for destructive sampling. Collectively, these technological developments suggest that future fraud-control systems will rely on multiple coordinated layers, local AI-driven data processing, tamper-resistant digital traceability, and laboratory confirmation to ensure robust and trustworthy detection of meat fraud (Dashti *et al.*, 2022; Parastar *et al.*, 2020; Zhang, Ma and Ma, 2025).

This chapter examines how modern analytical tools and digital technologies work together to detect fraud in meat and meat products. It begins by explaining the main concepts of meat fraud, adulteration, and mislabeling of origin or quality. The chapter also outlines the application of ML and DL in detecting fraud in meat and meat products. Finally, it concludes by addressing cyber vulnerabilities linked to AI adoption and the ethical issues of safeguarding data integrity and secure system deployment.

28.2 Fundamentals of Meat and Meat Product Fraud

Food fraud is defined as an issue affecting all food supply chains and the totality of the food industry, including customers and consumers. Food supply chains are more exposed, showing greater risks due to globalization and lengthening of supply chains (Robson *et al.*, 2021). Nevertheless, the European Union has not established a legal definition of food fraud, leading to inconsistent interpretations among researchers and regulatory authorities. On the other hand, Chaudhary *et al.* (2023) indicated that food fraud can be defined as deceptive practices used by the masses to manipulate food items for economic gain. These fraudulent practices could include misrepresentation on labels, ingredient substitution with less valuable materials, and presenting substandard products as high-end items (Sawyer and Izah, 2024).

28.2.1 Types of Meat Fraud

Meat fraud refers to a broad spectrum of intentional adulteration practices that compromise the authenticity, safety, and integrity of meat products, with high-value categories such as beef and lamb being particularly vulnerable (Table 28.1 and Figure 28.1). These fraudulent activities can take multiple forms, the most prevalent of which is species substitution (Njaramba *et al.*, 2021). Expensive meats are partially or fully replaced with lower-cost alternatives such as pork, poultry, horse, or donkey, and in some extreme cases, with nonconventional species like dog or cat. Other strategies include incorporating undeclared by-products such as offal, connective tissues, or blood vessels to artificially increase product volume (Darban Maghami *et al.*, 2022; Grundy *et al.*, 2023). Misrepresentation of key product information, such as geographical origin, breed, production system (for instance, organic or grass-fed claims), or even the product's freshness status when previously frozen meats are marketed as fresh, is another frequent form of fraud (Ross *et al.*, 2021). Additionally, illicit use of unauthorized additives, preservatives, antibiotics, or hormonal agents to improve visual quality or prolong shelf life further contributes to the complexity and severity of meat adulteration (Nnaji *et al.*, 2025). A study of Abd-Elhafeez *et al.* (2022) reported the examination of 400 meat product samples, collected from local food markets in Sohag City, including minced meat, kofta sausage, beef burgers, and luncheon meat,

TABLE 28.1

Examples of Different Meat Frauds

Type of Fraud	Real-Life Example	Risks	References
Substitution	Beef was replaced with horse meat (EU horse meat scandal)	Loss of trust, dietary/religious concerns	Meulen *et al.*, 2025
Misrepresentation	Labeling imported meat as "local" (mislabeling of "Kobe beef" in restaurants.)	Misleading purchase decisions	Jurica *et al.*, 2021
Adulteration	Mixing fillers into ground beef (addition of water or soy protein)	Reduced nutritional value	Abd-Elhafeez *et al.*, 2024
Illegal processing	Slaughter in unapproved facilities	Food safety hazards	Nkosi, Bekker and Hoffman, 2021
Waste diversion	Reselling expired meat	Illness, contamination	Kempen, 2024
Document fraud	Counterfeit halal/*kosher* certificates	Regulatory failure, consumer deception	Mortas, Awad and Ayvaz, 2022
Theft and resale	Stolen meat is sold in markets	Traceability issues, safety concerns	Čapla *et al.*, 2022
Unapproved enhancements	Use of illegal additives to improve appearance	Toxicity risks	Mičović, Mantovani and Jevšnik, 2023
Counterfeiting	Fake branding/packaging of premium meat	Economic loss, consumer deception	Ueda *et al.*, 2022

FIGURE 28.1 Meat fraud types.

to detect food fraud. Histological examination revealed that, in addition to skeletal muscle, the meat products contained a variety of tissues such as nuchal ligaments, bones, hyaline cartilage, fibrocartilage, arteries, cardiac muscle, tendons, and collagenous connective tissue forming the capsule of parenchymatous organs. Crystals of food additives were identified using light microscopy and SEM, while SEM also allowed visualization of bacterial contamination. Another study of Kamruzzaman (2021) stated that in 2013, Ireland and the UK faced a major horsemeat scandal when beef products were found to contain undeclared horse and pork meat. As a result, more than 10 million burgers and other beef items were recalled from supermarkets.

28.2.2 Limitations of Traditional Detection Methods

Conventional analytical techniques used to detect meat adulteration, such as PCR-based assays, ELISA, electrophoretic profiling, and various chromatographic methods, suffer from notable constraints (Alhazmi and Albratty, 2023). These include substantial operational costs, labor-intensive and time-consuming sample preparation steps, and diminished reproducibility (Alhazmi and Albratty, 2023). Their performance declines particularly in processed or heavily adulterated products where DNA and protein components may be significantly degraded (Du *et al.*, 2023). Moreover, these methods are typically destructive, confined to laboratory settings, and unsuitable for rapid or on-site authentication (Aprilia *et al.*, 2022). They also struggle to reliably analyze complex food matrices, such as emulsified sausages or heat-treated meats, restricting their feasibility for large-scale or routine industrial monitoring.

These limitations have accelerated interest in next-generation analytical strategies based on AI, ML, and DL. When combined with spectroscopic techniques, such as near-infrared (NIR) and Raman spectroscopy, these computational approaches enable fast, nondestructive verification of meat authenticity (Chaudhary *et al.*, 2022; Chen *et al.*, 2024). By leveraging pattern-recognition algorithms and predictive modeling, AI-driven systems can achieve high precision in detecting species substitution and quantifying adulterants, offering a promising alternative for real-time, high-throughput fraud detection (Singh *et al.*, 2025).

28.3 AI Tools for Fraud Detection

28.3.1 ML Techniques Used in the Meat Industry

ML involves designing computational models capable of autonomously acquiring knowledge and enhancing their performance through accumulated experience. Various methodologies exist within this field, each offering distinct learning strategies. In recent years, ML has demonstrated significant effectiveness in areas such as meat authentication and fraud detection, delivering highly promising outcomes. Generally, ML approaches are categorized into two principal types: supervised learning and unsupervised learning (Figure 28.2) (Greener *et al.*, 2022).

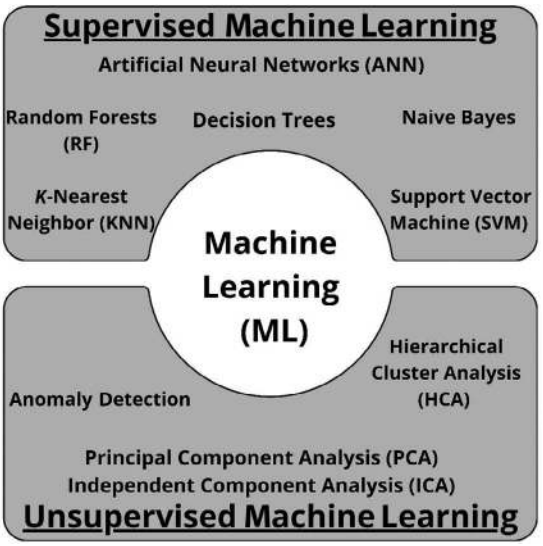

FIGURE 28.2 Machine learning models.

28.3.1.1 Supervised Learning

Supervised learning represents a core methodology within the field of ML, wherein algorithms are developed using datasets that contain predefined input–output pairs (Ren, Wang and Zhang, 2023). Through this framework, the model learns to associate inputs with their corresponding outcomes. Two primary forms of supervised learning exist: classification, which focuses on identifying discrete categories—for instance, distinguishing different types of meat—and regression, which aims to estimate continuous variables such as fat concentration or tenderness levels. Among the supervised learning techniques applied for both classification and regression tasks, the most widely utilized include ANN, decision trees, RFs, *K*-nearest neighbor (K-NN), Naive Bayes, and SVM. These algorithms have shown remarkable performance in meat authentication, achieving varying yet consistently high levels of accuracy across studies. These approaches are likewise employed to forecast shelf life, detect potential spoilage, and analyze consumer preferences derived from sensory evaluation data. In general, supervised learning contributes significantly to advancing decision-making and automation within the meat industry by facilitating rapid, precise, and nondestructive assessments of meat quality.

28.3.1.1.1 Decision Tree

Decision trees represent one of the most widely adopted supervised learning techniques for classification tasks (Lu, Ye and Zheng, 2022). In this approach, the classification process is organized in a hierarchical, tree-like structure that progresses from root to leaf nodes. The tree comprises three key components: root, internal, and leaf nodes (Ge *et al*., 2024). Internal nodes correspond to attribute-based tests, each branch reflects the outcome of such tests, and the leaf nodes deliver the final classification output by assigning a class label based on the overall decision process (Costa and Pedreira, 2023). The root node marks the initial step of the decision-making framework (González Rodríguez, Gonzalez-Cava and Méndez Pérez, 2020). Each decision tree is composed of data instances characterized by feature vectors, which contain descriptive attributes and corresponding class labels. The tree's hierarchical form enables intuitive visualization and straightforward interpretation (Lu, Ye and Zheng, 2022). Construction of a decision tree is an iterative process in which the dataset is recursively divided according to feature values, separating the samples into relevant subgroups until a specified stopping condition is achieved (Neelakandan and Paulraj, 2020). In classification, the feature space is partitioned into rectangular regions, with each region representing the most frequent class. During training, the decision tree algorithm systematically evaluates all possible division points for each variable to identify the most informative division (Costa and Pedreira, 2023). A major advantage of this approach is that it eliminates the need for fake variable formation during the classification process (Costa and Pedreira, 2023). Numerous studies have reported classification accuracies exceeding 90%, demonstrating the robustness of this model (Alsubai *et al*., 2024; Setiadi *et al*., 2022; Xu *et al*., 2023). For instance, Dashti *et al*. (2023) integrated Fourier transform infrared spectroscopy (FTIR) with multivariate classification algorithms to differentiate minced meats from various animal species (beef, lamb, chicken, and pork). The decision tree model was optimized to achieve perfect pork identification and a balanced rate of false positives and negatives. Despite their advantages, decision trees also exhibit some limitations. One major drawback is the tendency for excessive tree growth, which can lead to overly complex models containing a leaf for nearly every observation (Kulikov *et al*., 2023). Additionally, once a dataset is partitioned during training, the decisions cannot be revisited or modified, posing challenges for problem reevaluation.

28.3.1.1.2 Random Forest

A RF can be described as an enhanced ensemble extension of the decision tree algorithm, consisting of multiple trees constructed for both classification and regression purposes. It employs a collection of decision trees trained on randomly selected subsets of the original dataset, using sampling with replacement. For each subset, a random selection of features is drawn from the total feature set, and this tree-building process continues iteratively until an ensemble of classifiers achieving optimal accuracy is formed (Palimkar, Shaw and Ghosh, 2022). Similar to a decision tree, every tree within the forest independently generates a class prediction during the inference stage. Essentially, RF integrates multiple

decision trees, each exhibiting individual variability, into a collective model that is more robust, reliable, and less susceptible to overfitting (Halabaku and Bytyçi, 2024). Owing to its flexibility, resilience, and superior predictive capacity, RF has gained considerable traction in meat fraud detection (Mustapha *et al*., 2024). Nonetheless, the RF algorithm presents certain limitations, including challenges in model interpretability compared with simpler classifiers and reduced accuracy when an insufficient number of trees are generated (Lan *et al*., 2020).

28.3.1.1.3 K-Nearest Neighbor

K-nearest neighbor (K-NN) is a nonparametric algorithm widely utilized for classifying data points based on their similarity to existing samples (Wang, Chukova and Nguyen, 2023). The method operates on the principle that objects sharing similar characteristics are located close to one another in the feature space. Consequently, classification is determined by examining the proximity of an unclassified point to its neighboring data instances. Typically, the Euclidean distance metric is employed to measure the closeness between samples, and the class most frequently represented among the nearest neighbors is assigned to the new data point (Wang, Chukova and Nguyen, 2023). The algorithm identifies the *k*-nearest data points in the training set and assigns the category that dominates among those neighbors (Suyal and Goyal, 2022). Selecting an optimal *k* value is critical to balancing underfitting and overfitting. A very large *k* may include points from unrelated classes, while a very small *k* increases sensitivity to noise and outliers (Suyal and Goyal, 2022). The primary advantages of K-NN include its high predictive accuracy, computational efficiency during training, and simplicity, as it requires no explicit model building or optimization process. However, the prediction step can become computationally demanding when working with big datasets, making it less feasible for time-sensitive classification problems. K-NN has been extensively applied in engineering and pattern recognition, and its simplicity and accuracy have encouraged its adoption in agricultural research as well (Sudipa *et al*., 2024). For instance, Malikhah, Sarno, and Sabila (2021) applied K-NN to detect pork adulteration in beef using electronic nose data and reported excellent classification performance. Compared with other classifiers such as logistic regression (LR), SVM, linear discriminant analysis (LDA), and Naive Bayes, K-NN achieved the highest accuracy of 98.33% in distinguishing between pure beef, pork, and adulterated mixtures. Similarly, an experiment employing four metal oxide sensors to differentiate beef and pork samples based on odor profiles demonstrated that K-NN achieved the best performance, with a classification accuracy of 99.24% (Hamidon Majid *et al*., 2022). Moreover, Jia, Qin, and Zhao (2024) integrated NIRS and electronic nose technologies to detect adulteration of lamb meat with duck. Various classifiers, K-NN, RF, SVM, and backpropagation neural network (BPNN), were evaluated using an F1-score-based model reliability estimation (F1-score MRE). The recorded accuracy values were K-NN (85.21%), RF (81.94%), SVM (84.51%), BPNN (88.73%), and SSA-BPNN (94.36%). K-NN is considered a "lazy learning" algorithm because it performs no explicit model training before receiving queries, contrasting with "eager learning" methods such as decision trees, which structure the dataset before classification. The tuning parameter *k* is typically determined through cross-validation on the training set to ensure optimal predictive performance.

28.3.1.1.4 Support Vector Machine

SVM is a supervised learning algorithm widely employed for both classification and regression tasks. It is particularly valued for its powerful ability to separate data points using a hyperplane that clearly distinguishes between different classes (Cervantes *et al*., 2020). The algorithm functions by determining the optimal edge that maximizes the distance between vectors belonging to distinct categories. In this context, vectors represent numerical arrays that define the position of data points in a multidimensional feature space (Gaye, Zhang and Wulamu, 2021). When an SVM model identifies the optimal hyperplane, it essentially defines the line that divides the feature space into two distinct subregions, each corresponding to a specific class (Carta and Frigau, 2025). The fundamental objective of SVM is to establish a decision surface that classifies data points with the fewest possible misclassifications while simultaneously maximizing the margin between categories. Consequently, SVM models offer precise and consistent classification performance due to their emphasis on maximizing this edge. In fact, SVM has recently

gained significant prominence as a robust analytical tool for detecting meat adulteration and ensuring product authenticity (Siddiqui *et al.*, 2021). Numerous studies have demonstrated its effectiveness in meat adulteration with consistently high accuracy levels (Huang *et al.*, 2023; Siddiqui *et al.*, 2021). For instance, Siddiqui *et al.* (2021) developed a multiclass support vector machine (M-SVM) model to distinguish between authentic and adulterated meat sample products (beef, lamb, and chicken). For the cluster containing pure samples, the model achieved an overall classification accuracy of 81.25%. In contrast, when the adulteration proportion exceeded 10%, the detection accuracy for adulterated samples reached 71.21%. Among the evaluated meat types, beef and lamb samples, whether pure or adulterated, exhibited the highest classification performance, attaining an accuracy of 85%. In contrast, chicken samples recorded the lowest accuracy at 78% in both categories. This study presents an extensive spectral characterization of pure and adulterated samples of beef, lamb, chicken, and lard. Additionally, it proposes a fast and efficient M-SVM-based approach capable of reliably detecting lard adulteration across different meat matrices, even at minimal inclusion levels. In another way, and compared with RF and BPNN models, the SVM requires a smaller dataset for effective training, making it particularly well-suited for modeling applications related to meat adulteration detection (Huang *et al.*, 2023).

28.3.1.1.5 Artificial Neural Networks

ANNs are computational models designed to emulate the functioning of the human brain, drawing inspiration from biological neurons (Schmidgall *et al.*, 2024). These networks consist of interconnected neurons linked by weights, thresholds, and activation functions, which collectively process and propagate information (Schmidgall *et al.*, 2024). The fundamental unit, a perceptron, typically comprises three layers: an input layer, one or more hidden layers, and an output layer (Ünal and Başçiftçi, 2022). Each layer contains multiple neurons, which can enhance predictive accuracy while simultaneously increasing computational complexity (Ünal and Başçiftçi, 2022). The interconnections between neurons form a nonlinear and involved network, allowing the model to capture complex relationships within data (Schmidgall *et al.*, 2024). ANNs have been successfully applied across diverse domains due to their high classification accuracy, robustness, ability to model complex interactions, automation capabilities, and relative simplicity (Schmidgall *et al.*, 2024; Ünal and Başçiftçi, 2022). For example, a smart electronic nose was developed to detect both qualitative and quantitative adulteration of pork in beef using ANN-C and SVM-C as classifiers (Pulluri and Kumar, 2022). The study employed sample slicing windows, pattern recognition, normalization, and output blocks as datasets for validation (Pulluri and Kumar, 2022). ANN-C achieved remarkable performance, with a classification accuracy of 99.996% (Pulluri and Kumar, 2022). However, ANNs have certain limitations: input data often need to be converted to binary form, discrete variables cannot be directly used, and the models are prone to overfitting (Castillo-Girones *et al.*, 2025; Mondal, Maity and Nag, 2025). Furthermore, achieving optimal accuracy typically requires substantial computational resources.

28.3.1.1.6 Unsupervised Learning

Unsupervised ML operates on unlabeled datasets, directing algorithms to identify hidden patterns and organize the data according to similarity (Ma *et al.*, 2021). This approach primarily results in two types of grouping techniques: clustering and association. While other unsupervised methods exist, clustering and association are among the most frequently employed due to their broad applicability. In clustering, data points are grouped into clusters based on shared or distinct characteristics, without any prior labeling. The objective is to uncover inherent structures within the data. A notable challenge in clustering lies in determining the optimal number of clusters and interpreting the resulting groupings, which often requires expert domain knowledge. Association, on the other hand, seeks to detect relationships, patterns, or co-occurrences among dataset attributes, estimating the likelihood that certain items appear together. The most widely applied unsupervised ML techniques include *K*-means clustering, hierarchical cluster analysis (HCA), anomaly detection, principal component analysis (PCA), and independent component analysis (ICA). Among these, PCA and HCA are particularly prominent in food authentication and quality assessment applications due to their ability to simplify complex datasets and reveal meaningful structures.

28.3.1.1.7 K-Means Clustering

K-means clustering is a widely used unsupervised ML method that partitions datasets into *k* distinct clusters based on intra- and intercluster similarities (Chaudhry *et al.*, 2023). Each data point belongs to only one cluster, producing nonhierarchical and mutually exclusive groups. The algorithm begins by randomly selecting initial centroids, which represent the arithmetic mean of all points in a cluster. The Euclidean distance is commonly used to assign each data point to its nearest centroid. Centroids are then recalculated based on these assignments, and the process iterates until cluster convergence is reached (Abdalameer *et al.*, 2022). *K*-means is computationally efficient, simple to interpret, and scalable to large datasets, which makes it highly suitable for classification purposes (Ikotun, Almutari and Ezugwu, 2021).

28.3.1.1.8 Hierarchical Cluster Analysis

HCA is another unsupervised approach that constructs a hierarchy of clusters using either an agglomerative (bottom-up) or divisive (top-down) strategy. HCA produces a dendrogram, a graphical representation of the iterative clustering process based on similarity and grouping criteria. The algorithm evaluates similarities and dissimilarities within and between classes, and clustering can be influenced by choices such as distance metrics, scaling, linkage method, and sample selection (Ran *et al.*, 2023). HCA, often combined with PCA, has been extensively applied in food authentication, particularly for detecting non-*halal* components such as lard and gelatin (Rohman and Windarsih, 2020). The advantage of HCA lies in its ability to generate interpretable dendrograms without requiring the number of clusters in advance; however, it is computationally intensive for large datasets and sensitive to noise and outliers.

28.3.1.1.9 Anomaly Detection

Anomaly detection, often implemented using Gaussian mixture models (GMMs), is designed to identify observations that deviate significantly from expected patterns (Oluwasegun and Jung, 2023). The algorithm models normal behavior by analyzing multiple features of a sample, such as weight, mean, and covariance, and flags deviations as anomalies. GMMs are flexible and capable of handling both numerical and categorical data distributions. In the meat industry, anomaly detection is used to identify adulteration or non-*halal* products.

28.3.1.1.10 Principal Component Analysis

Principal component analysis (PCA) is an unsupervised, nonlinear statistical technique used to reduce dimensionality by transforming correlated variables into a set of orthogonal components, called principal components (PCs). These PCs capture the majority of variation within the data, simplifying analysis and highlighting significant patterns (Chaari *et al.*, 2023, 2024). PCA is one of the most widely used multivariate methods across scientific disciplines, including the identification of pigs and other non-*halal* derivatives in meat products (Ain Syaqirah Sapian *et al.*, 2023; Smaoui *et al.*, 2023). Additionally, PCA has been successfully applied in meat authentication. For example, it was combined with chemometrics to distinguish pure beef meatballs from those adulterated with pork (Rohman and Windarsih, 2020). Deep extreme learning machines (D-ELM) coupled with PCA achieved a 99.97% accuracy rate in detecting pork adulteration in beef (Du *et al.*, 2023).

28.3.2 Deep Learning

DL, a specialized branch of ML, leverages ANN with multiple interconnected layers to capture complex patterns within large datasets (Sarker, 2021). Among its architectures, convolutional neural networks (CNNs) are particularly prominent due to their exceptional capability in processing image and spatial data (Liu, Pu and Sun, 2021). CNNs automatically learn hierarchical features from raw input images, eliminating the need for manual feature engineering. This hierarchical learning allows DL models to perform highly accurate classification, detection, and segmentation tasks, making them especially suitable for visual inspection systems (Khan *et al.*, 2020). In the meat industry, DL has revolutionized conventional inspection techniques by facilitating automated, nondestructive quality assessments (Shi *et al.*, 2021). CNNs are applied to analyze meat cut images for defect detection, meat-type classification, marbling

TABLE 28.2

Machine Learning and Deep Learning Applications

Purpose	Model	Accuracy (%)	References
Classification of adulterated pork in beef and chicken meat	K-NN	98.33	Malikhah, Sarno and Sabila, 2021
Minced chicken meat adulterated with pork	SVM	97.78	Fengou, Tsakanikas and Nychas, 2021
Detection of beef adulterated with pork meat	ANN	91.27	Han *et al.*, 2020
Determination of minced beef adulteration	RF	87.78	Guo *et al.*, 2020
Adulteration detection of minced meat	Decision tree	95.33	Setiadi *et al.*, 2022
Classification of beef and pork meat	Naive Bayes	75	Wijaya, Sarno and Daiva, 2017
Adulteration of dog meat in beef meatballs	PCA	–	Rahayu *et al.*, 2018
Classification of lard from other animal fats	HCA and PCA	98	Ain Syaqirah Sapian *et al.*, 2023
Detection of beef adulterated with pork	PCA, CNN and RF	–	Huang and Gu, 2022
Detecting pork adulteration in beef for halal authentication	SVM	98.10	Sarno *et al.*, 2020
Chicken meat authenticity	ANN and SVM	>95	Parastar *et al.*, 2020
Duck meat adulteration in lamb rolls	PCA-SVM	96.25	Zhang, Ma and Ma, 2025
Detection of adulteration in mutton	CNN	–	Zhang *et al.*, 2022b
Determination of adulteration in ground beef	CNN	84–99	Bahmani *et al.*, 2024
Adulteration identification of beef and mutton	CNN and 2D correlation spectroscopy	100	Wang *et al.*, 2024
Adulteration detection in ground beef	CNN	99	Bahmani *et al.*, 2025
Classification of pork adulteration in beef-based	Extreme learning machine (D-ELM) and PCA	99.97	Avian *et al.*, 2022
Identification of counterfeited beef	SVM and CNN	98.84	Jo *et al.*, 2023

evaluation, and overall quality grading (Table 28.2). Furthermore, DL underpins robotic vision systems in processing lines, ensuring rapid, consistent, and precise sorting and packaging (Vasudevan *et al.*, 2024). With ongoing improvements in imaging technologies and computational resources, DL is increasingly becoming a critical tool for enhancing efficiency, accuracy, and food safety in meat production and inspection operations (Singh *et al.*, 2025).

28.3.2.1 CNN-Powered Imaging Techniques for Accurate Meat Adulteration Analysis

A novel and robust strategy for identifying and quantifying adulteration in minced mutton is presented in the study of Zheng *et al.* (2021), leveraging thermal imaging in combination with a CNN. Thermal video recordings were first obtained for 35 pure mutton samples, 35 pure pork samples, and 175 mixed samples containing mutton adulterated with pork at five concentration levels (10%, 20%, 30%, 40%, and 50%) during a controlled heating process (Zheng *et al.*, 2021). From these recordings, thermal frames corresponding to the rapid-heating phase were extracted, and feature data from predefined regions of interest were used to construct qualitative and quantitative CNN models (Zheng *et al.*, 2021). Model development involved comparing learning rates and mini-batch sizes to identify optimal training parameters. Subsequently, the best-performing classification network was selected for discriminating among pure mutton, adulterated mutton, and pure pork samples. In parallel, the most accurate regression-based CNN model was chosen for predicting the proportion of pork in adulterated mixtures (Zheng *et al.*, 2021). The optimized qualitative model achieved validation and test accuracies of 99.97% and 99.99%, respectively,

while the quantitative model yielded, for both validation and test sets, a determination coefficient of 0.9933, RMSE values of 0.0251 and 0.0252, and relative prediction deviation (RPD) values of 12.2487 and 12.2387 (Zheng *et al*., 2021). These findings demonstrate that thermal imaging coupled with CNN modeling provides highly accurate classification and precise quantification of meat adulteration. Given its low cost and operational simplicity, this approach offers substantial potential for practical use in food adulteration monitoring and regulatory control (Table 28.2). Similarly, Bahmani *et al.* (2025) explored thermal imaging as a tool for detecting adulteration in ground beef using two datasets, each containing different types of impurities: sheep lung and chicken gizzard. To determine the most effective feature extraction and classification strategy for differentiating adulteration levels, several algorithms, like local binary patterns (LBP), gray-level co-occurrence matrices (GLCM), and Gabor filters, were systematically evaluated. The CNN was also employed for end-to-end feature extraction and image classification. The algorithms were compared based on accuracy, precision, recall, specificity, and *F*-score. Across both datasets, Gabor filtering produced the strongest traditional ML performance, whereas LBP yielded the lowest. Nevertheless, the CNN consistently outperformed all other approaches, achieving overall accuracies exceeding 99% for both impurity types. These findings highlight the clear advantage of CNN-based modeling over conventional ML algorithms for detecting adulteration in minced meat. The experimental outcomes and corresponding data analysis confirm that thermal imaging, when paired with advanced DL techniques, is a highly effective method for identifying meat fraud and holds strong promise for real-time, online monitoring applications.

To verify the authenticity of meat slices Liu *et al.* (2023), used CNN with an architecture consisting of 14 convolutional layers organized into 4 blocks for robust visual feature extraction. This method includes residual connections, depth-wise convolutions, dropout, and batch normalization to enhance performance and stability. A total of 77,956 meat images were collected to train and evaluate the model across different meat categories. Using this dataset (comprising various types of meats), the proposed method achieved 99.38% for lamb slice authentication and 98.20% for beef slice authentication, demonstrating strong potential for practical, on-site adulteration detection by everyday consumers. In another study, a recurrence plot–based spectral transformation integrated with RP-CNN was used to identify pork-adulterated mutton (Zhang *et al*., 2022a). A total of 100 adulterated samples, prepared by mixing mutton with pork at five concentration levels (0.5%, 1%, 2%, 5%, and 10% w/w), along with 20 pure mutton samples, were used to construct the models (Zhang *et al*., 2022a). Both the classification network for detecting adulteration and the regression model for estimating pork content demonstrated consistent performance across fresh, frozen–thawed, and combined sample sets (Zhang *et al*., 2022a). The classification accuracies for the three datasets reached 100.00%, 100.00%, and 99.95%, respectively. For quantitative prediction of pork proportions, the determination coefficients (R^2) were 0.9762 for fresh samples, 0.9807 for frozen–thawed samples, and 0.9479 for the mixed dataset (Zhang *et al*., 2022a). These findings indicate that hyperspectral data, when processed through the proposed RP-CNN framework, offer strong capability for both identifying adulterated mutton and accurately estimating its pork content (Zhang *et al*., 2022a).

28.3.2.2 Applications of Hyperspectral and Spectroscopic Data Analysis and AI to Fraud Detection

AI has rapidly become a transformative tool in detecting meat adulteration, particularly through its integration with advanced image processing techniques. Image-based AI systems leverage visual and spectral data to identify subtle variations in color, texture, structure, or composition that may indicate adulteration—differences often imperceptible to the human eye. By combining image acquisition technologies such as HSI, multispectral imaging, NIR imaging, and conventional RGB photography with ML and DL algorithms, researchers have developed powerful, nondestructive, and rapid analytical approaches for meat fraud detection. Depending on factors such as the nature of the meat matrix, the type of adulteration, the instrumentation used, and the level of technical expertise, the integration between image acquisition techniques and AI-based analytical models varies across studies (Table 28.3). As this research area continues to evolve, it holds substantial promise for the development of efficient, portable, and easy-to-operate tools dedicated to meat quality monitoring and control.

TABLE 28.3

Overview of Research Integrating Spectro-Imaging and AI Approaches in Meat Fraud Detection

Aim	Spectro-Imaging Approaches	AI Methods	Results	References
Detection of beef adulterated with chicken, duck, or pork	MALDI-TOF-MS	Partial least-squares discriminant analysis (PLS-DA) and extreme gradient boosting (XGBoost)	*Accuracy*: 97.4%	Pu *et al.*, 2023b
Detection of plant and animal adulterants in minced meat	RGB color imaging	CV and SVM	Accuracy 100% in detecting meat adulteration Accuracy 76.1% in identifying the type of adulteration	Rady, Adedeji and Watson, 2021
Red-meat classification (i.e., lamb, beef, and pork)	Near-infrared (NIR) and visible (VIS)	3D-CNN	Accuracy of 96.9% for NIR Accuracy of 97.1% for VIS	Al-Sarayreh *et al.*, 2020
Differentiating distinct minced meat types (beef, mutton, and chicken)	HSI	CNN	*Accuracy*: 94%	Ayaz *et al.*, 2020b
Distinguishing fresh and frozen-thawed beef	HSI	CNN	*Accuracy*: 88.89%	Pu *et al.*, 2023a
Discriminate between freshly refrigerated, long-term refrigerated, and thawed beef meat samples	HSI	Partial least-squares discriminant analysis (PLS-DA) and SVM	*Accuracy*: 96.57%	Park *et al.*, 2023
Freshness assessment in lamb meat using hyperspectral imaging	HSI	Least squares support vector machine (LSSVM)	The integration of HSI with ML-based optimization techniques offers a powerful approach for achieving fast and precise evaluation of lamb meat freshness	Zhang, Ma and Ma, 2025
Monitor residual nitrite concentrations in emulsified pork sausage	HSI	XGBoost, CATboost, and LightGBM	The combination of HSI and sophisticated ML algorithms provides a rapid, nondestructive approach for real-time detection of residual nitrite levels in processed meats	Son *et al.*, 2024
Fish classification model	Multispectral imaging (MSI)	CNN, quadratic discriminant analysis (QDA), SVM, and linear discriminant analysis (LDA)	*Accuracy*: 98%	Xun *et al.*, 2024
Detection of foreign materials on poultry meat	HSI	Generative adversarial network (GAN)	The integration of spectral clustering, synthetic spectrum generation, and the U-Net framework achieved superior anomaly detection performance with substantially reduced dependence on manual annotation	Campos *et al.*, 2023
Developing a beef cut classification	MSI	LDA, SVM, and RF	The findings indicate that the optimized LDA classifier attained a prediction accuracy exceeding 90% through the integration of multimodal feature fusion	Li *et al.*, 2021

Over the past decade, HSI has emerged as a powerful and extensively adopted analytical tool for evaluating meat quality and safety. This technology enables the simultaneous collection of spectral and spatial data from samples in a rapid, noninvasive, and nondestructive manner (Bhargava *et al.*, 2024). HSI has been effectively employed to predict a wide range of meat quality attributes, including pH (Dixit *et al.*, 2021), tenderness (Lee *et al.*, 2025), intramuscular fat content (Dixit *et al.*, 2021), and marbling degree (Wold *et al.*, 2022). Moreover, it has demonstrated great potential in detecting adulteration, whether through the substitution of different meat species or the addition of nonmeat substances (Yang *et al.*, 2023). Given the complexity and high dimensionality of hyperspectral datasets, conventional statistical and ML algorithms such as SVM or K-NN are typically applied only after dimensionality reduction (Liu *et al.*, 2026). To address this, several preprocessing strategies have been proposed, including averaging spectra within regions of interest, applying PCA, and using spectral angle mapping techniques (Cruz-Tirado *et al.*, 2024; Saleem *et al.*, 2022). An alternative strategy involves treating each pixel's spectral signature as an independent observation, thereby enabling direct model training using statistical or learning-based approaches (Ahmad *et al.*, 2022). While these methods have yielded satisfactory outcomes, more recent advances emphasize the superiority of CNNs in automatically extracting both spectral and spatial features from hyperspectral data. CNN-based models have proven particularly efficient for assessing meat quality and authenticity. For instance, Ayaz *et al.* (2020) confirmed CNNs' enhanced capability to distinguish between minced beef, mutton, and chicken compared with traditional SVM and K-NN classifiers. Further, Al-Sarayreh *et al.* (2020) highlighted the efficiency and robustness of 3D CNN models for handling HSI data in meat analysis. In parallel, ML algorithms coupled with conventional RGB imaging have also shown remarkable success in detecting and quantifying both plant- and animal-based adulterants in minced meat (Rady, Adedeji and Watson, 2021). The proposed approach achieved perfect discrimination between authentic and adulterated samples, with accuracies reaching 76.1% and correlation coefficients (*r*-values) up to 0.98 for adulterant identification and quantification. Collectively, these findings underscore the transformative potential of AI-driven image processing as a reliable, rapid, and highly accurate approach for ensuring meat authenticity and detecting adulteration within the meat supply chain. Furthermore, Fengou, Tsakanikas, and Nychas (2021) employed multispectral imaging combined with SVM to differentiate between chicken and pork meat under various adulteration scenarios, obtaining an accuracy of 95.31%. In another investigation, Dashti *et al.* (2022) utilized FTIR coupled with multivariate analytical methods, including SVM and partial least squares, discriminant analysis (PLS-DA) using a radial basis function (RBF) kernel, to classify minced beef, lamb, and chicken adulterated with pork. The results revealed that SVM outperformed other classifiers, achieving 98% classification accuracy. In another investigation, K-NN and SVM were combined with HSI and multivariate analysis to detect chicken breed fraud. Breast meat images from four different breeds were captured in the NIR range (900–1,700 nm), preprocessed for spectral feature extraction, and subsequently analyzed, yielding a classification accuracy of 98% (Zhang *et al.*, 2020). Dashti *et al.* (2023) utilized a combination of shortwave infrared HSI (SWIR-HSI, 1,116–1,670 nm) and visible–near-infrared hyperspectral imaging (vis-NIR-HSI, 400–1,000 nm) to authenticate pork adulteration in beef, lamb, and chicken. Multivariate analyses incorporating SVM and ANN with backpropagation (ANN-BP) revealed that these models provided highly accurate meat adulteration detection. Guo *et al.* (2020) evaluated hyperspectral reflectance spectroscopy combined with multivariate methods to detect beef adulteration. The study included 30 pure minced beef samples and 90 adulterated ones at varying contamination levels. The RF model successfully identified adulterated samples, achieving a prediction accuracy of 96.87%. Feature selection via the successive projection algorithm further enhanced the model's robustness. Similarly, Sun *et al.* (2022) applied complementary spectral data integration to improve the classification of beef, mutton, and pork tissues using laser-induced breakdown spectroscopy (LIBS) and Raman spectroscopy. Three configurations, LIBS, Raman, and combined LIBS–Raman, were tested. A BPNN, with input features optimized through RF, was trained and validated using a tenfold cross-validation approach. The combined LIBS–Raman model demonstrated the highest accuracy, reaching 99.42%.

28.4 Integration of AI and Cybersecurity in Detecting Food Fraud

Cybersecurity encompasses the strategies, tools, and expertise required to safeguard digital infrastructures, including computer systems and communication networks, from unauthorized access or damage. In recent years, the frequency and sophistication of cyberattacks have escalated worldwide, disrupting numerous domains such as food quality and meat fraud detection. The integration of emerging technologies within industrial systems further amplifies vulnerabilities, making cybersecurity a critical consideration during technological adoption. A notable example is the cyberattack on JBS, one of the largest meat processing companies in the United States, which led to significant operational disruptions and product shortages (Chundhoo *et al.*, 2021). Given the vital role of the meat industry in maintaining global food security, protecting its digital and information infrastructures is imperative to prevent potential threats and ensure the continuity of the supply chain. Emerging technologies, including cloud computing security, IT network protection, IoT (Internet of Things) safeguards, blockchain-based security systems, and even metaverse defense mechanisms, are reshaping the overall landscape of cyber risk management. Core AI methodologies play a pivotal role in strengthening cybersecurity by enabling predictive threat detection, behavioral pattern recognition, and the verification of smart contracts. When integrated, these AI-driven tools enhance one another's capabilities, offering comprehensive solutions that address challenges related to transparency, traceability, auditability, and the protection of digital infrastructures within global food supply chains. Collectively, these advancements underscore the growing and transformative role of cybersecurity technologies in the food sector.

28.5 Blockchain and Traceability Technologies in the Meat Supply Chain

As global trade and food systems become increasingly interconnected, consumers face growing difficulty in verifying the true origin of their food. Blockchain-based traceability frameworks aim to close this information gap by offering accurate, verifiable records from production to retail (Ellahi, Wood and Bekhit, 2023). Blockchain technology, an open, shared database built upon a distributed ledger system, fundamentally transforms the conventional operations of food supply chains. It records and preserves every transaction across the chain, thereby minimizing the risk of data manipulation and ensuring the integrity of information. These characteristics enable real-time traceability and transparency throughout the production and distribution process. For instance, blockchain systems play a crucial role in combating substitution and authenticity fraud by allowing stakeholders to verify that premium products, such as organic foods, and maintain their authenticity from origin to point of sale (dos Santos, Torrisi and Pantoni, 2021). In addition, Lin *et al.* (2022) reported that 37% of Chinese consumers were willing to pay a premium for blockchain-certified US beef. In another way, the integration of blockchain with AI further enhances its functionality. By applying ML algorithms to historical blockchain data, systems can identify irregularities and predict potential fraud risks. Techniques like pattern recognition allow for the early detection of anomalies, such as inconsistent delivery schedules or unusual ingredient supplies (Ellahi *et al.*, 2025). When combined with blockchain's robust data integrity, AI serves as a powerful analytical extension of organizational infrastructure, enabling the food industry to transition from reactive responses to proactive, intelligence-driven decision-making. Despite these advancements, the large-scale implementation of blockchain technology in food traceability still faces significant barriers. Successful adoption requires collaboration among supply chain partners, financial investment, and consumer readiness to engage with digital traceability systems (Al-Farsi, Rathore and Bakiras, 2021). Challenges include technological immaturity, lack of standardized implementation guidelines, and operational complexity (Katsikouli *et al.*, 2021). Behnke and Janssen (2020) identified 18 prerequisites for effective deployment. Moreover, the high cost of infrastructure and the need for skilled personnel restrict accessibility for small and medium enterprises (Collart and Canales, 2022). Consequently, blockchain adoption is currently most feasible for premium products where consumers are willing to absorb the added cost. Nonetheless, persistent issues such as governance, trust, human error, data accessibility, intellectual property rights, and residual fraud risks must be addressed to achieve widespread, reliable

use of blockchain in global food supply chains. Through blockchain integration, secure tags, QR codes, and RFID (radio frequency identification) ensure real-time validation and transparency across the supply chain. Secure tags and RFID chips are employed to continuously track and monitor products, while QR codes linked to blockchain databases allow consumers to instantly verify product authenticity at any point in the distribution network (Mishra, Sethy and Behera, 2025). This interconnected system not only empowers consumers with immediate access to trustworthy information but also acts as a strong deterrent against fraudulent practices, significantly reducing the likelihood of data tampering or product misrepresentation (Bansal *et al.*, 2024; Sikder, 2023).

RFID technology is one of the most extensively utilized electronic tools for ensuring traceability within food supply chains. Serving as a more advanced alternative to traditional barcodes, RFID offers numerous advantages due to its ability to identify, track, and classify meat products automatically through electromagnetic waves in the radio frequency spectrum (Costa *et al.*, 2021; Qiao, Hao and Guo, 2023). By capturing data at multiple stages of the supply chain and transmitting it to a centralized database, RFID facilitates whole access to product information for various stakeholders (Qiao, Hao and Guo, 2023). Its primary function lies in documenting and sharing data related to the food products, from producers to consumers, thereby enabling the detection of process delays, quality deviations, noncompliance, and breaches in product integrity (Marindra, Pratama and Suroso, 2023; Syahputri and Sucipto, 2021). This traceability also allows rapid identification of contamination sources and supports efficient recall actions, minimizing the risk and impact of foodborne outbreaks (Sharif *et al.*, 2021). Furthermore, RFID has gained considerable traction in food tracking due to its cost-effectiveness, ease of configuration, and technological robustness. RFID-generated data can be analyzed through big data techniques and predictive models to reveal consumer behavior patterns and optimize distribution processes (Marindra, Pratama and Suroso, 2023; Syahputri and Sucipto, 2021). Numerous studies have evaluated its applicability to diverse food sectors, including livestock, meat, and meat products (Botilias *et al.*, 2023). For example, Qiao, Hao and Guo (2023) developed a traceability system for meat safety based on UHF RFID technology to establish a fully integrated information chain. Its main advancement lies in creating a complete and continuous record of traceability data, enabling precise acquisition of key information for each batch throughout all production stages: breeding, slaughter, transportation, and retail (Qiao, Hao and Guo, 2023). The system incorporates a cost-effective and robust UHF RFID reader that applies the Q-value algorithm to efficiently capture traceability data from meat products during both processing and distribution. It also supports multiple communication interfaces, including LoRa wireless, USB, RS485, and RJ45 Ethernet, ensuring broad adaptability for tag identification in diverse application environments (Qiao, Hao and Guo, 2023). The traceability platform was built using LabVIEW and integrates several functional modules, such as user and login management, farm operations, slaughterhouse processes, logistics tracking, and sales monitoring (Qiao, Hao and Guo, 2023). Despite its technological sophistication, RFID systems are not resistant to data reliability challenges. Manually uploaded information and the absence of robust verification mechanisms can lead to inaccuracies, data omissions, or misreads throughout the supply chain. These errors compromise the authenticity of traceability data, posing significant limitations for RFID when used in high-integrity applications such as food authentication or fraud prevention.

28.6 Cyber Threats Related to AI Technologies and Ethical Issues

The adoption of AI-driven technologies for identifying meat fraud and adulteration has significantly enhanced meat safety monitoring, but it has also introduced complex cybersecurity and ethical challenges that require immediate consideration. Recent studies show that AI systems are very effective at analyzing large datasets and quickly detecting fraud. However, they are also vulnerable to serious cyber threats such as ransomware, data poisoning, and adversarial attacks. These attacks can distort the accuracy of detection models. They can also compromise the security and reliability of the entire meat supply chain (Rizwan Abid, Ur Rahman and Khalid, 2025). These risks are amplified by the widespread use of interconnected IoT devices, which cybercriminals increasingly target through AI-enhanced phishing schemes and malware, lowering the expertise needed to carry out sophisticated intrusions (Latino and Menegoli, 2022). Moreover, the deliberate manipulation of AI systems using adversarial inputs

enables attackers to bypass detection mechanisms, creating opportunities for adulterated meat products to evade scrutiny and ultimately posing substantial risks to public health. AI- and IoT-driven meat authentication systems collect highly sensitive information, ranging from proprietary supplier records to consumer behavior patterns, making rigorous privacy protection and robust data-security safeguards essential (Dakhia, Russo and Merenda, 2025). Researchers increasingly report that biases embedded within AI training datasets can generate uneven or discriminatory outcomes, disadvantaging specific producers, geographical regions, or consumer groups (Bozeman *et al*., 2024). These concerns highlight the critical need for diverse, representative datasets that capture the full variability of meat products and supply chain environments, thereby reducing misclassification rates and ensuring equitable assessments (Dakhia, Russo and Merenda, 2025; Latino and Menegoli, 2022). The economic and operational consequences of cybersecurity failures in AI-enabled meat fraud detection are substantial. Breaches can disrupt supply chains, trigger regulatory sanctions, erode consumer trust, and produce significant financial losses (Adepoju, 2024). Employing integrated AI-based security frameworks consistently achieves faster threat identification and more accurate detection of cross-channel fraud. Nevertheless, excessive dependence on automated systems without sufficient human oversight or clear governance structures heightens systemic vulnerabilities. These challenges underscore the need for a balanced model in which AI capabilities are complemented by expert interpretation and transparent decision-making processes. From an ethical perspective, it is imperative that advances in fraud detection technologies remain accessible to producers of all scales. Ensuring that small and medium enterprises can adopt and benefit from these tools is essential for maintaining fair market competition and safeguarding public health across diverse economic contexts.

28.7 Conclusion

AI is increasingly recognized as a transformative driver within the meat sector, offering novel strategies that span the entire production continuum, from livestock management to consumer delivery. By leveraging data-centric approaches, AI tools like ML enhance operational efficiency, precision, and uniformity in meat production, processing, and distribution. Practical implementations, including quality evaluation, supply chain optimization, fraud prevention, and automation of processing workflows, highlight the advantages of embedding intelligent systems into conventional meat industry operations. Moreover, AI equips producers to align with rising consumer expectations for products that are safer, higher in quality, and ethically sourced. As algorithmic sophistication grows and computational resources become more available, opportunities for innovation within the sector continue to broaden. The convergence of IoT technologies, big data infrastructures, and real-time analytical tools is fostering a more intelligent and sustainable meat industry. Ultimately, the future trajectory of the meat industry is closely tied to the effective adoption and scaling of AI solutions. Although challenges related to data integrity, infrastructural constraints, and regulatory compliance persist, the potential for substantial long-term improvements is significant. Through targeted investment, interdisciplinary collaboration, and responsible deployment, AI is poised to fundamentally reshape the meat industry, promoting efficiency, sustainability, and innovation over the coming decades.

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Part III

Consumer Perspectives on Ethics and Market Trends in Meat Science

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29

Labeling and Transparency: Meeting Consumer Trust in Meat Products

Theodoros Varzakas

29.1 Introduction

Global greenhouse gas (GHG) emissions are largely affected by food production and consumption; almost one third of the global population's carbon footprint is estimated to arise from food systems (Thøgersen, 2021).

Dietary shifts toward more plant-based and plant-rich diets would be required to minimize the environmental impact of food and meet the nutritional needs of populations (Searchinger *et al.*, 2019).

The impact of food choices on the climate change is very well-known; however, consumers still need help in order to make informed decision-making (Thøgersen, 2021), and try to change their everyday consumption habits. Hence, nudge theory and behavioral economics could guide consumers throughout the decision-making process, as reported by ElHaffar *et al.* (2025) and Thaler and Sunstein (2009).

Consumers need eco-friendly food choices, hence eco-labels could be employed as a simple approach, not requiring high levels of literacy and numeracy (Rothman *et al.*, 2006; Slapø and Karevold, 2019). Eco-labels provide information or environmental quality claims to consumers so that they make informed decision-making without compromising their freedom of choice (Potter *et al.*, 2021; Thøgersen, Haugaard and Olesen, 2010).

According to Potter *et al.* (2021), an association of the implementation of these labels with an increased selection and purchase of more sustainable food products is observed. Populations, demographics, psychographics, situational context, and the labels' visual presentation display variations (Bschaden *et al.*, 2024; Rondoni and Grasso, 2021). Moreover, the interconnection between environmental labels with price convenience and taste along with other factors alone might affect behavioral change (Hoek *et al.*, 2017; Vanclay *et al.*, 2011).

Service innovation of blockchain technology (BCT) might offer a potential solution to traceability issues in the meat supply chain (e.g., window dressing, information fraud) (Kumar, 2016; Lemieux, 2016). Peer-to-peer transactions and ease traceability through BCT are facilitated by secure and approved information (Kumar, 2016; Lemieux, 2016). Moreover, BCT is defined as an electronic ledger for digital datasets, events, or transactions, governed by a widespread computer network (Condos, Sorrell and Donegan, 2016).

Sander, Semeijn, and Mahr (2018) demonstrated that the amount and complexity of certification labels makes consumers overwhelmed. Consumers' purchasing decisions, mediated by consumers' quality perceptions, are affected significantly by BCT implementation as a transparency and traceability system (TTS). They revealed the significance of a BCT-based TTS for the discordant perspectives of different stakeholders. The combination of this technology with DNA coding could offer serious advantages.

Consumers should make healthier and more sustainable food choices (Storcksdieck Genannt Bonsmann *et al.*, 2020).

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29.2 Eco-Labels

More sustainable food choices were made by consumers when traffic light labels along with posters were employed, thus reducing the sales of meat dishes significantly (Slapø and Karevold, 2019).

The share of low-impact food options increased significantly by traffic light labeling, as reported by Brunner *et al.* (2018). Osman and Thornton (2019) also found an association between traffic light labels and promotion of sustainable meal choices.

Montagni *et al.* (2020) tracked employees' food purchases and found the effectiveness of green labels across multiple locations of the same company in France and the United States. They also reported that promotion of healthy eating habits among employees in the workplace using a positive nudge could arise from food labeling.

Moreover, mixed or no effects of the interventions have been reported in various studies. For example, Pechey *et al.* (2022) found that the sustainability of customers' food choices regarding effectiveness of eco-labels (A to E with color codes) in worksite cafeterias was not affected significantly regarding influence of interventions. Similarly, Casati *et al.* (2023) introduced a carbon footprint label in a restaurant setting and found no significant direct effect. However, they reported that this information might affect positively their choices in the future. Lo *et al.* (2024) also found that carbon emission information labeling had a positive effect on the restaurant's perceived social responsibility.

Poor intervention designs (e.g., label placed on the menu and not on the displayed dish), the type of demographic targeted (blue collar) (Pechey *et al.*, 2022), and the eco-label format (single logo, traffic light, or no visual) might attribute to this ineffectiveness.

Finally, food eco-label interventions have been discussed by Bschaden *et al.* (2024) who concluded that the gastronomic setting effected significantly on the intervention's success.

29.3 Price and Other Factors

Vanclay *et al.* (2011) found that cheap low-carbon products increased sales by 20%. Consumers' decisions are affected by price, information format, and market share along with carbon labeling (Gadema and Oglethorpe, 2011; Hartikainen *et al.*, 2014; Lo *et al.*, 2024; Sharp and Wheeler, 2013).

Reinholdsson *et al.* (2023) suggested an association between the utilization of hedonic goals in vegetarian food promotion and overall positive effect on the sales of vegetarian meals. Similar results have been reported by Turnwald *et al.* (2019) in their randomized controlled experiment. Weijers *et al.* (2024) encourage a selection of plant-based meals in restaurants by testing three menu nudges that restaurant owners would be predisposed to apply.

Consumer's sustainable food choices could also be affected by the dish's regional origin. Generally, sustainability of a food product is impacted by the signal "locally grown" (Wijayatunga *et al.*, 2024). Locally produced food show positive attitudes (Kenny *et al.*, 2023). Ohlhausen and Langen (2020) investigated the most sustainable dish on a menu and the decoy effect (DE), in order to promote eco-friendly food choices outside home by comparison of the effectiveness of two different nudges, descriptive name labels (DNLs).

Finally, food choices are heavily affected by the dish type, along with the taste implications and related expectations associated. Drewnowski and Monsivais (2020) reported on taste and its effect on food choice, followed by cost and convenience. Taste and health perception of vegetarian diet in relation to adequate nutrition deterred most meat eaters (Rosenfeld and Tomiyama, 2020). Hence, a serious thought has been given in the shift from meat to vegan/vegetarian. In the context of experimental settings, Bradford, Hancox, and Bryant (2022) found that experimental conditions did not affect preference for meat or vegan food due to their stability.

29.4 Trust

Trust presents different sides and dimensions such as cognitive, emotional, and behavioral which are merged into a unitary social experience constitute trust (Lewis and Weigert, 1985). Our choice to trust and our reasons for doing so along with our "evidence" of trustworthiness means cognitive. Cognitive components constitute affective states (Jones, 1996).

Cognitive is being complemented by the emotional base. Hence, the formation of the emotional bond between the trustor and the person, group, or system where trust is built (Lewis and Weigert, 1985).

The interconnectedness of cognitive and emotional bases of trust have been stated (Mollering, 2006).

Of course, if trust in food systems is violated, then outrage is formed.

These bases for trust are significant in the maintenance of a trusting relation and are affected by perceived trustworthiness indicators (Barber, 1983; Mollering, 2006). Mollering (2006, p. 48) suggests a trustworthy actor to be someone not exploiting the trustor's vulnerability. Similarly, Poppe and Kjaernes (2003, p. 89) report on telling the truth and being sincere as a valid trust dimension. Manipulation or deception of trustees affect the trustworthiness of the stakeholders (Khodyakov, 2007; Lewis and Weigert, 1985).

Of course, trust is based on faith (Giddens, 1990; Luhmann, 1979; Simmel, 1978), but is dynamic when new information through social interaction is presented (Hobbs and Goddard, 2015; Mollering, 2006).

There is differentiation between trust and labeling (Tonkin *et al.*, 2015).

Garretson and Burton (2000) show labeling as a good example of trust showing perceptions of manufacturer credibility.

Moreover, formation of trust-related judgments about something other than a technical message can be carried out by label elements communicating technical information.

However, trust judgments can be formed through food safety labeling (Batrinou, Spiliotis and Sakellaris, 2008), food governance (Poortinga and Pidgeon, 2004), and specific food actors and food supply (Coveney, 2008; Van Rijswijk and Frewer, 2012).

Hence, consumers' trust in the food system is affected by their interaction with food labeling (Batrinou, Spiliotis and Sakellaris, 2008; Garretson and Burton, 2000; Poortinga and Pidgeon, 2004; Tonkin *et al.*, 2016).

Gellynck, Verbeke, and Vermeire (2006) reported that despite the abundant rise of information through labeling, traceability systems, and quality assurance schemes, the effect on consumer trust in meat as a safe and wholesome product is only limited.

Moreover, misunderstanding and misinterpretation could be caused by this overload and complexity of information on food products. Process traceability attributes such as origin and production method as a response to meat quality concerns could interest particular market segments.

In Figure 29.1, the association between food manufacturers and consumers is presented, showing the interaction between traceability and production for the manufacturers and the consumers taking into account factors of personal behavior, characteristics, and perception with regard to meat quality and safety. A similar framework has been presented by Gellynck, Verbeke, and Vermeire (2006).

Framing theory (Carragee and Roefs, 2004; Goffman, 1974; Harris *et al.*, 2017) explores how individuals' perceptions, attitudes, and decision-making are affected by the presentation or framing of information. Frames are "schemata of interpretation", empowering individuals to pinpoint, perceive, identify, and label events and situations within their social world. Hence, attribution of meaning to these occurrences,

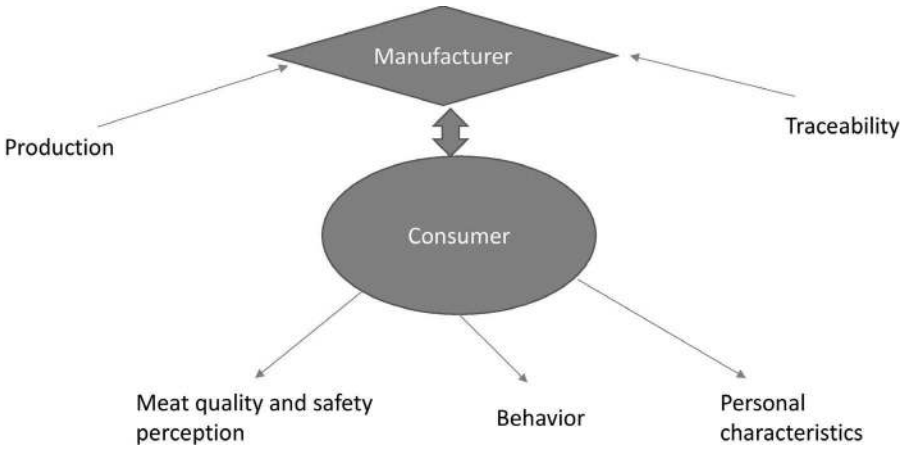

FIGURE 29.1 Association between food manufacturers and consumers.

facilitating potential actions, is achieved (Goffman, 1974). Presentation of information can shape the interpretation and understanding by people, ultimately influencing their responses and behaviors (Druckman, 2001).

29.5 Blockchain Food Supply Chain

People can be protected from fraudulent stakeholders by a trusted food supply chain network, hence providing a secure information structure about transactions.

The interorganizational system is being connected by information technology, hence achieving a reduction in business-to-business systems (B2B) boundaries for connection of farms, traders, and the food industry electronically. Artificial intelligence (Modgil, Singh and Agrawal, 2022; Modgil, Singh, and Claira, 2022; Singh, Modgil and Shore, 2023), Internet of Things (IoT), BCT, robotics, drones, as well as big data analytics (Ali and Thai, 2020) all are part of the adoption of Industry 4.0 and 5.0 technologies.

Future industry and revolution will be facilitated by BCT (Dubey *et al*., 2022; Zhao *et al*., 2019). Significant benefits will be brought by the integration of BCT with the supply chain in the agri-food industry (Yli-Huumo *et al*., 2016).

Traceability (Sharma *et al*., 2023a, 2023b; Kamilaris, Fonts and Prenafeta-Boldύ, 2019), transparency (Niranjanamurthy, Nithya and Jagannatha, 2019), and information sharing, leading to improved supply chain performance by integrating supply chain processes and activities (Mirabelli and Solina, 2020), are greatly enhanced by BCT. It can be used in the agri-food supply chain in the future (Sharma *et al*., 2023a, 2023b; Feng *et al*., 2020; Stranieri *et al*., 2021).

Sharma *et al*. (2024) showed five critical areas where blockchain can come up to enhance the agri-food supply chain performance by providing traceability, transparency, information security, transactions, and trust and quality. Safety, lower cost of transactions, and creation of trust among users to communicate within the whole supply chain without the intervention of a third party will be provided by BCT. Moreover, the operational capabilities need to be considered when introducing technology into practice. One of the most vibrant topics in strategic management, and a new concept in performance-based management, refers to the operational capability of an organization. Operational capability refers to skills, processes, procedures, and developments within the operations management system that give solutions to its problems by analysis of its operational resources (Helfat and Winter, 2011; Tan, Kannan and Narasimhan, 2007; Wu, Melnyk and Flynn, 2010).

29.6 Sustainable Labeling, Food Consumption, and Choices

Sustainable food consumption is associated with healthiness and social and economic impacts (Jackson and Holm, 2024; Kenny *et al*., 2023; Majer *et al*., 2022).

van Bussel *et al*. (2022) revealed the significance of environmental impact, food choices (local and organic), as well as ethical production in affecting consumers' perceptions of food-related sustainability.

Socioeconomic and political to psychosocial factors also affect consumer attitudes toward sustainable food (Solar and Irwin, 2010). Knowledge and concern about sustainability is more highly rated in women compared to men (Grunert, Hieke and Wills, 2014; Vecchio *et al*., 2015) according to European research on sociodemographic determinants (i.e., gender, educational level). In addition, a better understanding of sustainability comes from consumers with higher education (Ammann *et al*., 2023) and are more likely to focus on healthiness when purchasing food (Campos, Doxey and Hammond, 2011).

Moreover, price, taste, quality, and convenience are rated higher than environmental impact (Hoek *et al*., 2021; van Bussel *et al*., 2022).

Healthier and more sustainable food choices could arise from front-of-pack labeling (FOPL) (European Commission, 2020; Storcksdieck Genannt Bonsmann *et al*., 2020) where assessment of food label design is carried out with regard to effective communication with the consumer (Corallo *et al*., 2021). The authenticity of the products or services for buyers is being assured by trademarks and brand names developed by sellers (de Boer, 2003; Nakaishi and Chapman, 2024). Social, environmental, and animal welfare aspects are being addressed by current food systems, including food labels. Consumers' attention to how food

is produced requires a response and companies also desire the acquirement of a competitive advantage through implementation of sustainability-oriented business strategies and compliance with existing policies (de Boer, 2003; Latino, Menegoli and De Lorenzi, 2024; Torjusen and Vittersø, 2023). According to a recent EU report (European Court of Audits, 2024), approximately 120 public and private sustainability food schemes exist and consumers struggle to understand their role (Martini and Menozzi, 2021).

Desirable consumer choices may be influenced by labels (Majer *et al*., 2022; Potter *et al*., 2021). However, favorable changes due to sustainability labels show minor effects or are yet to be seen (Grunert, Hieke and Wills, 2014; Hoogland, de Boer and Boersema, 2007; Nakaishi and Chapman, 2024). Social and environmental sustainability food labeling is limited since it is complex and multiple labels exist, causing consumers' confusion (Moon *et al*., 2017; Yokessa and Marette, 2019). Hence, harmonization of the information provided is required (Futtrup *et al*., 2021; Torma and Thøgersen, 2024).

Terragni *et al*. (2025) reported that the most important dimensions for a sustainable food system were less food waste (53%) and animal welfare (50%), while reduced meat production (21%) and organic production (18%) the least important dimensions. The most preferred single label was that including information on social and environmental sustainability and healthiness of food. Those who perceived sustainability of their present diet required information regarding environmental sustainability, social sustainability, and health when purchasing food compared to those consuming a less sustainable diet.

29.7 Conclusions

Nutrient-enriched meats should be commercially produced assuring a good stability in terms of safety and quality, for example, flavor maintenance. These regulatory challenges should include the redefinition of standards of identity and establishment of policies that permit nutritional claims on packaging. This will create more nutritious and healthy meat products and will take place with stricter labeling on the fatty acids and specifically trans fatty acids. Consumer awareness will be increased by mass media promotion, as reported by Yazdanparast *et al*. (2025).

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30

Health Perceptions and the Demand for Alternative Meat Products

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30.1 Introduction

The demand for meat alternative products has grown rapidly in response to rising environmental, health, ethical, and sociocultural concerns associated with conventional meat consumption. Such increasing demand places a significant burden on natural resources, including land, water, and energy, while contributing to greenhouse gas emissions (GHGs) and biodiversity loss (He *et al.*, 2023; Hentschl *et al.*, 2023). Conventional meat production has been linked to multiple public health risks, including the use of antibiotics in livestock, which can promote antimicrobial resistance, and the consumption of processed or red meat, which is associated with cardiovascular diseases (Conceição, Queiroga and Laranjo, 2023; Enshaie *et al.*, 2025; Rahman *et al.*, 2026). Ethical considerations regarding animal welfare, religious dietary laws such as *halal*, and concerns over zoonotic disease transmission further emphasize the need for alternative protein sources (Bernstein and Dutkiewicz, 2021; Rahman *et al.*, 2024). Consequently, consumers are increasingly seeking meat substitutes, giving rise to a growing market for plant-based, fungi-derived, and insect-based proteins (Yimam *et al.*, 2024). The health benefits of alternative protein consumption are well-documented (Langyan *et al.*, 2022; Marotta *et al.*, 2025; Partanen *et al.*, 2025; Zhao *et al.*, 2024). For instance, plant-based diets and hybrid diets that partially replace meat with alternative proteins have been associated with lower blood pressure, improved lipid profiles, reduced platelet aggregation, and a decreased risk of cardiovascular disease (Partanen *et al.*, 2025). These alternative proteins contribute not only to the nutritional profile but also to functional properties such as water and fat binding, gelation, and fibrous texture, all of which are critical for consumer acceptance (Floret *et al.*, 2023; Partanen *et al.*, 2025). However, formulating plant-based products that meet sensory expectations remains a challenge due to inherent differences in protein structure, flavor, and digestibility compared to animal meat (Kumari *et al.*, 2024). Beyond plant-based proteins, mycoprotein, derived from fungi such as *Fusarium venenatum*, has emerged as a highly promising meat alternative (Cheriaparambil and Grossmann, 2025). Mycoprotein provides a protein-rich, high-fiber, and low-fat option, with a fibrous chitin–β-glucan matrix that mimics the texture of animal meat (de Figueiredo Trindade *et al.*, 2025). Insect-based proteins represent another sustainable and nutrient-dense alternative. Entomophagy has a long history in parts of Asia and Latin America but faces cultural resistance in Western countries due to perceived unpalatability and safety concerns (Kröger *et al.*, 2022; Olivadese and Dindo, 2023). Insects such as crickets, mealworms, locusts, and grasshoppers offer high-quality protein with essential amino acids, lipids rich in polyunsaturated fatty acids, and significant mineral content (Lampová *et al.*, 2024; Riaz, Irshad and Sazil, 2025). Incorporating insect-based meat has been shown to improve nutritional quality while maintaining desirable sensory characteristics (Borges *et al.*, 2022). Consumer perception is a critical factor in the adoption of all meat alternatives. Acceptance is influenced not only by health, environmental, and ethical considerations but also by sensory qualities, including texture, flavor, juiciness, and visual appeal (Onwezen and Dagevos, 2024). Products that closely mimic the sensory properties of conventional meat, through technologies such as extrusion, wet spinning, electrospinning, or

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3D printing, are more likely to achieve higher acceptance (Handral *et al*., 2022; Kumari *et al*., 2025). Effective communication regarding the environmental benefits, nutritional value, and safety of meat alternatives also plays a pivotal role in shaping consumer attitudes, particularly in regions where meat-centric diets dominate (Erhard, Jahn and Boztug, 2024). Younger, urban, and environmentally conscious populations are often early adopters of alternative protein products, while hybrid formulations and partial substitution strategies can facilitate broader acceptance among traditional meat consumers (Runte, Guth and Ammann, 2024). Hence, the growing need for meat alternatives is driven by an intersection of environmental sustainability, public health, ethical considerations, and evolving consumer preferences.

This chapter aims to provide a comprehensive overview of the rising interest in meat alternatives determined by health awareness, with particular attention to the ways nutritional quality, technological innovation, and public attitudes influence this rapidly transforming field. It reviews the broad spectrum of available substitutes, ranging from plant-derived analogues to insect-based proteins and fungal mycoproteins, and considers their nutritional profiles, safety implications, and capacity to satisfy consumers' expectations for healthier and more sustainable protein sources. By incorporating recent advances in structuring methods, including cell-cultured meat, additive manufacturing techniques such as 3D printing, and spinning processes.

30.2 Meat Alternative Types

30.2.1 Plant-Based Meat

Plant-based ingredients have attracted growing interest within the food sector as substitutes for animal-derived proteins, driven by rising health consciousness and expanding global populations (Table 30.1). Among the wide range of botanical protein sources, legumes stand out as the most traditional, nutrient-dense, and readily accessible options (Prasad *et al*., 2025). Their seeds typically contain 20–30% protein along with substantial amounts of minerals, vitamins, and dietary fiber (Khalid, Hameed and Tahir, 2023). In vitro assessments indicate that proteins in legume flours exhibit approximately 80% digestibility, with essential amino acid indices between 50% and 65% (Opazo-Navarrete *et al*., 2025). While legumes generally provide a more favorable essential amino acid balance than cereals, their protein profile remains inferior to that of meat due to low levels of sulfur-containing amino acids and tryptophan. Legume seeds are also rich in starch, usually 50–70%, consisting of amylose and amylopectin (Bangar *et al*., 2024). Their starch fraction is notably resistant to digestion, giving it nutritional relevance similar to that of dietary fibers. During heating, starch granules swell and integrate within protein gel networks, strengthening the structure and enhancing water-binding capacity (Scott and Awika, 2023). Dietary fiber contributes further by improving both water and fat retention (Akhlaghi, 2024). Together, these components give legume flours, concentrates, and protein isolates desirable functional properties. Recent research has increasingly focused on using legume-derived ingredients to formulate hybrid meat products (Feddern *et al*., 2024; Maningat, Jeradechachai and Buttshaw, 2022; Twarogowska, Van Droogenbroeck and Fraeye, 2022). For example, incorporating Belgian endive fiber into plant-based soy protein burgers was found to enhance the product's hardness while simultaneously improving baking yield and retaining moisture (Twarogowska, Van Droogenbroeck and Fraeye, 2022). A detailed review examining 13 commercially available chicken plant-based meat alternatives and 14 burger plant-based meat alternatives revealed that chicken plant-based meat alternatives with higher levels of various dietary fiber sources exhibited increased hardness and chewiness as measured by Texture Profile Analysis, but this was accompanied by a decrease in cohesiveness (Godschalk-Broers, Sala and Scholten, 2022). Elevated fiber content in chicken plant-based meat alternatives was also associated with higher moisture levels, although it led to greater cooking losses (Godschalk-Broers, Sala and Scholten, 2022). In the case of plant-based meat alternative burgers, an increased fiber inclusion corresponded with reduced expressible moisture, likely reflecting the distinct water-binding capacities of the different fibers used (Godschalk-Broers, Sala and Scholten, 2022). A thorough understanding of the physicochemical and functional behavior of plant proteins is fundamental for improving their application in nutrient-rich processed foods and hybrid meat formulations. Each plant protein source presents its own challenges, which must be addressed to optimize its technological performance.

TABLE 30.1

Overview of Meat Analogues by Protein Source and Processing Method

Meat Alternative	Type of Protein	Method	Comment	References
Meat analogue	Soy protein isolate powder, xanthan gum/ carrageenan/ pectin	Fiber spinning	Xanthan gum and carrageenan promote the formation of pronounced fibrous networks	Joshi *et al.*, 2023
Imitation of muscle fibers	Sodium alginate powder, soybean protein isolate	Wet spinning	Generating fibers with elevated protein concentrations or under alkaline pH conditions promotes the development of a porous network	Cui *et al.*, 2022
Xylose	Mung bean protein isolate, beet root, xylose, methylcellulose	3D printing	Adding xylose changed the interactions and microstructure of colorant-containing meat analogues, leading to texture changes	Wen, Kim and Park, 2022
Sausage	Mushroom and soybean protein isolate	Thermoextrusion	Sausages formulated with 15% mushroom and soybean protein isolate, combined with 35% water, exhibited a textural profile most closely resembling that of beef	Yuan *et al.*, 2022
Steak	Textured soybean protein and xanthan gum	3D printing	Adjusting process parameters, including the infilling-to-filling ratio and the specific infilling pattern, had a significant impact on the textural properties of the samples	Chen, Zhang and Bhandari, 2021
Extruded meat analogue	Soy protein and gluten	High moisture extrusion	Elevating the gluten content enhances the development of a fibrous network within meat analogues	Chiang *et al.*, 2021
Soy-based meat analogue	Defatted soy flour, soy protein, corn starch, mealworm larvae	Extrusion	Incorporating mealworm larvae into extruded meat analogues has the potential to enhance their nutritional profile, boost antioxidant activity, and improve sensory attributes	Cho and Ryu, 2021

30.2.2 Insect-Based Meat

In many regions of the world, insects have long been integrated into traditional diets and are even regarded as gourmet foods. In contrast, Western consumers generally exhibit strong reluctance toward entomophagy, often perceiving insects as unsafe or unpleasant to eat (Schollers, Steen and Fraeye, 2020). Evidence from recent studies suggests, however, that acceptance can be improved when insects undergo advanced processing techniques that transform them into more familiar food formats (Liceaga, 2021). Consequently, hybrid meat products represent a promising pathway for introducing insects as an alternative protein source (Magalhaes, Gonçalves and Trindade, 2024). Nutritionally, many edible insects contain protein levels comparable to conventional animal sources such as beef, fish, and shrimp, and in certain species, the protein content is even higher (Shah *et al.*, 2022). Protein digestibility varies among insect species, ranging from 75% to 98%, only slightly lower than that of conventional animal proteins (Rodríguez-Rodríguez *et al.*, 2022). For instance, chapulines (grasshoppers of the genus *Sphenarium*), palmworm beetles, adult termites, locusts, and various other grasshopper species exhibit particularly high protein concentrations (Hasnan *et al.*, 2023). In addition, insects contain bioactive compounds with anti-inflammatory and antioxidant properties, which can positively influence lipid and glucose metabolism, contributing to potential health benefits (Sánchez-Estrada, Aguirre-Becerra and Feregrino-Pérez, 2024). Edible insects possess suitable physical and functional attributes for use as non-meat ingredients

in fresh or emulsified meat systems. Their incorporation can also help improve consumer perception, particularly when the insects are not visually identifiable within the product. Using "invisible" insect ingredients has been shown to reduce food neophobia and facilitate consumer acceptance of insect-based foods (Alhujaili, Nocella and Macready, 2023). From a sustainability perspective, insect farming is more resource-efficient than traditional livestock production (Li *et al*., 2023). Insects require significantly less land, water, and feed, leading to a smaller carbon footprint and reduced environmental pollution (Li *et al*., 2023). Despite these advantages, safety concerns and consumer acceptance remain major challenges for insect-based food products. Some species may trigger allergic reactions in sensitive individuals (Ganseman *et al*., 2023). Overall, insects represent a sustainable and cost-effective alternative protein source, offering high efficiency, low resource requirements, and potential for incorporation into diets to replace conventional animal meat partially.

30.2.3 Mycoprotein-Based Meat

Mycoproteins, protein sources generated from microbial systems, have drawn increasing interest as sustainable alternatives to animal meat, primarily because their production requires fewer resources and incurs lower economic costs compared with traditional livestock-based proteins (Khan *et al*., 2024). Mycoproteins represent a health-promoting, low-fat protein source commonly incorporated into hybrid meat analogues (Panda *et al*., 2025). Recent research highlights filamentous fungi as promising meat alternatives due to their high protein content (up to 50% dry weight), sustainable production via fermentation, and fibrous texture mimicking meat. Mycoprotein is valued as a sustainable whole-food ingredient with high levels of protein and dietary fiber (Derbyshire *et al*., 2023). While its protein concentration surpasses that of many plant- or fungus-derived alternatives, it remains lower than conventional meat proteins. For instance, Gamarra-Castillo *et al*. (2022) examined *Aspergillus oryzae* as a promising filamentous fungus for generating protein-dense meat analogues. The researchers optimized fermentation conditions, particularly the carbon-to-nitrogen balance, to obtain a fungal biomass capable of reproducing key attributes of beef burgers, including texture, coloration, and water-holding performance (Gamarra-Castillo *et al*., 2022). The formulated patties contained roughly 45% protein, exhibited a substantially lower fat content, and received favorable sensory evaluations (Gamarra-Castillo *et al*., 2022). These findings underscore the capacity of fungal systems to address the persistent textural limitations associated with many alternative protein products and to enhance the overall quality of meat substitutes. In addition, Risner *et al*. (2023) estimated that the production cost of mycoprotein is approximately $3.55/kg, which is nearly $3.00/kg less than that of choice-grade beef ($6.56/kg), underscoring its economic advantage. Produced through fungal fermentation, mycoproteins possess a fibrous structure and mouthfeel that closely resemble those of meat, further reinforcing their suitability for meat analogue applications. Among the fungal species investigated, *F. venenatum* remains the most established organism for industrial-scale mycoprotein production (Cheriaparambil and Grossmann, 2025). In the United Kingdom, the company Quorn™ manufactures mycoprotein derived from *F. venenatum*, incorporating egg albumin and selected additives to create various meat replacement products. More recently, the US-based company Nature's Fynd introduced Fy Protein™, a novel mycoprotein ingredient derived from *Fusarium flavolapis*, which has been demonstrated to be safe for human consumption (Furey *et al*., 2022). Despite these advances, only a limited number of fungal strains currently meet the requirements for commercial-scale mycoprotein production. This highlights the need for broader exploration of alternative filamentous fungi and for further optimization of their fermentation characteristics to expand the range and functionality of mycoprotein-based meat analogues.

30.3 Emerging Technologies in Meat Alternative Development

Cultured meat, also referred to as cell-based meat, is produced in vitro from animal stem cells. Initially, these cells are expanded through proliferation to achieve sufficient biomass before being seeded onto scaffolds, where they grow, differentiate, and mature into muscle tissue suitable for harvesting (Jara *et al*., 2023). Commonly used cell types include muscle, adipose, and connective tissue stem cells, and

additional components such as flavoring agents are often incorporated to enhance sensory attributes and closely replicate conventional meat (Lee, Lee and Jo, 2026). Most cultured meat production to date has been confined to laboratory-scale systems, where growth conditions differ significantly from natural muscle development, potentially affecting the quality of the final product. Furthermore, current production costs are high, highlighting the need for process optimization to enable economically viable scale-up for global food supply (Kim *et al*., 2025). Optimization strategies include selecting specialized cell types for targeted tissue cultivation, formulating appropriate growth media, choosing suitable bioreactor systems, and employing low-emission energy sources (Kim *et al*., 2025). Cultured meat presents an emerging protein source for human diets and may serve as an alternative to conventional meat. Theoretical models suggest that its production requires significantly fewer resources than traditional livestock rearing. For example, it is estimated that the same quantity of beef burgers obtainable from a single cow could theoretically be produced within 1.5 months via cultured meat, whereas conventional farming would require around half a million cows over 1.5 years. Reducing livestock-related emissions is critical for addressing climate change and public health, as conventional meat production contributes approximately 14.5% of GHGs and demands substantial freshwater resources (Solomon, Gupta and Ncho, 2023). Beyond environmental considerations, producing meat in a controlled in vitro system reduces the risk of zoonotic diseases such as mad cow disease and enhances animal welfare (Siddiqui *et al*., 2025).

30.3.1 Spinning Process

Meat analogue formation can be realized using both the spinning methods: wet spinning and electrospinning (Kumari *et al*., 2025). Electrospinning is a technique in which a high electrical potential is applied to a polymer or protein solution, causing the formation of ultrafine fibrils at the nanometer scale. When the electric field overcomes the surface tension of the solution, a charged jet is ejected from the spinneret and elongates rapidly, resulting in the deposition of continuous nanofibers onto a grounded collector (Ji *et al*., 2024). These fibers exhibit a high surface-area-to-volume ratio and can be assembled into mats that mimic the hierarchical structure of muscle tissues. Several related factors influence the electrospinning performance and the morphology of the resulting fibers (Kailasa *et al*., 2021). A more stable and uniform electric field generally promotes the formation of finer fibrous structures by increasing the bending and stretching of the polymer jet (Kailasa *et al*., 2021). However, when the applied voltage surpasses a critical threshold, fiber defects such as bead formation and an increase in fiber diameter are commonly observed (Al Saif and Cselkó, 2025). Voltage is considered one of the most sensitive and easily adjustable operating parameters. In conventional electrospinning systems, the applied voltage typically ranges between 10 kV and 30 kV, whereas near-field electrospinning operates at much lower voltages, often below 5 kV (Xu *et al*., 2023). In addition to voltage, the flow rate of the feed solution plays a crucial role in determining fiber diameter, degree of alignment, and the stability of the Taylor cone. An inappropriate flow rate can disrupt jet formation, affecting droplet shape and uniform deposition of fibers on the collector (Aghababaei *et al*., 2024). Finally, the distance between the spinneret and the collector must be carefully optimized, as it controls the time available for solvent evaporation and fiber solidification. Shorter distances can result in insufficient drying, leading to fused or interconnected fiber networks (Aghababaei *et al*., 2024). Unlike wet spinning, electrospinning does not require acidic coagulation baths and can operate at ambient temperatures, making it suitable for heat-sensitive biopolymers (Günal-Köroğlu *et al*., 2025). However, the technique demands solutions with carefully tuned viscoelastic and conductivity properties, and the resulting nanofibers often lack sufficient mechanical strength unless combined or cross-linked with additional biopolymers. Despite these challenges, electrospinning shows significant promise for generating highly aligned, fibrous structures that enhance the textural realism of plant-based meat analogues.

30.3.2 3D Printing Technology

3D printing is a fabrication approach that creates physical three-dimensional objects from digitally designed models using computer-aided design tools (Mani *et al*., 2022). This technique has become a

widely adopted technique for fabricating scaffolds in tissue engineering applications (Mani *et al*., 2022). This method works by extruding softened or molten material through a controllable nozzle, which precisely deposits the material in sequential layers (Patel and Taufik, 2024). As each layer solidifies, the structure gradually builds up to form a printed product with features that can mimic the organization and appearance of animal flesh. To achieve successful printing performance, the protein matrix typically requires modification through cross-linking treatments and various preprocessing steps (Sohel *et al*., 2025). These adjustments enhance the mechanical stability, flow behavior, and shape-holding capacity of plant-protein formulations so that they can be extruded smoothly, maintain structural integrity during deposition, and set into well-defined layers after printing (Sohel *et al*., 2025). Using 3D-printed scaffolds provides precise control over cell composition, density, and spatial distribution, which enhances the ability to produce cultured meat that closely mimics the structural and textural properties of animal muscle (Handral *et al*., 2022). For instance, an edible scaffold composed of chitosan, sodium alginate, and collagen/gelatin was shown to support cell adhesion and proliferation effectively, facilitating the formation of a structured cultured meat matrix (Lee and Choi, 2024). Plant-derived materials are increasingly being explored as scaffolding substrates due to their low cost, abundance, sustainability, and easy accessibility (Vargas-Ovalle, Demitri and Madaghiele, 2025). Materials such as wheat glutenin and pea protein isolate have successfully been used to create functional 3D scaffolds (Peng *et al*., 2023). However, maintaining adequate nutrient and oxygen diffusion throughout these structures remains a challenge, particularly when scaling up cultured meat production (Bomkamp *et al*., 2022). Recently, the integration of "smart" materials with 3D printing, termed 4D printing, has been explored to further improve the visual appeal and color responsiveness of insect-based products. For example, inks combining cricket powder with purple potato powder successfully produced printed items with stable shapes and dynamic color changes (ranging from bluish-purple to red, blue, purple, and green) in response to varying pH conditions (Sundarsingh *et al*., 2024) (Figure 30.1). However, these products exhibited a softer texture than control samples due to elevated moisture content, which may be undesirable for hard-textured snack applications.

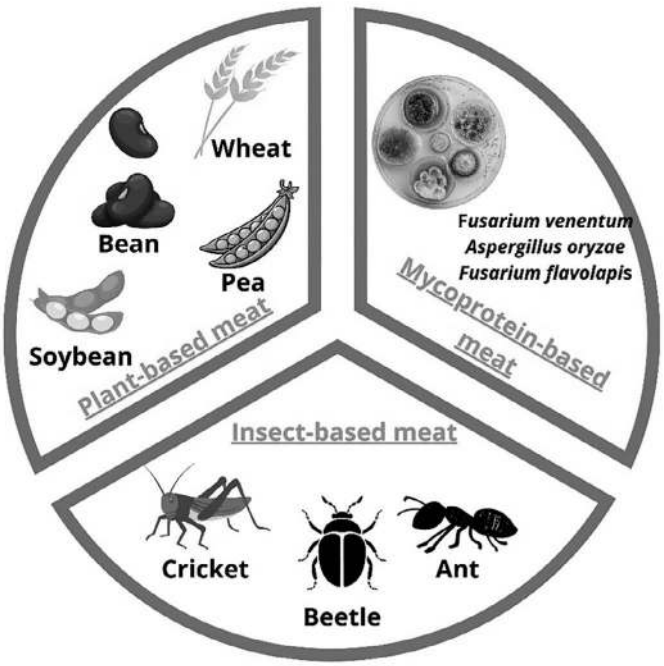

FIGURE 30.1 Different types of meat alternatives.

30.4 Health Demand and Nutritional Characteristics of Alternative Meat Products

Growing global interest in alternative meat products has accelerated largely due to consumers' heightened focus on cardiovascular health, chronic disease prevention, and environmentally sustainable dietary patterns (Chen *et al.*, 2023). Rising obesity rates and concerns linking red and processed meat intake to metabolic disorders have further strengthened demand for substitutes that offer improved nutritional profiles without compromising sensory quality (Figure 30.2) (Hall, 2023). Farvid *et al.* (2021), in a meta-analysis of 148 prospective studies, confirmed strong links between meat intake and colorectal cancer and also observed positive associations with lung and breast cancers. Although processed meat consistently increases cancer risk, variations in meat type, processing, and cooking methods complicate risk assessment.

Plant-based meat alternatives are commonly perceived as healthier because they have lower levels of saturated fat and provide more dietary fiber compared with red and processed meats (Szenderák, Fróna and Rákos, 2022). This perception aligns with epidemiological evidence showing that plant-forward dietary patterns are associated with reduced risks of cardiovascular disease (Szenderák, Fróna and Rákos, 2022). In addition, observational data indicate that plant-based diets are linked with lower incidences of type 2 diabetes, heart disease, and certain cancers, largely due to reduced intake of red and processed meat (Ivanova *et al.*, 2021). Controlled trials further support these findings: replacing animal meat with plant-based meat alternatives has been shown to lower LDL cholesterol and support short-term weight management, likely attributable to increased fiber and polyunsaturated fat intake (Ivanova *et al.*, 2021).

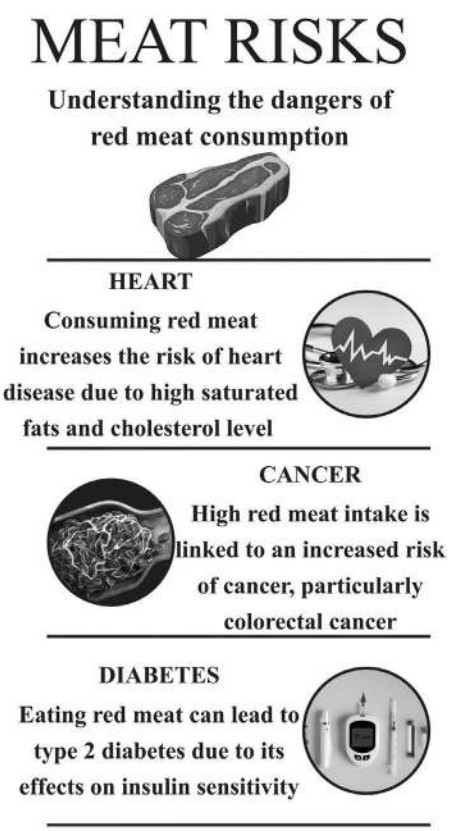

FIGURE 30.2 Relative health risks associated with unprocessed red meat and processed meat consumption.

In the study of Krawczyk, Fernández-López and Zimoch-Korzycka (2024), a formulation and characterization of soy protein–based burger analogues fortified with insect-derived protein were obtained from *Alphitobius diaperinus*. Three distinct formulations were prepared, including a reference sample without insect inclusion (B0) and two enriched variants containing 5% (B5) and 10% (B10) whole buffalo powder (WBP). The incorporation of insect protein resulted in a reduction in the pH of the burger formulations. As the proportion of WBP increased from 0% to 10%, a consistent shift in the lipid profile was observed, characterized by higher total fat and saturated fatty acid contents, alongside a concomitant decrease in monounsaturated and polyunsaturated fatty acids. In contrast, increasing levels of WBP did not produce significant changes in overall protein concentration or cooking yield, indicating that insect protein enrichment altered lipid composition without adversely affecting protein content or processing performance.

When viewed collectively, these three categories of meat alternatives provide complementary nutritional strengths. Plant-based analogues excel in scalability and fiber enrichment, insect-based foods offer exceptional micronutrient densities, and mycoprotein stands out for its clean-label attributes and minimal processing requirements.

30.5 Consumer Perceptions of Alternative Meat Products

Consumers generally approach foods produced with novel technologies with caution, and their willingness to try novel products is strongly shaped by their level of trust in food-system actors (Siegrist and Hartmann, 2020). Prior research indicates that 3D food printing, in particular, is often viewed unfavorably. Many participants in earlier studies stated worries about potential health risks associated with 3D-printed foods and which were largely rooted in the belief that these products are highly artificial (Zhu *et al.*, 2023). A key barrier to broader acceptance appears to be the public's limited understanding of what 3D food printing entails; most consumers have little exposure to such products and therefore respond with hesitance and doubt. Providing information that highlights benefits, such as improved taste, greater convenience, and enhanced nutritional profiles, may reduce these negative perceptions (Chang, Hsia and Chen, 2024; Pereira, Barroso and Gil, 2021). Yet these concerns persist even more strongly for 3D-printed cultured meat. Overall, cultured meat is commonly associated with perceptions of unnaturalness, a response that can elicit feelings of disgust and, consequently, reduce consumer willingness to accept these products (Herziger, 2024; Locarno, 2023; Wilks, Hornsey and Bloom, 2021). Concerns about safety and nutritional adequacy further contribute to consumer skepticism (Siddiqui *et al.*, 2022). Food neophobia represents an additional hurdle in consumer acceptance (Fasanelli *et al.*, 2025). This barrier is typically less pronounced for plant-based alternatives, which have been present on the market for longer and have already achieved a degree of familiarity among the public (Giacalone, Clausen and Jaeger, 2022). A key obstacle to the widespread adoption of plant-based meat substitutes is their flavor, which many consumers perceive as less appealing than that of conventional meat (Jahn, Furchheim and Strässner, 2021; Yule and Cummings, 2023). For this reason, manufacturers are encouraged to develop plant-based options that mimic traditional meat products as closely as possible. At present, the industrial formulation of plant-based meat analogues relies on a broad range of plant-derived proteins, with soy and pea proteins remaining the dominant choices because of their favorable techno-functional behavior and relatively low production cost (He *et al.*, 2020). Among the sensory indications, visual appearance, particularly color, is typically the first attribute evaluated by consumers (Altmann, Trinks and Mörlein, 2023; Malheiros *et al.*, 2025). Consequently, manufacturers aim to replicate the color dynamics of the meat products they intend to imitate, ensuring similarity in raw form as well as throughout the cooking process. To achieve this, various pigments and color precursors are incorporated into formulations. For example, beetroot extracts or soy leghemoglobin are often used to reproduce the characteristic red hue of uncooked meat (Chaari *et al.*, 2023; Wu *et al.*, 2024). Ultimately, consumer perceptions play a decisive role in determining whether innovative food products succeed in the marketplace (Xavier *et al.*, 2025). It is, therefore, crucial to consider consumer expectations and concerns early in the development process (Rai *et al.*, 2023).

30.6 Market Aspects of Meat Alternatives

The global sector dedicated to meat alternative products is projected to attain a value of US$8.1 billion by 2026 (Vallikkadan *et al.*, 2023). This steady rise is largely linked to consumers becoming more aware of the health drawbacks associated with conventional meat consumption and the risks of insufficient protein intake (Vallikkadan *et al.*, 2023). Among world regions, Europe dominates the market with 51.5%, followed by North America (26.8%), Asia-Pacific (11.8%), Latin America (6.3%), and the Middle East and Africa (3.6%) (Kumar *et al.*, 2023). A consumer survey conducted in the United States, China, and India revealed markedly different acceptance levels of meat alternatives. Approval rates were highest in China (95.6%) and India (94.5%), whereas the United States reported a lower endorsement rate (74.7%) (Wang *et al.*, 2025). The expansion of this market is further supported by the swift growth of the food service sector and by aggressive promotional strategies adopted by companies specializing in plant-based meat analogues. Heightened health awareness in developing economies has also encouraged consumers to reconsider their choices. As a result, the vegetarian and plant-forward food segment is expected to offer promising opportunities for manufacturers seeking to develop innovative meat-replacement solutions. Textured vegetable protein–based items, in particular, are gaining strong traction in North America and Europe owing to their sensory similarity to meat and their favorable nutritional attributes. Key players identified in the meat analogue industry include Morningstar™, Meatless B.V., Amy's Kitchen™, Cauldron Foods™, Beyond Meat™, Garden Protein International Inc., VBites Food Ltd., and Quorn Foods™, as well as producers such as Farms™, MGP Ingredients™, and Sonic Biochem Extractions Limited (Vallikkadan *et al.*, 2023).

30.7 Conclusion

Across global markets, health perceptions have emerged as a central, though not exclusive, motivator driving the adoption of plant-based, insect-derived, fungi-based, and cultured meat products. Consumers rarely choose these alternatives for personal well-being, environmental impact, animal welfare, technological trust or skepticism, and gastronomic experience. Plant-based analogues are often marketed as healthier substitutes for traditional meat due to lower levels of saturated fat, the absence of cholesterol, and the potential to increase dietary fiber and phytochemicals. Insect- and fungi-based alternatives present a different scenario: they provide high-quality protein, essential micronutrients, and in some cases bioactive compounds or fiber, yet consumer uptake is constrained more by cultural and psychological barriers than nutritional inadequacy. Here, unfamiliarity, food neophobia, and disgust frequently overshadow the demonstrable health benefits. Emerging technologies such as cultured meat and advanced fabrication techniques, including 3D printing and spinning, add further complexity to health perceptions. Cultured meat is often framed as a "cleaner" source of protein, offering reduced exposure to pathogens, antibiotics, and contaminants linked to conventional animal farming. Yet limited longitudinal data, regulatory uncertainty, and the perception of unnaturalness foster skepticism. Similarly, 3D printing and spinning allow precise control over nutrient composition, texture, and bioavailability, creating opportunities for products tailored to specific dietary or health needs. Nonetheless, the advanced nature of these processes can heighten concerns about overprocessing, demonstrating that technological capability alone does not automatically generate positive health perceptions. Plant-based products often provide favorable fatty acid profiles and fiber; insect-based products supply high-quality protein; fungi-based alternatives offer fiber, select micronutrients, and bioactive components. Nutrient adequacy, however, is not guaranteed and depends on careful formulation, fortification, and integration into balanced diets. Health perceptions are shaped within a broader sociocultural and informational context. They are influenced by individual knowledge, cultural norms, media narratives, front-of-pack labeling, and trust in institutions and brands. Clear nutritional information, evidence-based health claims, and accessible explanations of production methods help align perceptions with reality. Market strategies increasingly position alternative meat products at the intersection of health, sustainability, and ethics. While environmental or ethical messaging alone may not resonate broadly, health-focused positioning must be

supported by high-quality product design, including taste, texture, convenience, and affordability. For insect- and fungi-based products, allergenicity, gut microbiota interactions, and individual tolerance require more attention. For cultured meat and other novel technologies, comprehensive risk-benefit analyses are essential for informing regulators and consumers alike. Regulatory frameworks must provide clear guidance on safety, labeling, and health claims to support informed choice and promote innovation. Harmonized regulations across jurisdictions would facilitate market expansion while minimizing consumer confusion.

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31

Cultural and Regional Differences in Meat Consumption Patterns

Victoria Bell, Jorge Ferrão, José Guina, and Tito Fernandes

31.1 Introduction

The future of food is being shaped by evolving lifestyles, the shift of consumer preferences, prevalent industrialization, and rapid advancements in technology (e.g., AI and precision agriculture). Due to population growth and resource scarcity, sustainable food security is more crucial than ever, although many parameters menace global and traditional food systems, including regulation, climate change, conflicts, geopolitical concerns, pandemics, and consumer acceptance (Galanakis, 2024).

Driven by demographic increase and the increment in consumers' purchasing power, the demand for food has been enlarging throughout the years, with notable preferences for animal-based foods. Historical and archaeological research has enabled us to better understand and follow the evolution of the place and role of meat in the human diet (Chiles and Fitzgerald, 2018).

The OECD–FAO Agricultural Outlook 2025–2034 (OECD/FAO, 2024) provides a comprehensive assessment of the ten-year prospects for agricultural commodity and fish markets at national, regional, and global levels. These data, analysis, and evidence-based recommendations support policymakers around the world in the efforts to end hunger and boost global food security (Figure 31.1) (OECD, 2025).

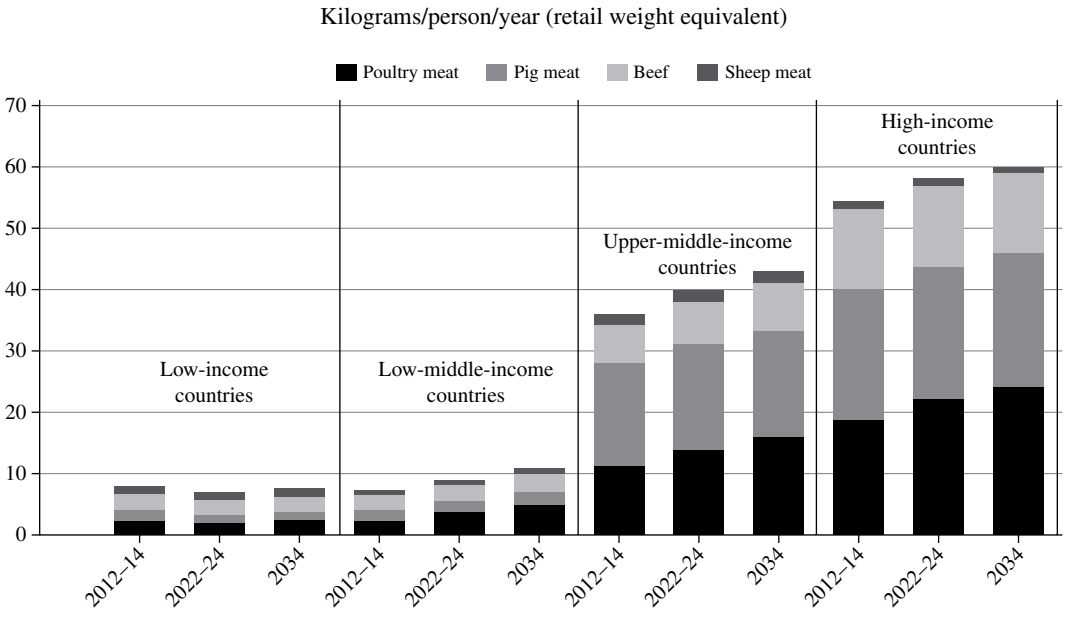

FIGURE 31.1 Animal source foods in total food intake. (From OECD/FAO, 2024.)

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The EAT-Lancet Commission presented an extensive literature review supporting the need for a substantial dietary shift, which includes a drastic reduction in global consumption of animal-based foods, particularly red meat, and a greater than 100% increase in plant-based foods, particularly fruits and vegetables (Willett *et al*., 2019). This report also provides an updated analysis of what constitutes a healthy, sustainable, and just food system in the context of today's scientific, social, and environmental realities, emphasizing cultural diversity and the importance of adapting healthy diets to regional and local contexts. A new focus on food justice expands the framework to include equity and human rights across the entire food system (Rockström *et al*., 2025).

The legal framework for functional and novel foods, including cultured meat, is evolving to ensure their safety and consumer acceptance. Despite all efforts to date, nevertheless, they have been insufficient to achieve a planetary health diet within the given time frame. Cultural and regional differences significantly influence food, namely, meat (e.g., beef, veal, pork, lamb, mutton, poultry meat) consumption, driven by economic factors, tradition, religion, and evolving global influences (Hamad and Tayel, 2025).

Meat consumption carries significant cultural characteristics, symbolizing wealth, strength, and prosperity in many societies, and playing roles in religious practices and social rituals, and can evoke complex feelings, including pleasure and disgust. People experience the taste and texture of meat in significantly different ways, with variations across ages, genders, and cultures (Issanchou, 1996).

Levels of meat consumption diverge not only at the global level but also on the societal level, namely, between sociocultural groups. Dietary behaviour is part of heritage and lifestyles, with individual habits shaped by an intricate interaction of circumstantial background situations and social, cultural, and economic elements (Lee and Choi, 2022).

There are a wide range of studies using different designs relating to the determinants of decisions to evaluate meat consumption (Gillison *et al*., 2022). Currently, there is few literature reviews that covers recent empirical findings on meat eating by specific social groups or classes, and findings rarely present the meat consumption habits of social groups that differ by age, gender, family status, social status, and norms (Raptou *et al*., 2024).

On average, high- and middle-income countries have the highest levels of meat consumption, while in high-income countries, meat consumption has stagnated or declined, and there is vast information on how socioeconomic characteristics, social status, norms, and structural context shape meat consumption (OECD/FAO, 2023). Meat consumption in rapidly emerging economies such as Brazil and China has increased over the last 40 years and, overall, global meat consumption is predicted to continue rising until 2050 due to increasing economic and population growth.

A sustainable meat consumption level is approximately 15–20 kg per year per person, significantly lower than current consumption levels in high-income countries (Willett *et al*., 2019). The overconsumption of meat, and the connected overproduction of meat animals, contribute significantly to climate change, deforestation, and biodiversity loss, impact on water and land, and public health risks. While many studies show links between high red and processed meat consumption and increased risks of noncommunicable diseases, such as colorectal cancer, cardiovascular disease, and type 2 diabetes, some research suggests the relationship is complex and potentially influenced by dietary context and methodology (Goedeke *et al*., 2024).

Meat has been connected to rituals and traditions, served on festive occasions, and revealing hospitality, but presently considered in need of a global shift toward diets with less meat considered essential for a sustainable future, with the potential to decrease resource use, lower greenhouse gas emissions, support animal rights, and address social inequalities simultaneously (Poore and Nemecek, 2018).

While a strong scientific consensus exists that reducing meat and dairy consumption is beneficial for both planetary and human health, there is a lack of widespread agreement on the magnitude of the health benefits for individuals and only detectable in large populations (Gibbs and Cappuccio, 2022). Willingness to reduce meat and dairy consumption across some populations is relatively low (12.8–25.5%), albeit increasing, the motivations for reducing meat and dairy are varied, health concerns are increasingly cited as a primary driver, even surpassing environmental and animal welfare concerns. There are several potential barriers and enablers in terms of capability, opportunity, and motivation to reduce meat consumption (Graça, Godinho and Truninger, 2019).

It should be emphasized that present dietary guidelines do not take into consideration strong evidence of meat harm or benefit, the size of such benefit or danger, and thought for personal likes, dislikes, and food-related values (Qian *et al.*, 2020). Furthermore, there is no evidence on the link between meat intakes with cardiovascular, metabolic, and cancer-related conditions or events, hampering more transparent, robust, and reliable recommendations. The impracticality for conducting large, long-term randomized clinical trials on most dietary, lifestyle, and environmental exposures makes the criteria inappropriate in these areas (Slotnick *et al.*, 2023).

As social groups within communities vary in their preferences and capabilities regarding diets, there is a need to know how meat consumption differs among social groups and what the specific options are for interventions to achieve sustainable levels of meat consumption. Although the reasons for the particular consumption patterns of social groups do not always lead to motivations or possibilities to reduce meat consumption, knowledge about these reasons may allow us to address social groups with targeted measures (Wiesli, 2025).

In developed countries, a sustainable food ecosystem can be achieved through implementing a comprehensive approach that includes promoting plant-based diets and reducing meat consumption, minimizing food waste throughout the supply chain, supporting sustainable and organic farming practices that conserve natural resources, shortening food supply chains by eating local and seasonal foods, and integrating farming systems. This type of system may even incorporate edible insects, seaweeds, plant-based and cultured meats, underutilized crops, hydroponics, biotechnology, robotics, and blockchain network technology (Union of Concerned Scientists, 2022).

In many developing countries, especially in populations with diets heavily reliant on staple crops, meat is still considered as essential for a healthy diet, but health and environmental issues, presently not an area of interest, are emerging as meat consumption rises in Africa, and strategies are needed to address these challenges alongside the region's nutritional needs (Gbejewoh, Marais and Erasmus, 2022).

31.1.1 The Symbolism of Meat

The inclusion of meat in the human diet is believed to have been a turning point in our evolution. Around the world, meat's significance extends beyond what might be anticipated from its nutritional utility and we commonly relate the origins of "civilized" humanity to the beginnings of hunting or of farming, and this is likewise why meat has been a symbol of affluence, strength, and virility (Vrijsen *et al.*, 2025).

In many societies, hunting and sharing meat has historically been a symbol of wealth, power, and social connection. Economics, nutrition and health considerations, ethical and religious influences, and ecological concerns all are shown to have a significant symbolic component in addition to their overtly practical meaning (Fiddes, 1989).

While there is an abundance of nutritional benefits to eating meat, it is popularized that less is sometimes more, and a more varied diet that includes more fish, fruit, vegetables, and nuts is encouraged. Beyond its cultural symbolism, the flavor of meat has shaped culinary traditions and gastronomic preferences worldwide, and different types of meat contribute to the diverse array of global cuisines (Nungesser and Winter, 2021).

Historically, meat was a luxury item, making its presence on the table a sign of prosperity, wealth, abundance, and high social status. However, in some cultures, the concept of "meat as wealth" persists to this day in many countries, especially low-income ones (e.g., Ethiopia, Mozambique, Nigeria), where meat is still considered a luxury food due to lower per capita consumption in a large portion of the population; meat remains an infrequent or special occasion food compared to staple crops like cereals, roots, and tubers (Clonan, Roberts and Holdsworth, 2016). Meat is central in building a sense of belonging that exists at the intersection of national, cultural, and community identities. Meat holds diverse cultural significance, acting as a symbol of prosperity, a central element in religious practices, a marker of social identity (including gender and class), and a crucial component of traditions and celebrations like feasts and festivals. Cultural factors such as historical availability, religious beliefs (e.g., halal, Hindu dietary laws), and changing social norms (e.g., Westernization, veganism) shape the consumption and perception of meat across different communities (Ranta and Ichijo, 2022).

The role of meat in cuisine goes beyond mere sustenance, as it is intrinsically linked to cultural traditions, societal values, and familial dynamics, influencing household gatherings and communal celebrations, shaping societies and traditions, celebrating the richness of human heritage and bonds (Francis, 2025).

Global meat consumers can detect differences in eating quality of meat products and may have similar thresholds for tenderness and juiciness' acceptability, but according to region may have different requirements for traits like flavor and marbling (de Araújo *et al.*, 2022).

Flavor is affected by consumer preparation methods, familiarity with different flavor presentations, and animal production systems, mainly when comparing forage-fed versus grain-fed beef. Pork consumers have been shown to be affected by meat pH, color, water-holding capacity, animal diet, and the presence of boar taint compounds. Lamb meat across the globe has more variation in diet/nutrition and production parameters than pork and beef, depending on more intense sheep meat odor resulting in more variability in lamb-eating quality (Miller, 2020).

31.2 Meat Production and Global Warming

The two big sources of greenhouse gas emissions are energy and global food production (Clark *et al.*, 2020). In various developed countries, a small number of large multinational corporations control food production and a significant portion of global meat production, through consolidation and vertical integration, dominating the market in beef, pork, and poultry and fixing prices on both ends of the supply chain. This means just a handful of corporations control nearly all of our food production from farm to fork, processing, and distribution. Furthermore, they develop and control markets for specialty feeds, seeds, animal genetics, fertilizers, and pesticides, and this undermines sustainable food systems and food sovereignty (Figure 31.2) (Sievert *et al.*, 2024).

The increase in greenhouse gas emissions originated from four main sectors—energy; industrial processes and product use; agriculture, forestry, and other land use; and waste—and has resulted in climate change and global warming. There is a wide range of estimates due of greenhouse gas emissions from livestock. The root causes of the problem of meat production, especially red meat (beef and lamb), appears to be a major contributor to the global warming potential attributable to people's diet (Clune, Crossin and Verghese, 2017).

Indeed, sources of gas generation from livestock production is not just related to the animals themselves and include several elements such as digestive fermentation and eructation by ruminants, manure

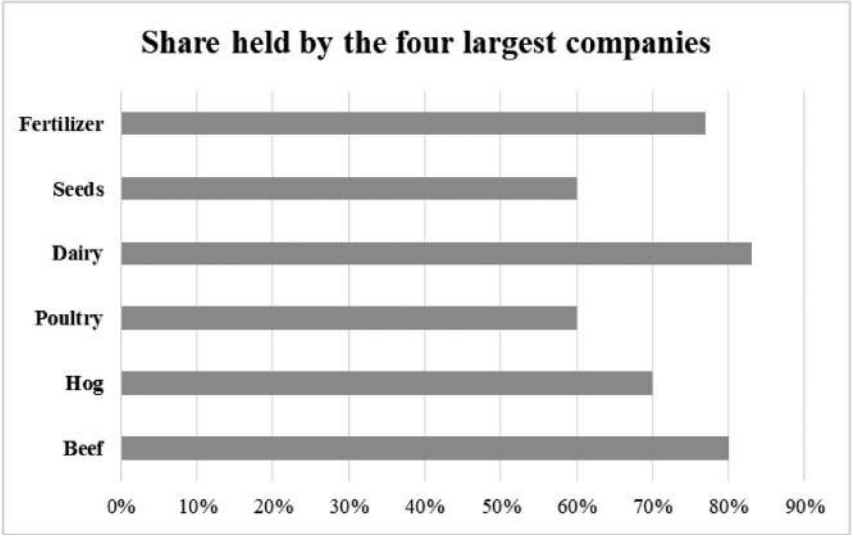

FIGURE 31.2 Concentration in agriculture. Sectors controlled by large companies. (From Farm Aid, 2025.)

output, feed production (fertilization, transport, and processing of feedstuffs), energy input in all stages of production, expansion of feed crops and pastures, slaughtering, and other scope of assessments which are included or not in most global estimates (Eska, Lee and Park, 2024).

Changing how we produce meat can reduce greenhouse gas emissions, but not enough to offset the growing demand for beef and its contribution to the climate crisis. According to FAO (2016) data, 14.5% of all human-caused greenhouse gas emissions are attributable to livestock farming, an industry that emits not only carbon dioxide, but also methane and nitrous oxide—two gases considered to play a similar role to CO_2 in driving global warming (FAO, 2016). FAO in 2023 has released a new, lower estimate that livestock produce 12% of global greenhouse gas emissions sparking a debate, as some peer-reviewed studies suggest a higher percentage, 14.5–19.6% (FAO, 2023).

More recently, it was concluded that greenhouse gas emissions of beef production are extremely variable depending on the livestock production system and slaughtering age used, capable of reducing the range of emissions to 15–35 kg CO_2e per 100 g protein (Morais *et al.*, 2025). Ruminant gas (methane) can be reduced by up to 40% or more through several strategies, including dietary changes like adding specific additives (e.g., ionophore antibiotics such as monensin) or certain types of seaweed.

A quarter of global greenhouse gas emissions in the food industry are said to result from beef production alone. Interesting to enhance the fact that this is followed by rice cultivation, the main staple food for more than half of the global population being a major source of greenhouse gases from plant-based food production, generating indeed more greenhouse gases than pork, poultry, lamb, mutton, and dairy production (Qian *et al.*, 2023). The greenhouse gas emissions per kilogram of rice are far lower than those for beef.

Carbon emissions, primarily from burning fossil fuels, deforestation, industrial processes, agriculture, and waste management, are the main drivers of climate change, air pollution, and ecosystem disruption. Energy production is the largest contributor, followed by agriculture, forestry, and land use changes (United Nations (UN), 2025). Ruminants significantly contribute to methane emissions. The contribution of methane emissions to global greenhouse gases is relatively high, and the share of ruminants within this is roughly 6% of the global total, although methane has a much shorter atmospheric lifetime than carbon dioxide (Beauchemin *et al.*, 2020).

However, many other climate change sources, such as the September 2022 ruptures in the Nord Stream pipelines, released an unprecedented, record-breaking amount (half a million tons were released into the atmosphere) of methane, a powerful greenhouse gas, into the atmosphere (United Nations (UN), 2023). This event, leading to significant climate concerns due to methane's potent short-term warming potential, represented the largest single human-caused methane release ever recorded. While the amount was substantial, it accounted for less than 0.1% of total annual human-made methane emissions (Harris *et al.*, 2025).

There are some contradictory reports on ruminant digestive fermentation contributions to a significant percentage of global methane emissions, with figures often around 27% of total compared to 24% for oil and gas industry (US EPA, 2025). While meat production contributes significantly to emissions, especially methane and nitrous oxide, it is not the largest single source of global warming but still generally stated that meat production is a crucial cause of climate warming (Spiro, Hill and Stanner, 2024; Xu *et al.*, 2021).

Indeed, the largest source of global greenhouse gas emissions comes from the burning of fossil fuels for electricity, heat, transportation, and industry, which accounts for over 75% of total global emissions. In contrast, ruminant emissions, though a contributor to methane, represent a much smaller portion of total global greenhouse gas emissions (Yenice, 2024).

World wars and conflicts represent well above 5% of global emissions, but countries continue to hide the true scale and accurate measurements of rapidly rising atmospheric greenhouse gas concentrations and corresponding global temperature rise were accepted by the world's scientific community (Houghton, Jenkins and Ephraums, 1990).

31.3 Cultural Differences in Meat Consumption

Presently, meat eaters face conflicts over meat consumption due to recent increasing demands for reduced-meat diets to promote human and environmental health (Ruby, 2012; Spiro, Hill and Stanner, 2024).

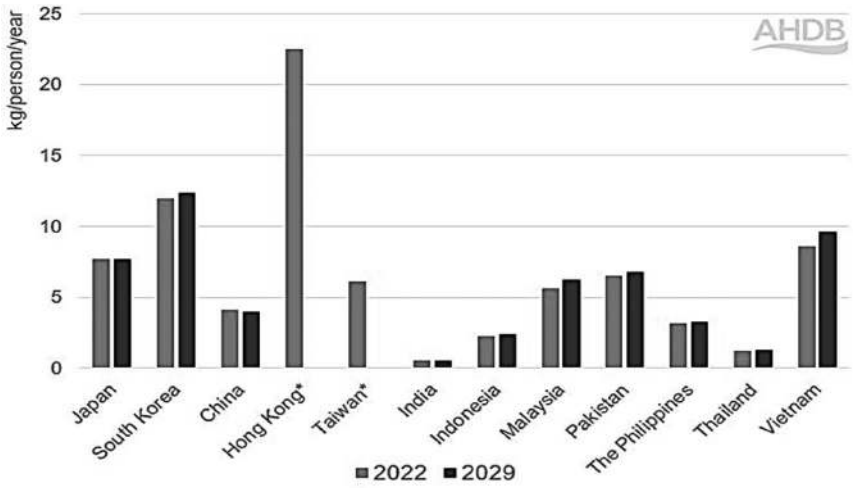

FIGURE 31.3 Beef consumption per capita in selected Asian countries. (From AHDB, 2025.)

However, attitudes toward consuming meat have been shown to be culture-specific and cultural differences in meat consumption are significant, varying by region, religion, and ethnicity, resulting in vastly different global meat consumption rates and dietary practices (Hansen *et al.*, 2021).

Globally, meat consumption is driven by many common factors while diversity in how these factors play out in different geographies is likely to vary across countries, and total growth in meat consumption is projected at 47.9 Mt between 2025 and 2034 (Euromeatnews.com, 2025). Meat consumption in developing countries continues to increase, and it is projected that current emerging economies will drive future demand for meat resulting from expected income increases and rapid population growth. This could dwarf the impact of declining meat consumption in current developed countries (OECD/FAO, 2024).

Meat-related eating practices are a multi-determined issue that challenges disciplinary borders and requires integrated approaches and an overarching framework to be properly studied and understood while addressing transitions in food and eating (e.g., psychology; sociology; history; economics; marketing; political science; agricultural and food science) (Atkins and Michie, 2013).

Attitudes toward consuming meat have been shown to be culture-specific. Cross-cultural variations in meat intake are significant, varying by region, religion, and ethnicity, resulting in vastly different global meat consumption rates and dietary practices. These cultural practices, alongside socioeconomic factors, play a crucial role in shaping the patterns and rates of meat consumption worldwide but religious affiliations might not influence ethnic differences in meat consumption behaviors (Lee and Choi, 2022).

Meat consumption is both a complicated and delicate issue and thus has been described as a mixed blessing. The increasing presence of meat products in the diets of sub-Saharan African populations have consequences for human and planetary health in this region. The increased production and consumption of meat and dairy have been associated in the region with both adverse health and high environmental impacts, including prevalence of noncommunicable diseases and climate change (Mensah *et al.*, 2022; Willett *et al.*, 2019).

Meat consumption in Asia varies significantly by country, but the region is the world's largest meat consumer. Pork is the most consumed red meat in Asia, particularly in South Korea, Vietnam, and China, while chicken is the most popular in some Southeast Asian countries (Figure 31.3).

31.4 Religious Influences

Religions acknowledge the symbolic power of food and meat, as it is frequently offered to honor gods, deities, ancestors, and the sacred through offerings. Many studies have reported that the religions that affect meat consumption are Islamism, Judaism, and Hinduism/Jainism. Religious prohibitions on beef in

Hinduism and pork in Islam and Judaism demonstrate how beliefs restrict specific meats, while ethnic variations, like East Asians consuming more pork and Africans consuming more chicken, highlight distinct meat preferences (Filippini and Srinivasan, 2019; Gowder, 2024; Heiman, Gordon and Zilberman, 2019).

31.4.1 Hinduism

Hinduism, the world's third-largest religion, favors a vegetarian diet and protects the cow as a sacred animal and source of prosperity. Beef is therefore deemed to be nonedible and people rarely eat meat. The 1.2 billion Hindus worldwide represent 15% of the world's population, with some 80-95% being concentrated in India alone and an estimated 100 million Hindus live outside of India, mainly in Mauritius, South Africa, and Uganda. For them, the cow acquired a deeply revered and sacred status, symbolizing divine goodness, motherhood, and natural bounty, preventing them from eating beef. However, the consumption of its products, milk, yoghurt, ghee, butter, cheese, is not considered contradictory to this reverence (Bruckert, 2014).

31.4.1.1 Jainism

Jainism is one of the three most ancient religions of India, believing that all living beings, including plants, animals, and humans, have souls of equal value. Jains are strict vegetarians, eating vegetables that grow above the ground, refraining from meat, seafood, eggs, and root vegetables.

31.4.2 Islam

Muslims and the Islamic faith, the second-largest religion in the world, are the fastest-growing religious group, representing some 25% of the global population (ca. 2 billion), with views based on the Islamic principles of "Halal" (lawful and permissible) and "Haram" (unlawful and forbidden) as prescribed by the Qur'an and Hadeeth, guiding social and political as well as personal life (Putra, Wulandari and Khasan, 2023).

Halal foods, including water halal, are permissible for consumption, whereas Haram foods are strictly prohibited, including items like animals not being slaughtered in an Islamic manner (called "Zabihah"), pork, blood, and alcohol. Beef, lamb, and mutton, even when labeled organic or free-range, are only considered Halal and is widely consumed by Muslims around the world, if certified under guidelines on how animals are treated and slaughtered. While fish is widely accepted, there are varying opinions among different Islamic schools of thought regarding other seafood, such as shellfish, with some being considered forbidden (e.g., shrimp, lobster, crabs, and frogs) (AHL, 2024).

31.4.3 Judaism

Judaism forbids pork because the Torah, the first five books of the Hebrew Bible, specifies that only animals that ruminate, chewing their cud, and have split hooves (i.e., cows, oxen, goats, sheep, buffalo, and deer) are fit for purpose (*kosher*). While pigs have split hooves, they do not chew their cud, making their meat non-*kosher* and thus forbidden for consumption. Prohibitions on pork are a well-known example of religious influence on meat consumption in these faiths (Redding, 2015).

Fish if they have both scales and fins are *kosher*, but shark, octopuses, squid, and seafood are excluded.

31.4.4 Buddhism

There are approximately 540 million Buddhists worldwide, ca. 7–10% of the global population, found in China, Thailand, Japan, Myanmar, Sri Lanka, Cambodia, and Thailand, making it the fourth-largest religion globally. Buddha had no objection to eating meat offered to him. Though not strictly forbidden by Buddhist teachings, many of those following the Buddhist religion opt out of eating meat so that they are not causing suffering to animals while stating that animals should not be killed for meat. The Buddhist diet holds no place for pork or eggs (Benn, 2004).

The Buddha permitted meat consumption under the triply clean rule (not seen, not heard, not suspected to be killed for the consumer), as the animal was not killed for him, though he did not reject vegetarianism. Most Buddhists eat at least some meat; vegetarianism is not a universal requirement, though Mahayana Buddhism generally prohibits meat-eating for monastics, while Theravada Buddhism permits meat under the triply clean rule (Diem, 2012).

31.4.5 Catholicism

Neither the Church nor the Bible says that eating meat is a sin. The norms concerning abstinence from meat are binding upon members of the Latin Catholic Church from age 14 onward. A summary of current practice: On Ash Wednesday, Good Friday, and all Fridays of Lent: everyone of age 14 and up must abstain from consuming meat. The practice of abstaining from meat, as part of fasting and regulation of food, developed further in the ancient and medieval periods and no longer mandated to abstain from meat on all Fridays. Nevertheless, Catholics are asked to abstain from eating meat on Fridays as an act of penance, reviving a centuries-old tradition.

31.5 Ethnic and Regional Differences

Ethnicities differ in terms of attitudes, beliefs, and patterns of meat consumption often due to cultural, religious, and socioeconomic factors that influence dietary practices and preferences for specific meats and cooking methods (Lee and Choi, 2022).

Globally, the United States has one of the highest per capita meat consumption rates, while many African countries have the lowest meat consumption per capita globally, with Gabon recording the highest per capita amount of meat available. Afro-Americans have the highest total meat consumption among ethnic groups studied, followed by East Asians, Whites, and then Hispanics (Verain and Dagevos, 2022).

In the UK, East Asians tend to eat more pork and processed meats than other groups. South Asian respondents were more likely to follow a low/no meat dietary pattern than White interviewers, while no differences were observed between White and Black. Negroes consume significantly more chicken compared to other ethnic groups. South Asians in developed countries are statistically less likely to be meat-eaters compared to other groups (Table 31.1) (Çoker, Pechey and Jebb, 2024).

TABLE 31.1

Consumption (in kilograms) Per Capita in the Main Latin American Countries

Country	Beef (kg/person/year)	Chicken (kg/person/year)	Pork (kg/person/year)
Argentina	44.8	44.5	16.4
Bolivia	6.5	22.1	3.1
Brazil	24.6	40.8	19.5
Chile	26.3	NA	19.9
Colombia	8.7	32.3	13
Equador	NA	NA	11
Guatemala	NA	NA	5.7
Mexico	9	32.3	23.03
Panama	NA	NA	17.5
Paraguay	12.1	NA	10.1
Peru	4.2	46.7	10
Dominican Republic	NA	NA	12.9
Uruguay	43	NA	20.5
Venezuela	3.7	27.1	NA

Source: Emergentcold LatAm (2025).
Abbreviations: NA: data not available.

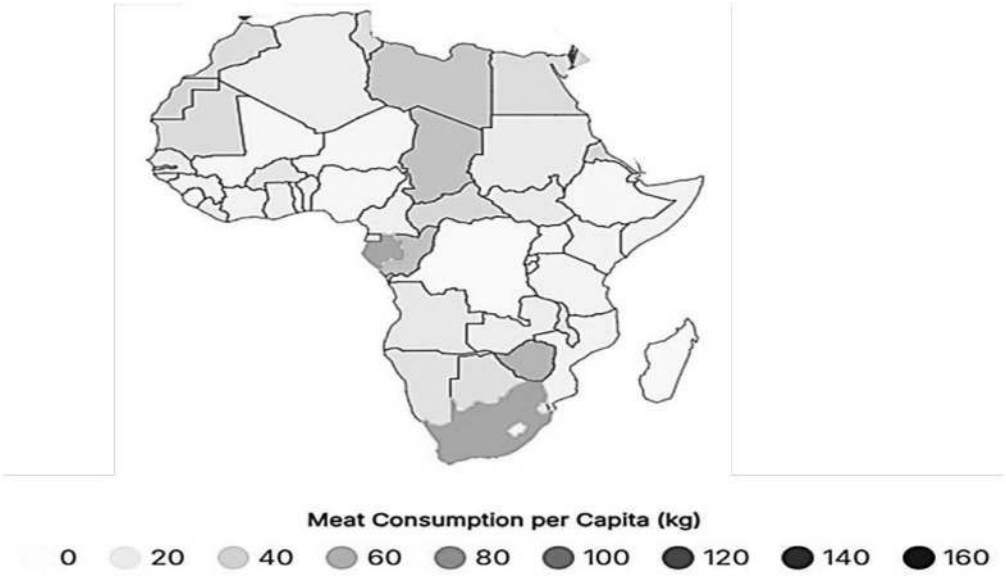

FIGURE 31.4 Meat consumption in Africa, by country (kg/capita).

Latin Americans show gradually increasing per capita meat consumption, catching up to levels in developed countries. Argentina remains among the world's top beef-consuming countries, but as beef becomes less affordable, Argentinians are shifting to other proteins, although the overall trend in Latin America still shows increasing meat consumption, largely driven by poultry.

Argentina, together with the United States, Brazil, Kazakhstan, Paraguay, Canada, Uruguay, China, India, New Zealand, and Australia, have huge grasslands supporting cattle farming and meat production (Figure 31.4). Countries like Burundi, Ethiopia, and Afghanistan have some of the lowest meat consumption rates (Figure 31.5) (Millstein, 2025).

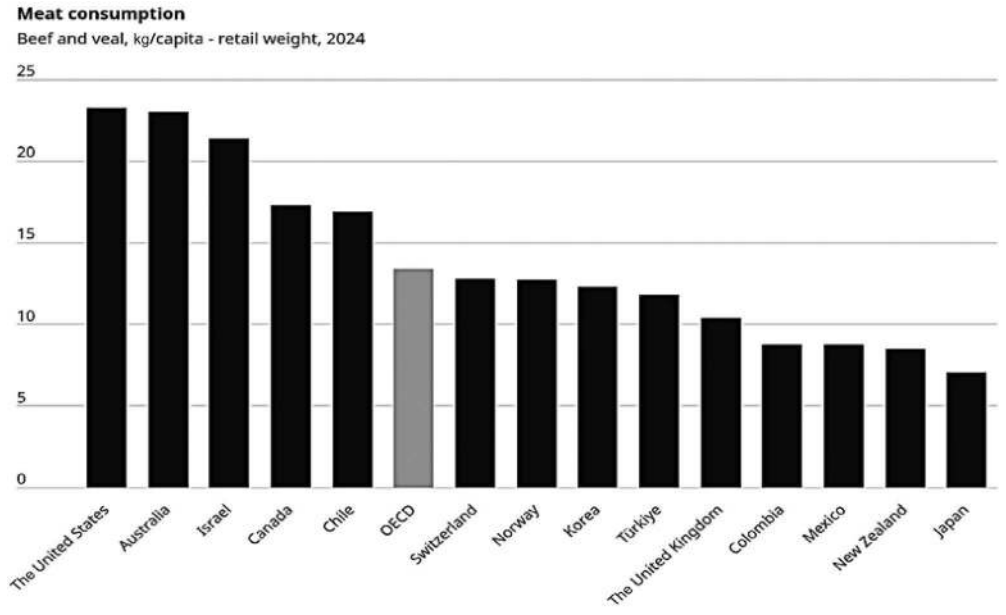

FIGURE 31.5 Meat (beef and veal) consumption by country 2024. (From World Population Review, 2025.)

31.6 Socioeconomic and Geographical Factors

Socioeconomic factors like income, education, and urbanization strongly influence meat consumption, with higher income and urbanization generally leading to increased consumption, although consumption may plateau or decline at very high-income levels in developed nations. Geographical factors also play a role, as countries with historically strong pastoral farming traditions tend to have higher meat consumption, and consumption patterns also vary between high-income and low-income regions (Clonan, Roberts and Holdsworth, 2016).

Meat consumption often follows an inverted U-shape, increasing with income initially but then potentially decreasing at higher income levels in some societies (Raptou *et al.*, 2024).

In some East Asian cultures, meat is viewed more as a festive food, while in West and sub-Saharan Africa, where the communities depend directly or indirectly on livestock value chains for food, as input to crop production, transport, as a source of cash, investment, and storage of wealth, for ritual and social purposes, or as insurance during impending crises, meat is more expensive and less accessible, making it a luxury food item for many, while health, environmental sustainability, and animal welfare are not priority concerns (Font-i-Furnols, 2023).

While in high-income countries are emerging food system models and alternative food sources, including edible insects, seaweeds, plant-based and lab-cultured meats, underutilized crops, hydroponics, and next-generation fish farming, in Africa food security is still a persistent challenge to ensure an adequate food supply for communities (Habib *et al.*, 2025).

As global scrutiny intensifies over the environmental impact of agro-food systems, particularly livestock farming and high meat intake, Africa's distinct context stands out. Average meat consumption in Africa is around 9.6–15 kg per capita per year (2021–2023), with chicken being the most consumed type of meat. Global calls to reduce meat consumption do not apply uniformly to Africa, less than half the global average of 35 kg. Indeed, meat consumption in Africa remains far below global norms and should not be conflated with the overconsumption patterns of the Global North (OECD/FAO, 2023).

Over 32 traditional meat products constitute one of the ancient cultural heritages of the North African and Mediterranean countries: Egypt, Libya, Tunisia, Algeria, and Morocco. The list of North African ethnic meat products, with their close connection to the culture, heritage, and the local identity, may be grouped into five categories using both traditional and scientific knowledge related to their preparation. The identified categories are (i) salted and/or marinated meat products but not dried; (ii) dried not fermented meat products; (iii) fermented semidry/dried meat products; (iv) smoked meat products, and (v) cooked and/or candied meat products (Gagaoua and Boudechicha, 2018).

Wild meat consumption plays a crucial role in the livelihoods and diets of many communities, particularly in regions of Africa and Asia, where it often serves as both a critical food source and a vital part of the local economy. Wild meat value chains—including hunting, harvesting, marketing and consumption—and the implications of consuming wild meat on biodiversity conservation and zoonotic risks have been studied but requires careful and continuous consideration (Grace *et al.*, 2024).

31.7 Meat Consumption by Different Social Groups

Meat consumers are a heterogeneous group with unpredictable attitudes, motivations, and perceptions of issues like animal welfare and food safety. Socioeconomic and demographic characteristics, social status, norms, and structural context shape meat consumption unevenly and most findings on meat consumption have been characterized by gender, age, family status, social status, social norms, and context (Wiesli, 2025).

31.7.1 Gender Differences

It is well-known that globally women tend to prefer plant-based options and consume less meat than men, in particular red meat (Neumann, Stanley and Cárdenas, 2024), and on average they score higher

in nutrition knowledge (Klink *et al*., 2022), while men with lower perceived socioeconomic status exhibit a greater preference for meat and tend to eat more filling food (Chan and Zlatevska, 2019b).

Also, men have greater overall caloric and protein needs, which contribute to higher meat consumption, but cultural associations with meat as a symbol of power and masculinity are also a significant factor (Hopwood *et al*., 2024).

Many findings on sex differences in meat consumption are in line with previous literature with reasons being linked to masculinity (Camilleri *et al*., 2024), women being more health conscious and take more often environmental and animal welfare-related issues into account (Sares-Jäske *et al*., 2022).

31.7.2 Age

Meat consumption is highest in the middle age group of 35–54 year-olds. Younger individuals have stronger, yet more segmented attitudes toward meat consumption, and tend to consume more red meat, due to a desire to increase one's protein intake when committed to sports, compared to older individuals, while middle-aged adults eat the most meat in genera (Tschanz *et al*., 2022). Red meat consumption is deeply rooted in some food cultures, but in most ethnic pluralism, some older persons tend to reduce or even stop eating red meat due to chewing problems and metabolism changes (Loiselle *et al*., 2024).

31.7.3 Social Status

This refers to the level of social value, prestige, respect, competence, honor, and influence in a community, often influenced by socioeconomic factors. Social status is linked to meat consumption both historically and as a symbol of wealth and power, although this relationship is complex and variable across cultures, possibly associated with globalization and masculinity (Chan and Zlatevska, 2019a).

There are both evolutionary and modern perspectives that suggest meat consumption to be prestigious high-status. While the effects of education or income on meat consumption are clear (Mata *et al*., 2023), there is not much evidence among different professional occupations (Ge, Scalco and Craig, 2022).

Country development has conventionally resulted in increased meat consumption with evidence of continued consumption increases in many of the emerging-economy countries (e.g., China and Brazil), probably due to greater affordability (Whitton *et al*., 2021).

For the working class, even in high-income countries, red meat is appreciated but still too expensive (Giacoman, Ayala Arancibia and Alfaro, 2021).

31.7.4 Family Status

Evidence is scarce on how norm perceptions sustain meat consumption, differ within and across individuals, and it is widely acknowledged that what we eat, how much we eat, and why we eat are influenced by what others around us eat (Higgs and Thomas, 2016; Wolfswinkel *et al*., 2024).

Family cohesion, harmonious living, and domestic tranquility were found to be drivers of and barriers to reducing household meat consumption (Hesselberg, Pedersen and Grønhøj, 2024) but how children and adolescents engage in and possibly influence the process toward more sustainable diets has been the subject of limited research. Nevertheless, they can act as catalysts for change within families through "reverse socialization", which involves their parents learning from them (Grummon, Zeitlin and Lee, 2024).

Moreover, although eating habits established in early childhood may track into adult life, children played a crucial role as "gatekeepers" in influencing household meat consumption patterns in regard to more sustainable diets, often exploring new food options, evidencing the children's role on a bottom-up transmission of meat preferences to their parents in the context of family meals.

In Europe, educational achievement appears to be the best predictor for meat consumption and food label reading rather than income (Klink *et al*., 2022; Loginova and Mann, 2025), while in low-income countries, meat consumption is primarily limited by affordability, as meat and other animal products are significantly more expensive, and meat demand amid high and rising consumer costs and weak income growth is reduced (OECD/FAO, 2024).

31.7.5 Social Norms

Cultural norms regarding meat consumption can be reflected in differences among White, South Asian, and Black ethnic groups within a society. Symbolic concerns, such as threats to national dietary customs and cultural identity, are the primary drivers of negative attitudes toward meat consumption, rather than economic fears (Çoker, Pechey and Jebb, 2024).

Motives and barriers for meat consumption are very much variable and they, in addition to the intrinsic and extrinsic characteristics of the meat, are also related to consumers' attitudes and beliefs (Font-i-Furnols, 2023).

Dietary choices, including meat consumption, are intertwined with broader political, social, and moral values, and even a substantive connection between political orientation and meat-eating has been described in Germany, with vegetarians tending to cluster on the left side of the political spectrum. Indeed, it was found an interesting interplay of political orientation, moral foundations, and meat consumption (Grünhage and Reuter, 2021).

31.7.6 Framing Effects and Benchmark Groups

Context effects that impact the decision-making ability significantly influence meat consumption by shaping social norms, individual emotions, and perceptions of necessity, naturalness, and taste. Factors such as the specific social group, cultural background, gender, and even the immediate environment play a crucial role in whether people choose to consume meat (Kwasny, Dobernig and Riefler, 2022).

Meat consumption patterns and rituals depend on the individual location and circumstances, different social, temporal, and situational contexts, shaping consumer behavior, tending to increase meat intake when eating out (Horgan *et al*., 2019; Ritzel and Mann, 2023).

While globally policymakers are at a crossroads as the world faces serious challenges from rising temperatures, unpredictable weather, and other climate-related effects, they are pressured to consider new solutions to address these challenges (Said *et al*., 2025). However, eating less meat is not the way everyone should aim to tackle the climate crisis. It is an essential step for many of us, but in a world racked by malnutrition and hunger, it can be only part of the answer to rising temperatures. Indeed, in most low- and middle-income countries in 2024, with more than 820 million people with malnutrition and over 151 million stunted children, the imperative is not climate changes but to ensure people have adequate nutrition (The World Bank, 2025).

Certainly, the question remains on how to harmonize and integrate environmental policies with food systems, which will require a thorough investigation into global agriculture, supply chains, consumer behavior, and the fundamental dynamics of food systems.

31.8 Concluding Remarks

The state of the art does not yet provide validated tools for meat consumption among all of the social groups, demonstrating research gaps in the field, but it is clear that differences on levels of meat consumption among social groups are mostly based on geography, religion, gender, social status, and class, including specific factors such as education and income, family status, and social norms.

In high- and middle-income countries, movements have been advocating a progressive reduction of meat consumption and shift to plant-based diets, considered crucial for reaching climate targets, addressing public health problems, and protecting animal welfare. There is no substantial data for the Global South countries and "sustainable" beef farming struggles to offset the escalating global demand, therefore the environmental impact of meat production can vary considerably.

Nevertheless, the global food demand in 2050 is predicted to be double that in 2005, while meat demand will increase 70%, driven by growing populations and rising incomes in developing countries. To meet this greater demand, it is essential to increase the production of foods, including meat, but this should be accomplished in an environmentally endurable manner.

In order to implement a sustainable food system, social, nutritional, public health, and environmental aspects of meat consumption need to be discussed among multi-sector stakeholders to provide livelihoods for many communities and to improve farming practices for more viable meat sourcing, while addressing the economic and social dimensions of food production and access. Cross-cultural research may give insights into the influence of different cultural backgrounds and values on changes in meat consumption and responses to interventions.

New benchmarks must be developed for global meat/food security projections to identify gaps, uncover opportunities for improvement, and set data-driven goals, and quantitative scenario studies to inform policy analysis and the public debate on the future of meat consumption and food production.

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32

Marketing Strategies: Predicting Consumer Behavior in a Changing Meat Industry: Implications for Meat Product Marketing

Elena Raptou and Theodoros Varzakas

32.1 Current Trends in the Meat Industry

Recent evidence has depicted the meat sector as steadily expanding in aggregate volumes, although the market conditions have become more volatile and the industry's social legitimacy has been more publicly challenged than ever before. Contemporary meat markets are shaped by a combination of low supply growth, volatile input and disease-related risks, and a trade environment in which although volumes remain large, they are sensitive to short-run disruptions (FAO, 2025). In 2024, global meat production increased by almost 1.3%, reaching approximately 365 million tons, while world meat exports recovered to about 40.2 million tons. At the same time, international prices augmented, with the FAO Meat Price Index averaging 117.3 points in 2024, recording an increase by 2.8% compared to 2023, and mostly driven by higher ovine and bovine prices and a smaller increase in poultry meat (FAO, 2025). Trade patterns are consistent with this demand pressure and with heightened exposure to supply shocks, since global meat trade rebounded in 2024 to 42.5 million tons, with strong bovine import demand from the United States supporting growth, although the highly pathogenic avian influenza continued to pose production risks for parts of the poultry supply chain (FAO, 2025).

Beyond short-run market performance, the longer term is characterized by a "mix" of aggregate growth and "compositional" change, in which total volumes continue to rise globally, while the combination of the meat types consumed changes over time, particularly toward poultry (Font-i-Furnols, 2023; OECD/FAO, 2021; FAO, 2025). According to FAOSTAT estimates, global meat production and consumption both are projected to increase toward 2030, with population growth comprising the primary driver and with the largest proportional increases being expected in Africa, followed by Asia and the Pacific, while growth in Europe is predicted to be comparatively marginal (Font-i-Furnols, 2023; OECD/FAO, 2021). More specifically, recent research showed that per capita meat consumption growth in high-income countries will slow, and consumers will increasingly substitute poultry for beef and pork, as environmental, health, and ethical attributes become more salient in food choice (OECD/FAO, 2021).

This substitution is enhanced by production-side determinants and product attributes, since poultry is expected to remain the most affordable meat and the most frequently positioned as more nutritious because it offers a higher protein-to-fat ratio than many substitutes, whereas red meat production is widely perceived as more resource- and greenhouse gas–intensive. Accordingly, poultry's share of protein from all meat sources is projected to reach approximately 45% by 2034, with global consumption reaching most of the incremental meat consumed in this period (OECD/FAO, 2021). At the same time, global production growth is estimated to rise to 406 million tons, with additional demand expected to be concentrated in parts of Asia and Latin America, and with diets in low- and middle-income countries projected to shift toward higher animal product consumption as income increases (OECD/FAO, 2021). With respect to EU, European Commission forecasts anticipated a slight decline in EU total

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meat availability from 69.8 kg per capita in 2020 to 68.7 kg per capita in 2030, with beef and pork meat displaying declines, whereas poultry presenting increasing projections in the same period (European Commission, 2019; EPHA, 2021). These estimations align with a broader body of the literature linking changes in meat demand to economic pressures and increasing concerns about health impacts, environmental footprint, and animal welfare, alongside the growth of more environment-friendly meat and alternative proteins (Willett *et al*., 2019; Estévez-Moreno *et al*., 2021; Font-i-Furnols, 2023; Font-i-Furnols and Guerrero, 2022; Realini *et al*., 2022). In this direction, plant-based and other alternative proteins are largely adopted in dietary patterns (Curtain and Grafenauer, 2019; Fresán, Errendal and Craig, 2020; Onwezen *et al*., 2021), although their aggregate dietary share seems to remain rather small in high-income countries (OECD/FAO, 2021).

32.2 Consumer Attitudes toward Meat and Meat Products

Motives and barriers for both meat and alternative meat consumption extend beyond intrinsic product characteristics to include consumer attitudes, beliefs and perceptions, stressing the importance of reliable and valid consumer information. In the contemporary food systems, consumer attitudes toward meat products are increasingly affected by the interrelationship among environmental sustainability considerations and ethical concerns, and the perceived unhealthiness of meat foods, although meat purchases remain strongly dependent on sensory gratification, cultural identity, and the social normalization of meat as a "proper meal". Recent evidence showed that there are widespread justifications through which individuals rationalize meat consumption, although there is a growing ethical, environmental, and health criticism (Piazza *et al*., 2015; Roozen and Raedts, 2023; Rothgerber, 2020; Verain, Dagevos and Jaspers, 2022). The cognition that eating meat is "natural", "necessary", "normal", and "nice" (the 4Ns) functions as a culturally enhanced "common sense", aiming to reduce moral discomfort and cognitive dissonance by presenting meat as biologically appropriate (natural), nutritionally required (necessary), socially common (normal), and hedonically pleasant (nice).

Furthermore, endorsement of the 4Ns seems to be linked with stronger meat attachment and lower willingness to reduce consumption, since it enables consumers to maintain a positive moral self-image and reduce guilt about "eating animals" (Ioannidou, 2023; Piazza *et al*., 2015; Rothgerber, 2013; Rothgerber, 2020). For instance, recent evidence from Italy noted that the 4Ns are actually rationalizations that allow meat eaters to avoid guilty conscience and support their preferences (Testa *et al*., 2025). One of the most widely used frameworks to explain these orientations toward meat is the meat paradox, which refers to the cognitive and emotional discomfort that can emerge when individuals ascribe moral value to animals or endorse sustainability ideals, whereas at the same time continue to enjoy meat consumption (Gradidge *et al*., 2021; Oleschuk, Johnston and Baumann, 2019; Roozen and Raedts, 2023). Hence, there is an apparent conflict, since the same consumers who acknowledge the negative externalities associated with meat production, may maintain positive attitudes and stable meat purchases. Prior research indicated that consumers may rely on various strategies to copy with internal conflicts and sustain the inconsistency between their moral concerns and their eating practices. For instance, they may underestimate animals' emotions and their capacity to suffer, or even disassociate the living animals with the meat that they consume (Buttlar and Walther, 2018; Oleschuk, Johnston and Baumann, 2019; Testa *et al*., 2025). In such cases, moral, health and sustainability motives compete with hedonic attributes (e.g., taste and texture), identity representations (e.g., tradition, masculinity symbolism), and purchase and meal preparation habit (Buttlar and Walther, 2022; Jahn, Furchheim and Strässner, 2021).

Overall, consumer attitudes toward meat can be explained through multilayered evaluations, in which product expectations about taste, freshness, appearance, and convenience coexist with broader concerns about health risk, safety, ethics, environment, and policy regulation, affecting how meat is justified and what information is credible. The "classic" attribute bundle, including price, sensory quality, freshness and visual appearance, remains explicitly significant for analyzing consumer choice, but food safety and perceived health implications constantly emerge as highly salient concerns, shaping purchase behavior (Dill *et al*., 2021; Hobbs, 2021; Hötzel and Vandresen, 2022; Sasaki *et al*., 2022). This implies that the

perceived "positive" attitudes toward meat as a valued food can coexist by attitudes that require reassurance about production practices, contamination risks, and health impacts, especially when consumers have to compromise with perceived uncertainty.

32.2.1 Consumers' Environmental Concerns

Recent empirical research has underlined that consumers can acknowledge the environmental footprint of livestock; however, the motivation for dietary shifts still assign priority to taste, quality cues, and established routines in purchase and consumption decisions. For instance, in a large cross-country survey from France, Brazil, China, Cameroon, and South Africa, respondents perceived livestock farming as producing serious environmental impacts, whereas many considered meat reduction as a mitigation strategy. However, the adoption of these perceptions varied by country and were correlated with sociodemographic characteristics and consumption patterns, illustrating their function as socially grounded beliefs that depend on regional aspects and lifestyle indicators (Kirbiš, Lamot and Javornik, 2021; Liu *et al*., 2023; Magalhaes *et al*., 2023). In particular, women and more educated respondents were more likely to recognize environmental repercussions related with meat consumption Furthermore, sustainability concerns were associated with higher acceptance toward meat substitutes among light meat consumers, vegetarians, and vegans, whereas daily and regular meat consumers placed most importance on sensory quality (Liu *et al*., 2023). In a similar direction, evidence from Brazil indicated environmental concerns as a significant factor forming consumer perceptions and attitudes toward meat products and a growing challenge for the meat sector, yet remain secondary to pleasure, tradition, and price (Burnier, Spers and de Barcellos, 2021; Hötzel and Vandresen, 2022; Veiga *et al*., 2023).

Furthermore, the influence of individuals' environmental concerns on actual purchase and consumption practices seems to be moderated by consumers' knowledge and the credibility of the sources disseminating environmental information, as well as the extent to which environmental impacts are perceived as personally relevant and amenable to behavioral change. Empirical research on US households showed that information on the association between environmental (and health) externalities and meat production was not linked with consistent increases in consumers' willingness to pay price premiums for either environment-friendly beef or plant-based meat substitutes (Katare *et al*., 2023). These findings also underlined a time heterogeneity in consumers' preferences, with present biased consumers being less responsive to messages that emphasize delayed benefits, and more future-oriented individuals showing comparatively higher willingness to pay a premium for plant-based substitutes (De Marchi *et al*., 2016; Katare *et al*., 2023). Thus, it seems that detached informational nudges are less likely to shift food choice behavior, especially when people prioritize motivators like price, taste expectations, and established consumption habits rather than long-run repercussions, such as environmental impacts.

Previous literature has noted that consumers often respond more strongly to reliable signals concerning traceability, certification, and legality, which reduce the perceived uncertainty by providing concrete assurances (Chaudhary, Sharma and Vemireddy, 2024; Lin, Huang and Li, 2023; Nguyen and Nguyen, 2025; Ying *et al*., 2025). In Brazil, during the COVID-19 period, perceived importance of traceability and the legality of slaughterhouses was positively correlated with purchase intentions for certified beef, whereas subjective knowledge increased both the perceived value of traceability and purchase intentions (Quevedo-Silva *et al*., 2022). Thus, it seems that environmental concerns are shaped into the cultural environment and they are substantially influenced by local public debates and trust level in institutions and certification systems. These findings indicate that market-based assurances, such as certification schemes, smart packaging, and supply chain information, can help reframe environmental concerns by emphasizing consumer demand for system integrity and transparency.

32.2.2 Consumers' Ethical Concerns

Ethical debates about meat consumption have become increasingly prominent in food-related research, in which dietary choice is less restricted by availability and affordability and more influenced by ethical and moral disbelief. With respect to meat products, meat eating is often evaluated not only as a

nutritional practice, but also as a morally consequential act involving animals, ecosystems, and vulnerable human communities (a detailed discussion is included in Croney and Swanson, 2023; Northrope *et al*., 2024; Schwitzgebel, Cokelet and Singer, 2023).

Ethical concern is perceived as a constructed set of moral claims and constraints that consumers invoke and negotiate in order to reconcile everyday meat practices with increasingly salient expectations about animal welfare, environmental responsibility, public health, and moral justice. Besides individuals' beliefs, perceptions, and expectations, "ethical meat consumption" is also shaped by the cognitive and affective mechanisms that regulate moral discomfort. and the social norms adapting moral ideas to common practices (Gradidge *et al*., 2021; Hötzel and Vandresen, 2022; Croney and Swanson, 2023). Croney and Swanson (2023) presented this viewpoint as a need for explicit moral deliberation, arguing that scientific evidence can inform, but cannot defend value-oriented questions on the harms associated with rearing and killing animals for food and their moral justification, or the values that should be prioritized. Under this perspective, consumer concern should be perceived as a moral signal, which can inform how industry and policymakers set standards and design regulation, particularly where a sector's social license depends on public perceptions of legitimacy and fairness (Hampton, Jones and McGreevy, 2020; Henchion, De Backer and Hudders, 2017; Hötzel and Vandresen, 2022; Croney and Swanson, 2023).

A significant body of literature has sought to explain why moral concern often fails to translate into abstention. The "meat paradox" (also stated above) describes the cognitive affective conflict, in which many individuals simultaneously care about animals and at the same time they enjoy eating them. One way this tension is alleviated is through dichotomization, where people maintain strict categorical boundaries between animals perceived as companions and animals categorized as food, sustaining moral outrage about some forms of animal harm while normalizing others (Dhont *et al*., 2020; Dillon-Murray, Ward and Soar, 2024; Ioannidou, 2023). Although they frequently express ethical concerns about meat as ambivalence or moral discomfort, these are managed through cognitive strategies enabling consumption. The meat paradox literature has demonstrated that in response to dissonance and guilt, individuals may maintain their usual meat consumption levels by engaging in belief-based coping strategies to adjust beliefs, perceptions, and moral attention, rather than altering behavioral patterns (Loughnan, Haslam and Bastian, 2010; Bastian and Zentes, 2013; Ioannidou, 2023; Rothgerber, 2020). These strategies include justifications (e.g., fate, health), endorsement of the 4Ns rationalizations, dissociation of meat from its animal origins, and denial or downplaying of animal suffering, as well as broader forms of moral disengagement (Piazza *et al*., 2015; Rothgerber, 2020; Testa *et al*., 2025; Ioannidou, 2023). Such processes can help explain how ethical concern can coexist with strong meat attachment and why interventions that heighten moral conflict may elicit polarized or defensive reactions, rather than meat consumption reductions.

Research on moral communication has delineated that appeals based on shame and guilt may trigger reparative and defensive responses for self-protection. For instance, Kranzbühler and Schifferstein (2023), in their experimental study of "meat-shaming" labels, showed that exposure to shaming messages can reduce immediate purchase intentions, while increasing two distinct motivational directions. First, the "restore motivations" direction, which reflect intentions to repair individual's self-image (e.g., by planning to eat less meat), and second, the "protect motivations" direction, portraying self-protective responses characterized by distancing and withdrawal (e.g., avoiding vegetarians) (Antonetti and Maklan, 2014; Kranzbühler and Schifferstein, 2023). Thus, it seems that shame-based appeals may generate short-run compliance for some consumer segments; however, they may also increase identity threat and encourage social distancing, limiting the effectiveness of ethical-directed strategies in settings, in which belonging and intergroup dynamics are strong (Croney and Swanson, 2023; Rothgerber, 2020; Kranzbühler and Schifferstein, 2023).

Beyond guilt and shame, consumer aversion has been found to affect attitudes toward meat products, with Buttlar and Walther (2022) supporting that feelings of disgust may activate a "hedonic shift" to reduce positive sensory associations with meat, while strengthening negative moral associations. In that case, consumers' ambivalence reduction can make meat avoidance easier to sustain, suggesting that moral disgust (e.g., by animal cruelty information) is mostly pronounced in consumer segments who attribute higher mental and emotional capacities to animals. On the other hand, individuals who exhibit higher levels of moral disengagement display attenuated moral-disgust responses, indicating that these dissonance-management tendencies shape how ethical information is experienced and evaluated (Buttlar and Walther, 2022).

Empirical research showed that expressed ethical concern is imperfectly reflected in actual purchasing behavior, hence a citizen–consumer gap is produced, in which individuals express moral expectations, such as stronger animal welfare protections. However, their purchase decisions remain restricted by situational and informational constraints at the point of purchase, including price sensitivity, limited availability of preferred options, low confidence in labeling schemes, and cognitive "overload". In such case, although animal welfare, sustainability, and food safety considerations are frequently reported, purchase routine is predominantly driven by price and perceived product quality (Hötzel and Vandresen, 2022). Recent research has also noted that consumers have conceptualized animal welfare as a public good, which should be protected through regulation and agro-food industry standards, rather than being "entrusted" to individual's ethical shopping practices (Hötzel and Vandresen, 2022; Ammann *et al*., 2023; Benni *et al*., 2024). This governance-oriented frame is important for understanding moral constraints, since ethical public expectations can generate political pressures, shaping regulation, retailer standard, and the food industry ethics, even when individual's willingness to pay premiums is limited or heterogeneous (Krystallis *et al*., 2012; von Keyserlingk and Hotzel, 2015; Hötzel and Vandresen, 2022; Ammann *et al*., 2024).

Building on the meat paradox framework, consistent patterns of variation in how moral conflict about meat is experienced across various population groups have been identified. In particular, several research have documented systematic differences across dietary groups in moral emotions, such as guilt and disgust, and in endorsement of justifying beliefs, with omnivores generally showing weaker moral emotions and stronger justifications than vegetarians. In addition, gender differences have been portrayed, with women expressing stronger concerns for animal welfare and greater acceptance toward meat reduction compared to their male counterparts (Gradidge *et al*., 2021; Ioannidou, 2023). Consistent with this pattern, an exploratory study conducted in Australia found that men reported higher meat consumption and higher selfishness, whereas women reported higher animal-oriented empathy, with these psychological traits showing statistically significant links to meat intake mainly across the male subsample (Dillon-Murray, Ward and Soar, 2024).

32.2.3 Consumers' Health Concerns

Health consideration emerges as one of the most frequently invoked motives for reducing meat consumption. However, it has operated in a rather ambivalent way, since meat is simultaneously perceived as nutritionally beneficial and as a potential contributor to chronic disease risk, with the balance between these appraisals varying across consumer segments, cultural contexts, and informational environments. For instance, in Europe, health-related beliefs have often provided the most direct cognitive path through which consumers develop favorable evaluations for reducing meat to support a healthier lifestyle and decrease disease risk. On the other hand, environmental and animal welfare beliefs may be less predictive of attitudes in specific population groups (Seffen and Dohle, 2023). Therefore, health considerations often function as a more immediate and personally salient motivator of dietary change, whereas other factors are more likely to be overridden during purchase process by established habits, convenience constraints, and price sensitivity (Macdiarmid, Douglas and Campbell, 2016; Stubbs, Scott and Duarte, 2018).

Furthermore, a significant consumer proportion holds a broad belief that high meat consumption (especially red and processed meat) is linked to elevated long-term health risks. For instance, in Spain, survey evidence indicated that health considerations constitute the most frequently cited motive for reducing meat intake, exceeding reported concerns about animal welfare and environmental impacts. These findings further suggest a widely shared belief that high levels of meat consumption may contribute to serious health problems, while a smaller subset of consumers reports feelings of guilt when they interpret their own meat-eating practices as unhealthy (Font-i-Furnols and Guerrero, 2022; SmartProtein, 2021). These results are consistent with the broader perspective that public health debate increasingly presents meat reduction as a preventive strategy for noncommunicable diseases, and hence such anticipated benefits can meaningfully shape attitudes and intentions (Willett *et al*., 2019; Chen *et al*., 2023; Seffen and Dohle, 2023).

Recent research indicated that health-related interpretations of meat are heterogeneous and socially patterned with consumers frequently relying on culturally familiar heuristics (e.g., "red meat is heavy") and translating health concerns into a logic of moderation rather than complete avoidance. Xazela *et al.* (2017)

showed that while most respondents reported awareness of potential health risks associated with meat consumption, there was an uncertainty about what meat quantity would be compatible with a healthy diet. Thus, health-motivated risk management was mostly expressed through portion reduction or selective reduction of red meat, rather than through a broader shift to non-meat options (Xazela *et al*., 2017), implying that population-level health improvements are more likely to be achieved through incremental reductions in meat intake than through strategies, assuming a widespread adoption or complete meat avoidance within niche segments (de Bakker and Dagevos, 2012; Stubbs, Scott and Duarte, 2018).

In addition, the widely held belief that meat is indispensable to a balanced and healthy diet may reduce consumers' receptiveness to meat reduction messages, and also complicate the interpretation of dietary guidance, since meat is simultaneously constructed as a dietary component associated with elevated health risks and as a dependable means of ensuring nutritional adequacy. A substantial share of consumers in Spain perceive meat as nutritionally essential (protein and micronutrients), although they recognize that excessive consumption may be harmful (Font-i-Furnols and Guerrero, 2022; SmartProtein, 2021). In a similar vein, Seffen and Dohle (2023) described a widely held assumption in Germany that abstaining from meat increases the risk of nutritional deficiencies, including inadequate protein intake. This belief is also well-documented in earlier consumer research and helps explain why health-related cognitions can simultaneously motivate reduction through expectations of disease prevention, and at the same time inhibit it through anticipated deprivation and concerns about "missing meat" (Piazza *et al*., 2015; Seffen and Dohle, 2023). Even among health-oriented meat reducers, complete avoidance may be perceived as posing nutritional adequacy risks. In particular, flexitarians are frequently depicted as health motivated, yet they express concerns that complete meat elimination might result in nutrient shortfalls, and hence switch to a moderated reduction and selective meat substitution rather than strict abstention (Dagevos, 2021; Verain and Dagevos, 2022; Verain, Dagevos and Jaspers, 2022; Caso *et al*., 2023).

Empirical findings documented that health-motivated meat reduction is socially patterned and varies systematically across both sociodemographic groups and dietary profiles (Bifaretti, Pavan and Grigioni, 2023). Evidence from Latin America indicated that a substantial proportion of respondents reported attempts to reduce foods of animal origin, with a higher likelihood among females compared to males, and with health considerations cited as a key motivation (Bifaretti, Pavan and Grigioni, 2023; Font-i-Furnols and Guerrero, 2022; Testa *et al*., 2025). Furthermore, Testa *et al*. (2025) delineated that flexitarians in Italy are portrayed as more health-oriented than "meat lovers", reporting lower risk propensity and greater attention to chronic disease risks, whereas high-justification segments seem less inclined toward health risk avoidance. Health maintenance was also the most frequently reported reason for reducing meat intake in Spain, suggesting that health provides a socially acceptable justification for change that can coexist with constant attachment to meat, since it can be expressed through consumption moderation rather than through a moral meat eating rejection (Font-i-Furnols and Guerrero, 2022).

32.3 Theoretical Approaches in Consumer Behavior

Consumer behavior has always been a topic of great interest since it has a crucial impact on both society and the industry. Decisions choices may vary according to their involvement level, ranging from habitual choices through limited problem-solving to extended problem-solving, with repetition, perceived risk, and prior experience determining how the decision-making model is enacted. Furthermore, consumer behavior may be affected and explained by external influences, such as culture, social class, reference groups, and marketing communication strategies. According to the American Marketing Association (AMA, 2025) "consumer behavior refers to the study of how customers (individuals and organizations) satisfy their needs and wants by choosing, purchasing, using, and disposing of goods, ideas, and services". Kotler and Keller (2011) conceptualized the consumer behavior process as an interactive and flexible system of decisions and experiences, driven by the joint influence of psychological processes, contextual constraints, and marketplace communication tools across pre-purchase, purchase, and post-purchase stages. In a thorough literature review, Stankevich (2017) treated consumer behavior as a multistage and context-dependent decision process, rather than a single-purchase act, examining the actors involved in the consumption decision (i.e., individuals, groups, and organizations) and the processes

through which they select or dispose the products/services, the experiences, or the ideas to satisfy the consumer needs, encompassing the consequences of the processes for both the consumer and the society.

It should be noted that the most widely accepted definitions of consumer behavior are not restricted to the act of acquiring or purchasing, but they also include the whole range of the post-purchase consumer activities, such as the usage, the evaluation, and the disposal of products, services, and ideas. For instance, disposal may be associated with multiple perspectives, extending from an environmental approach (such as the discarding or recycling of product residues or packaging) to a market-focused perspective (such as online product resale), and/or a reusage point of view emphasizing the reallocation within households or social networks. This expanded perspective is further supported by the social marketing framework, positing that the marketing role should extend beyond purchase and consumption, in order to address the consumer practices that follow acquisition. Thus, the study of consumer behavior has also to examine how individuals make decisions regarding the allocation of the resources in scarcity (i.e., financial resources, time, and effort) to purchase products and services. Accordingly, it encompasses the investigation of the following questions: (a) what consumers buy, (b) why they buy it, (c) when they buy it, (d) where they buy it from, and (e) how frequently they buy it (Siomkos *et al.*, 2024).

There are various approaches in consumer research seeking to provide theoretical frameworks on consumer decision models that underline different consumer types, different mechanisms of choice, and specify the assumptions about behavior drivers, and what counts as a decision (Pantouvakis, Siomkos and Christou, 2015; Schiffman and Kanuk, 2009; Siomkos *et al.*, 2024; Zellman, Kaye-Blake and Abell, 2010). These approaches present distinct assumptions concerning the level of consumer rationality, the degree of consumer deliberation and external influence, as well as the cognition level in purchase and consumption choice. The models of economic man, passive man, cognitive man, and emotional man are classified among the most influential types of consumer decision-making, with each one providing a different disciplinary framing of how alternative options are assessed, and why behaviors may appear stable or changeable over time. In addition, these theoretical models can be interpreted as complementary approaches, as the consumer behavior process is usually multifactorial, reflecting constraints and incentives, learning processes and outcomes, cognitive constructions and emotional characteristics, which may vary systematically across different product categories and contexts. The different approaches to consumer behavior are analytically described below.

32.3.1 The Model of Economic Man

Under the model of economic man approach, the consumer behaves as an agent who chooses the product of his/her interest among alternative options in product bundles in order to achieve utility maximization subject to constraints. Therefore, consumer's choice is explained by the expected consequences for the chooser's welfare, with preferences assumed to be stable and ordered for permitting comparison across alternatives, and constraints, such as prices, disposable income, time allocation, and information costs affecting product selection. Within this approach, the decision-making process is rational, mapping preferences and constraints, with consumers searching for information to the degree that marginal expected benefit of additional information exceeds the marginal cost. The economic man model can explain consumer responsiveness to prices and income restrictions, and also predict substitution patterns among alternative products (Pantouvakis, Siomkos and Christou, 2015; Siomkos *et al.*, 2024). Furthermore, this model approach can also contribute to policy assessment since it includes consumer surplus evaluation and the effects of policy interventions, such as taxes, subsidies, and labeling schemes on consumer behavior.

However, there are certain limitations regarding the theoretical implications of the model of economic man. First, the assumption that preferences are consistent and stable seems to neglect the possibility that they may be constructed during the decision-making process, and also overlooks the fact that culturally embedded meanings, variations in attribute description, and decision structure usually affect what consumers want and how they evaluate their options. Second, the consumer is presumed to be able to perceive relevant attributes, process information, and evaluate trade-offs without constraints, and third the feasible set of alternatives is perceived as exogenously given. In practice, alternative options are often produced endogenously by individual searching and/or marketing communication channels, which can

expand or narrow the alternatives' set. In consequence, the theoretical framework of the economic man comprises a powerful tool for modeling consumer responses to incentives and various constraints, but comparatively weak to explain how consumers represent decision problems, interpret information, and manage trade-offs among alternative options (Pantouvakis, Siomkos and Christou, 2015; Urbina and Ruiz-Villaverde, 2019; Siomkos *et al*., 2024). In an analytical review, Urbina and Ruiz-Villaverde (2019) provide an in-depth discussion on the model of economic man, focusing on its assumptions and providing criticisms from five economic approaches: behavioral economics, institutional economics, political economy, economic anthropology, and ecological economics.

32.3.2 The Model of Passive Man

Contrary to the rational economic view of consumers, in the model of passive man, the consumer is portrayed as submissive and mostly determined by external factors, such as persuasive communication strategies, past learning, and institutional arrangements (e.g., availability). Under this prism, the behavior is elicited or comprises the result of environmental contingencies, and the decision process is conceptualized as a response to marketing tools. Therefore, the model of passive man shifts the decision explanation from the individual to the external environmental factors, and instead of viewing the consumer as an active decision-maker who evaluates his/her alternative options and chooses the product that best fits to his/her preferences, it depicts him/her as mainly influenced by external forces (Micu, 2010; Zellman, Kaye-Blake and Abell, 2010; Roos and Gustafsson, 2011; Pantouvakis, Siomkos and Christou, 2015; Siomkos *et al*., 2024). Under this perspective, this model is useful because it seeks to explain why consumer behavior can be stable and predictable, even in cases when consumers do not reflect on their choices. Thus, consumers may appear to have consistent preferences, although this consistency can arise from repeated exposure to product promotion, convenient placement, and positive past experience. The model of passive man may have strong implications in environments where individuals have limited time or restricted motivation to act (e.g., low-cost repeated purchases), as it underlines how immediate conditions like product placement, discounts, availability, and social approval can shape attention and action.

However, there are specific limitations on the theoretical background of the model of passive man since it overlooks how consumers pursue their goals and resist to external influences. Furthermore, it fails to explain consumer behavior associated with certain values and commitment, such as switching brands for ethical reasons, choosing novelty despite convenience costs, or keeping consumption patterns that conflict with environmental pressures. It also suggests that consumers are similarly susceptible to marketing strategies and external factors, although there are significant differences in individuals' information, habits, attitudes, and commitments.

32.3.3 The Model of Cognitive Man

Under this framework, the consumer is considered as an active problem-solver whose behavior is based on information processing and inference (Batkoska and Koseska, 2012; Pantouvakis, Siomkos and Christou, 2015; Siomkos *et al*., 2024). More specifically, the consumer decision process is structured by a sequence of cognitive acts, including the perception of a specific need, information searching, the evaluation of alternative options through attribute comparisons, the intention forming, and the learning process. The model of cognitive man assumes that the consumer decision is based on internal mental processes and not only explained by consumer preferences and constraints, whereas purchase decision is often viewed as a solution to a problem or an act to satisfy a need involving stages of information seeking and gathering, evaluation, and decision. Consumers are supposed to learn from experiences, store information, and recall it from their memory in order to shape future behavior and reflect past experiences to current choices (Batkoska and Koseska, 2012; Pantouvakis, Siomkos and Christou, 2015; Siomkos *et al*., 2024).

In comparison with the model of economic man, this model rejects the assumption of thorough information, taking into consideration cognitive limits and decision processes that may bypass utility maximization. Furthermore, compared to the passive man, the cognitive man is an active participant in decision-making, and not just an obedient responder to marketing stimuli.

32.3.4 The Model of Emotional Man

This approach assumes that the consumer is motivated by subjective criteria and makes purchase decisions based on emotions, such as love, fear, affection, and pride, which shape attention, evaluation, and choice (Pantouvakis, Siomkos and Christou, 2015; Siomkos *et al.*, 2024). The principal limitation of the model of emotional man refers to the under-specification of the role of knowledge, constraints, and deliberation. More specifically, since many consumer decisions are planned and consequential, this approach fails to explain systematic responses to price changes, learning from repeated experience, or external influences.

Emotions are described as automatic appraisal processes shaped by developmental and personal past, and can be divided into primary (early, reactive) and secondary (adult, cognitively complex) forms (Ekman, 2003; Iinuma and Kogiso, 2021). Secondary emotions arise from more elaborate cognitive processes, such as a combination of primary emotions with expectations and evaluations of possible outcomes and are often considered as unique in humans (Leyens *et al.*, 2000). As noted in Iinuma and Kogiso (2021), emotions can contribute to both rational and irrational decisions and interact with other drivers of decision-making process, such as limited information, cognitive biases, and risk-taking tendencies. For this reason, emotions should be incorporated in decision-making models intended to predict both rational and irrational behaviors. Early decision-making research has treated choice as a predominantly cognitive process, caused by logical reasoning and cost-benefit evaluation. However, contemporary evidence indicated that affective functions are integral to choice, especially under conditions of ambiguity, uncertainty, and risk (a detailed analysis in Lakomski and Evers, 2010; Crivelli, Acconito and Balconi, 2024a, 2024b; Crivelli, Allegretta and Balconi, 2023). Empirical work has indicated that cognitive and emotional evaluations affect each other bidirectionally (Iinuma and Kogiso, 2021), enhancing the development of dual decision-making models, in which choices arise from the interaction of two systems that may compete to cooperate: in particular, the first system is associated with affective appraisal and intuitive heuristics, whereas the second one supports conscious deliberation and controlled reasoning (Schiebener and Brand, 2015).

Figure 32.1 presents the key concepts of the theoretical approaches in consumer behavior, as discussed above.

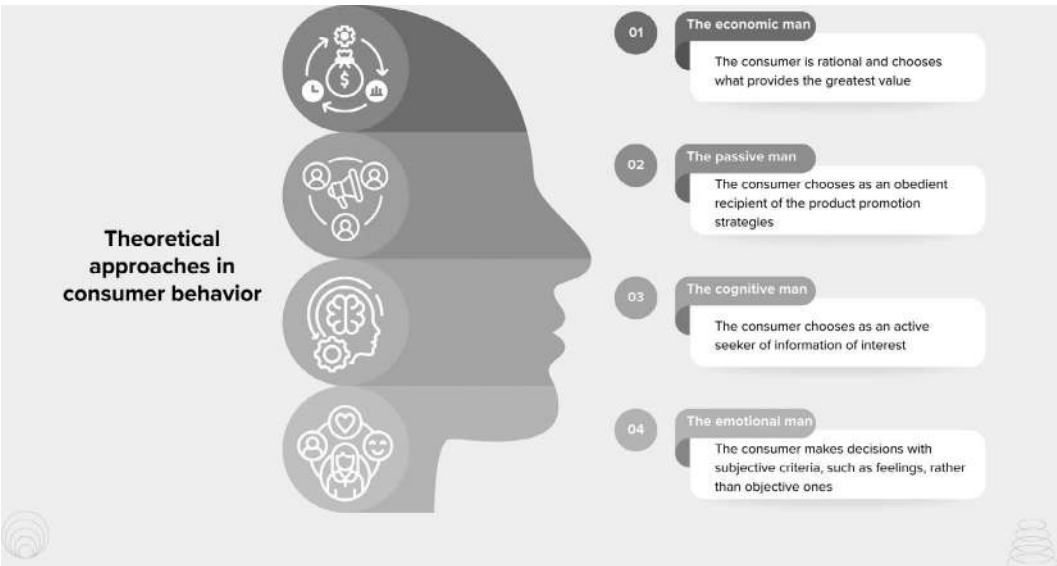

FIGURE 32.1 Theoretical approaches in consumer behavior. (Based on Pantouvakis, Siomkos and Christou, 2015; and Siomkos *et al.*, 2024.)

32.4 Modeling Consumer Behavior: The Decision-Making Process

The consumer decision process constitutes an information-processing sequence of five different stages, in which individuals recognize a consumption-related "problem", search for alternative "solutions" and assess them, make their decision, and then evaluate their final outcomes. It constitutes a foundational framework in consumer behavior research encompassing (a) the problem (or need) recognition, (b) the information search, (c) the evaluation of alternatives, (d) the purchase decision, and (e) the post-purchase assessment, and it also organizes individual's key cognitive and behavioral tasks, the market and informational environment, and the post-choice learning that affects consumer choices and future preferences (Schiffman and Wisenblit, 2019; Solomon, 2022, 2023).

32.4.1 The Five-Stage Model of Consumer Decision Process

In particular, the five-stage model decomposes consumer's choice into distinct tasks, rather than as in-whole description of all the decisions, although in practice consumer's decision may feature compression, repetition, or omission of one or more stages, especially under low involvement, time pressure, habitual purchases, and strong brand loyalty.

32.4.1.1 First Stage: The Problem Recognition

The initial stage of the decision-making process begins by the time consumers perceive a discrepancy between an actual state and a desired one (Bruner and Pomazal, 1988). This discrepancy may be triggered either by internal stimuli, such as depletion and aspiration, or by external factors, like advertising, peer comparison, and environmental cues that can reframe desired or acceptable products and services. It should be noted that problem (need) recognition may be classified into two broad types. Some consumers exhibit an actual state orientation, in which they recognize a problem when a product's performance falls below an acceptable level. On the other hand, other consumers exhibit a desired state orientation, in case the aspiration for something "new" or "improved" can itself initiate the decision-making process (Schiffman and Wisenblit, 2019).

The problem recognition stage comprises an act of "classification" and preference construction since individuals translate desires into evaluative criteria and acceptable trade-offs. Consumers' motivation is activated, after interpreting the gap as notable to justify the allocation of time, budget, and attention.

32.4.1.2 Second Stage: The Information Search

Following the problem recognition, at the second stage of the decision process, consumers engage in information search and acquisition (Schiffman and Wisenblit, 2019; Solomon, 2022, 2023). Search is typically characterized as both internal, including past experiences and beliefs, and external encompassing information from product and service reviews, peers, retailers, opinion leaders, and digital platforms. The extent of consumer's information search is moderated by perceived risk, product involvement, time pressure, information costs, and level of expertise. From an analytic standpoint, the information search is constrained by attention and cognition, since it may not be deliberate as consumers are also subject to passive exposure through social media and other external sources.

Furthermore, the perceived importance of a choice constitutes a significant determinant of information search extent (Posavac, Herzenstein and Sanbonmatsu, 2003). When a decision is regarded as important, consumers typically "invest" greater cognitive effort, seek for additional information and advice from interpersonal sources or experts, and engage in more systematic evaluation of competing attributes, especially when trade-offs among alternatives' attributes are unavoidable (Willman-Iivarinen, 2017).

32.4.1.3 Third Stage: The Evaluation of Alternatives

This stage involves the "transformation" of the selected information into comparisons among different options, and ultimately, preferences. In assessed options, consumers integrate product and service attributes, beliefs, and emotions. Although traditional economic theory suggests that compensatory decision rules may be applied permitting trade-offs among attributes, empirical research has shown that consumers often use non-compensatory rules, such as lexicographic or conjunctive decision rules, which exclude the options that fail to meet minimum thresholds (Schiffman and Wisenblit, 2019).

The evaluation of alternatives includes the belief formation, presenting what the consumer thinks about characteristics, such as the quality and the social meaning of a product, the value weight of each attribute, the affective responses, and the social considerations related to ethical implications, moral values, and status signaling. This viewpoint can explain why consumers may prefer options that increase the symbolic utility of a product or service, even if it fails to provide the necessary functional criteria.

32.4.1.4 Fourth Stage: The Purchase Decision

This stage concerns the conversion of preference into action (e.g., purchase, consumption), including the selection of the appropriate seller, the supply channel, the payment method, and the delivery conditions. At this point, it should be noted that the most preferred alternative is not always the purchased option, since implementation constraints such as product availability, unexpected budget restrictions, time pressure, and complexity in purchase or consumption terms may appear and redirect consumer behavior. Furthermore, the perceived risk can significantly influence consumer decisions, as individuals may seek for purchase warranties, product return flexibility, or trusted sellers in order to reduce uncertainty.

In digital marketing environments, the purchase decision stage has received intensified attention due to the way choices are presented and their effect on the final decision. For instance, if one option is preselected (as a default), there is increasing possibility that consumers will accept the default. In addition, if products are sold as a package (bundling), or the product price is split into parts (e.g., price and shipping costs), the offer may seem more attractive for purchase and consumption. Scarcity claims (e.g., "only a few left") may also impact the final decision, as they use to raise consumers' perceived urgency and enhance faster purchases (Solomon, 2022, 2023).

32.4.1.5 Fifth Stage: The Post-Purchase Behavior

After the final purchase stage, consumers tend to compare outcomes with expectations, generating satisfaction or dissatisfaction with the decision-making process. A key determinant of the post-purchase responses is the assessment of the perceived performance against prior expectations, with satisfaction emerging when the performance meets or exceeds expectations and dissatisfactions arising in case performance is perceived as insufficient, failing to meet the expected standards (Solomon, 2022, 2023).

In case the purchase is regarded as of major importance or the competing alternative options are similarly attractive, consumers may experience cognitive dissonance (thinking, for example, "Did I make the right choice?") (Fernandez-Lores *et al*., 2024; Telci, Maden and Kantur, 2011; Wilkins, Beckenuyte and Butt, 2016; Ibrahim Awwad *et al*., 2025; Wang, Yu and Chen, 2025). This tension can become even more intense when post-purchase information, such as negative reviews, peers' criticism, or a lower price elsewhere, conflicts with the decision or the expectations. In order to reduce dissonance, consumers may engage in reassurance-seeking behaviors, emphasizing the chosen product's advantages, avoiding information that might challenge the decision, or relying on "safety nets" like return policies and purchase warranties. Therefore, the cognitive dissonance should not be identified with consumer dissatisfaction because it concerns a post-decision discomfort rooted in perceived inconsistency of uncertainty about having made the "right" choice. Figure 32.2 summarizes the five stages of the consumer decision-making process.

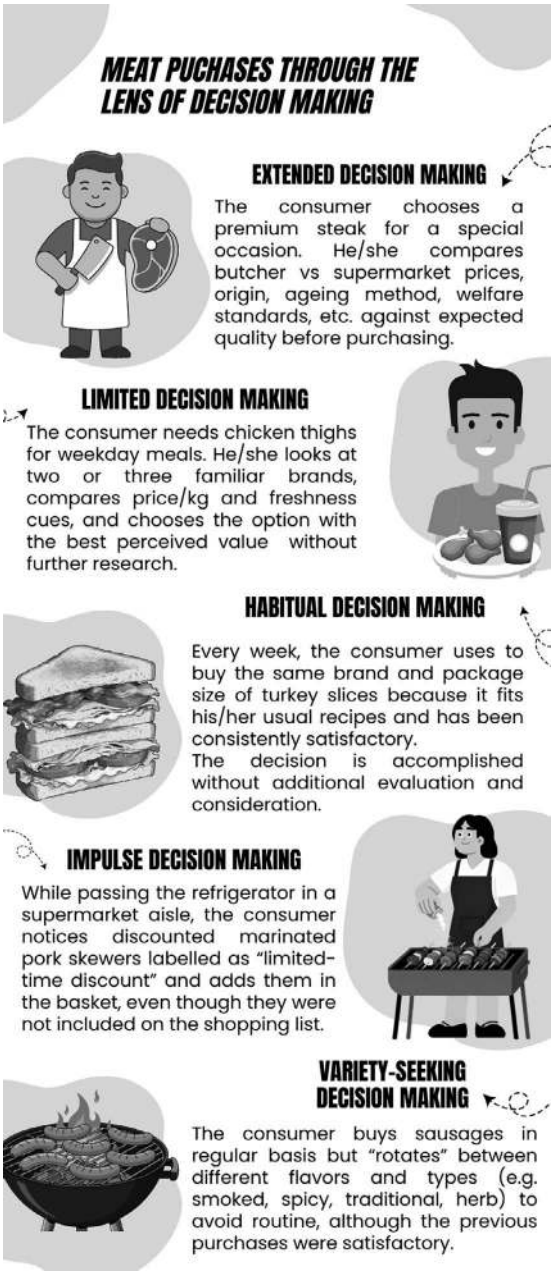

FIGURE 32.2 The five-stage decision-making process. (Adapted from Solomon, 2023.)

32.4.2 Consumer Decision-Making for Animal Welfare Meat Products: An Empirical Example

Nowadays, there is an emerging trend toward the consumption of higher animal welfare products. The consumer decision process can be described across the above-described five stages as follows:

First, the problem (need) recognition takes place when the consumer identifies the desire to decrease ultra-processed foods and align everyday meals with higher animal welfare and health standards. Second, during the stage of information search, the consumer seeks information through product

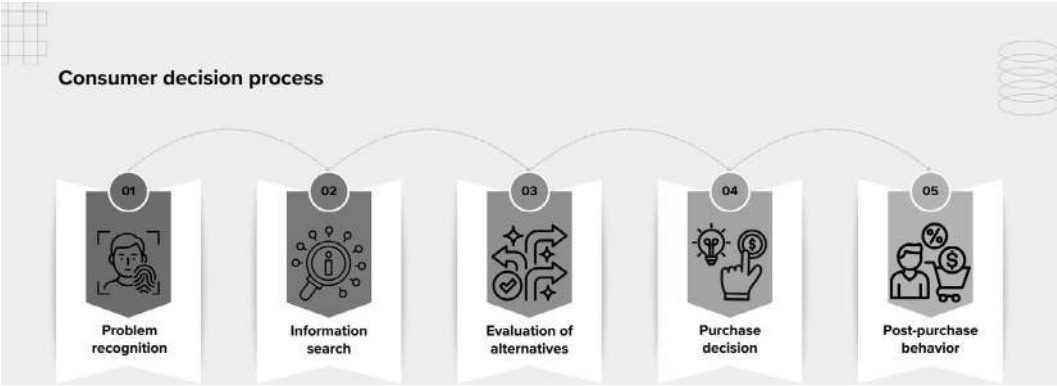

FIGURE 32.3 Consumer decision process for animal welfare meat products. (Created by authors.)

labeling, packaging, retailers, and peers, focusing on cues, such as welfare certification, country of origin, antibiotic-use claims, and production methods. Third, during the evaluation of alternative options, the consumer compares certified free-range or organic meat with conventional products and weights the higher price against the perceived benefits in welfare, quality, personal values, utility, and satisfaction achievement. Fourth, in the purchase decision stage, the consumer seeks to balance values and preferences with price and income constraints, and although decides to purchase the certified product, reduce the quantity to remain within budget. Finally, the post-purchase evaluation involves the assessment of both functional outcomes related to the taste and the perceived quality of the product, and consistency with personal values, and ethical and health priorities. In case the consumer feels satisfied, it is more likely to repeat the purchase, despite the product's higher price compared to its conventional alternatives. Figure 32.3 illustrates consumer decision-making for animal welfare meat products.

32.5 Types of Decision-Making

Consumer decision-making is analyzed as a set of processing modes that differ in the amount of cognitive effort invested, the degree of uncertainty managed, and the extent to which behavior is affected by deliberation versus acquired habits and situational cues (Pantouvakis, Siomkos and Christou, 2015; Solomon, 2023; Siomkos *et al*., 2024). Five types of decision-making will be discussed in the following sections: the extended, the limited, the habitual, the impulsive, and the variety-seeking decision-making, with individuals shifting across modes depending on the perceived risks, consumer involvement in the decision process, time pressure, prior experience and environmental characteristics.

32.5.1 Extended Decision-Making

The extended decision-making concerns an information-intensive choice, which emerges when consumers perceive high financial, functional, social, or identity-related risks, and therefore expect that additional cognitive effort will reduce uncertainty and improve purchase outcomes. The main characteristic of the extended decision-making is the expansive and clear problem representation, with consumers clarifying goals, specifying evaluation criteria, and managing uncertainty through search and comparison. Furthermore, the product is of high value (or highly evaluated) and the consumer's decision often has long-lasting effects or it is not reversible (Engel, Blackwell and Miniard, 1995; Pantouvakis, Siomkos and Christou, 2015; Siomkos *et al*., 2024; Stankevich, 2017). Under the extended decision-making, post-purchase evaluation is considered substantial, as purchase outcomes often generate learning about the evaluation of the product attributes' weights and update beliefs about brands. Figure 32.4 presents the main characteristics of extended decision-making.

FIGURE 32.4 Extended decision-making. (Based on Pantouvakis, Siomkos and Christou, 2015; Siomkos *et al.*, 2024; and Stankevich, 2017.)

32.5.2 Limited Decision-Making

The limited decision-making process arises when the purchase is considered important to require some evaluation, yet not so prominent for an extensive search and comprehensive comparison (Engel, Blackwell and Miniard, 1995; Pantouvakis, Siomkos and Christou, 2015; Siomkos *et al.*, 2024; Stankevich, 2017). In such cases, consumers may possess prior experience, making detailed market exploration unnecessary. Under these conditions, decision-makers examine a limited set of alternatives, account for limited salient attributes, and employ simplified rules to decrease cognitive effort. In limited decision-making, consumers may alter their brand preferences when promotions shift the perceived value or when situational cues change the perceived risk. Since the consequences of an unsatisfactory outcome are restricted, consumers are less likely to invest in extensive information. Under the limited decision-making, consumers may switch brands (within a restricted subset of options) when promotional and marketing tools shift the perceived value, or when salient cues alter the perceived risk. This mode is prevalent in rather familiar product categories where some uncertainty persists, although prior experience provides an adequate framing for choice. Figure 32.5 depicts the main characteristics of limited decision-making.

32.5.3 Habitual Decision-Making

Habitual decision-making refers to a type of consumer choice, in which purchasing is mostly regular and completed with minimal deliberation. It is observed when involvement is low and the purchase is perceived as relatively unimportant. In this context, consumers do not proceed to information search and rely on established patterns of behavior, rather than engaging in active evaluation of alternative options. Instead, choice is defined by routines acquired through repeated experience, and as positive outcomes accumulate, consumers develop high familiarity with both the product and the purchasing context (Engel, Blackwell and Miniard, 1995; Pantouvakis, Siomkos and Christou, 2015; Siomkos *et al.*, 2024; Stankevich, 2017).). The key concepts of habitual decision-making are presented in Figure 32.6.

32.5.4 Impulsive Decision-Making

This type of decision-making refers to unplanned or weakly planned choices driven by immediate situational stimuli and affective responses. It differs from habitual choice, since the latter reflects behavioral stability acquired through repetition, whereas an impulsive choice constitutes a deviation from

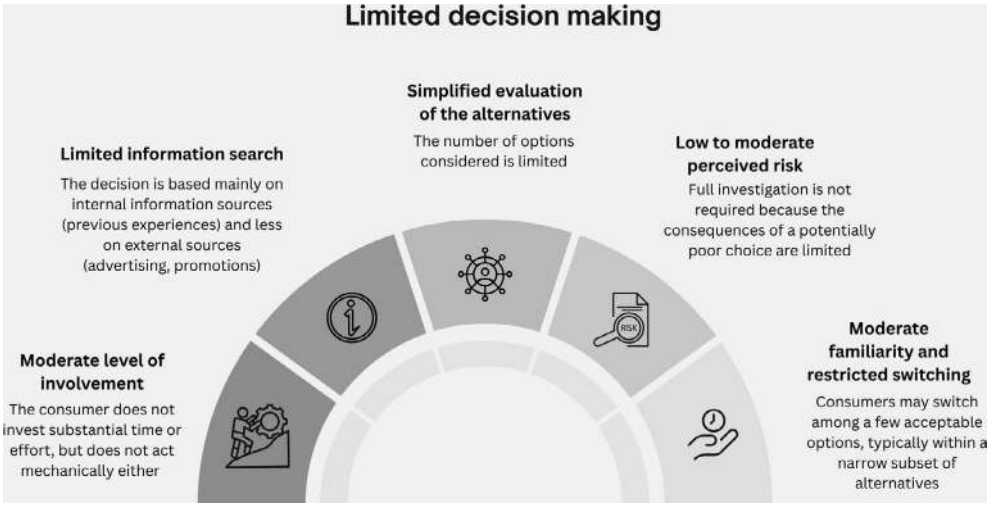

FIGURE 32.5 Limited decision-making. (Based on Pantouvakis, Siomkos and Christou, 2015; Siomkos *et al.*, 2024; and Stankevich, 2017.)

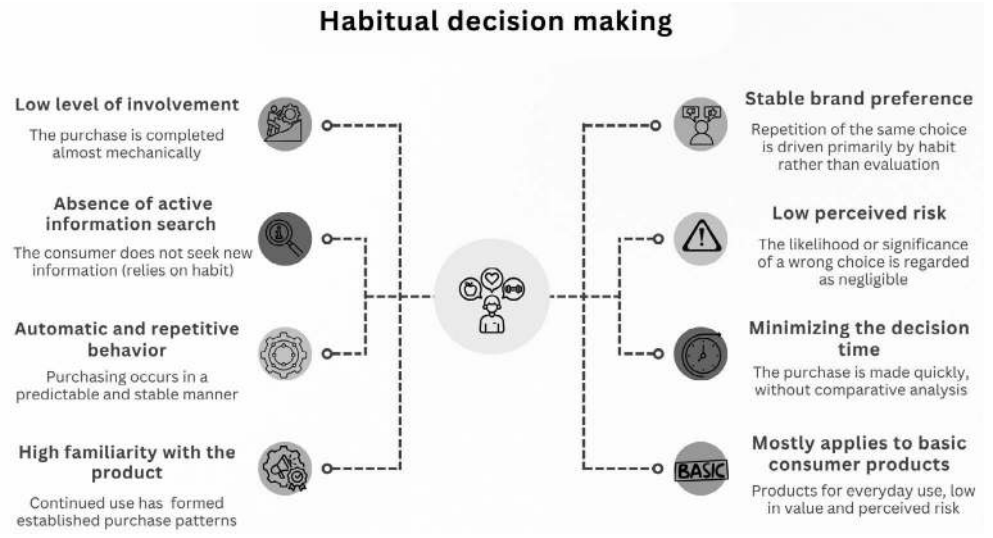

FIGURE 32.6 Habitual decision-making. (Based on Pantouvakis, Siomkos and Christou, 2015; Siomkos *et al.*, 2024; and Stankevich, 2017.)

consumer's intentions or long-run goals. It is characterized by the reweighting of goals during the decision-making process in a way that immediate gratification, convenience, curiosity, or social symbolism are preferred over considerations about price optimization, usage, or long-term utility (Strack and Deutsch, 2004; Hofmann, Friese and Strack, 2009; Veling *et al.*, 2017). Impulse decisions are facilitated by conditions that compress deliberation (e.g., emotional arousal, fatigue, time pressure), and environments structured to increase cue visibility and reduce behavioral barriers (e.g., prominent displays, limited-time cues, one-click purchase). In such settings, consumers may rely on rapid evaluations and heuristics and make impulse purchases, with post-purchase evaluations often being ambivalent, ranging from pleasure to regret, which can either reinforce the behavior (in case of a rewarding outcome) or generate corrective intentions (in case of regret). Table 32.1 analytically presents the characteristics of impulsive decision-making.

TABLE 32.1

Impulsive Decision-Making

Characteristics	Explanation
Low planning or unplanned purchase	The purchase occurs without prior intention or with minimal prior planning
High situational influence	Choice is strongly shaped by immediate contextual stimuli (e.g., displays, promotions)
Affect-driven motivation	The decision is guided by desire, mood, or anticipated gratification rather than deliberate evaluation
Limited information search	The consumer invests little effort in gathering information or comparing alternatives
Reduced deliberation and self-control	The decision is made quickly, often under time pressure, fatigue, or emotional arousal
Greater responsiveness to convenience	Highly visible and easily accessible products are more likely to be chosen
Potential post-purchase ambivalence	The outcome may be followed by satisfaction, but also by regret if the purchase conflicts with prior goals

Source: Based on Stack and Deutsch, 2004; Hofmann, Friese and Strack, 2009; and Veling *et al.*, 2017.

32.5.5 Variety-Seeking Decision-Making

Unlike impulse buying, variety-seeking decisions can be planned, involving switching among alternative products, categories, or brands to avoid declining individual's utility from the repetition and the boredom associated with constant purchases. The consumer's objective is to restrict boredom or repetition, explore alternatives, or express identity through experimentation, rather than meeting functional needs. Over time, consumers tend to alternate within a choice set since repetition reduces the product attractiveness, triggering search efforts for change and diversity. Variety-seeking behavior demonstrates that switching can signal an enduring preference for novelty and change, rather than dissatisfaction or weak loyalty. In addition, variety-seeking can coexist with habitual purchasing at different levels of decision-making, with consumers insisting on buying within a category while varying the specific brand, the flavor, or the packaging they select. A thorough review of variety-seeking in consumption is provided by Zhang (2022). The main features of variety-seeking decision-making are presented in detail in Table 32.2.

These decision-making types are best viewed as outcomes of interaction between consumer motivation and capacity, learning process, and the decision environment. When time and attention are scarce,

TABLE 32.2

Variety-Seeking Decision-Making

Characteristics	Explanation
Low to moderate involvement	The decision usually entails low risk, but the consumer is engaged enough to seek for change
Switching driven by novelty	The consumer changes brands or products mostly to avoid fatigue, rather than dissatisfaction
Positive evaluation of the experimentation	Trying new options is perceived as enjoyable
Broad consideration within a category	The consumer explores multiple alternatives within the same product category (e.g., flavors, brands)
Low perceived risks and low switching costs	The consequences of a suboptimal choice are limited, which makes experimentation acceptable
Sensitivity to assortment and new offerings	Variety-seeking increases when the market offers new products, limited editions, or wide assortments

Source: Based on Zhang, 2022.

consumers are less likely to proceed to consumption choices through the extended decision-making framework. On the other hand, habitual and impulsive choices are more likely to occur when environments simplify the decision process and make certain options more prominent. Furthermore, limited decision-making may comprise the "default" for many everyday purchases in case consumers seek for adequacy rather than optimization, whereas variety-seeking arises when switching to alternatives is relatively low-cost and novelty provides utility and satisfaction.

32.5.6 Decision-Making and Meat Purchase Behavior

Figure 32.7 conceptualizes meat purchasing as a set of different decision-making types, illustrating how the same product category can be marketed through different cognitive and situational processes.

FIGURE 32.7 Decision-making and meat purchase behaviors. (Created by authors.)

Five decision types are presented: the extended, the limited, the habitual, the impulsive, and the variety-seeking decision-making, each followed by an example uncovering distinct decision and purchase models and communicating the claim that consumer choice varies systematically with factors, such as involvement, perceived risk, familiarity, time and attention constraints, and cue salience. In particular, the extended decision-making is illustrated as a high-effort process, in which the consumer selects the premium meat product for a special occasion and remains active in information searching and multi-attribute evaluations (e.g., comparing butcher versus supermarket prices, origin, aging method, and welfare standards). The example shows that when meat purchases are considered as highly important (e.g., due to price, social meaning, social visibility), consumers are more likely to evaluate the relevant attributes in order to justify the purchase through explicit comparison. In the limited decision-making example, presented as an intermediate mode, the consumer's actions follow the expressed need for a weekday chicken thighs meal and "tests" only a small set of familiar brands, comparing a restricted number of cues, such as price per kilogram and freshness cues, before selecting the option perceived as the most appropriate and cost-effective. Figure 32.7 illustrates that consumers frequently make purposive choices while allocating attention and restricting the scope of comparison. Decision-making remains intentional, whereas information search is limited since the benefits of a more extensive analysis are perceived as rather small compared to the additional time and the cognitive effort required.

Furthermore, in habitual decision-making, evaluation is largely displaced by repetition, with the consumer purchasing the same brand and package size of sliced turkey on a regular basis, as it aligns with established meal routines and has consistently provided reliable and favorable outcomes over time. Therefore, the habitual decision-making frames meat purchase as a rather automatic process, with the decision being realized through behavioral persistence and enhanced by familiarity and low perceived risk. Figure 32.7 also delineates impulsive decision-making, a decision mode that is mostly triggered by situational factors. In the illustrated scenario, the consumer selects a pack of marinated pork skewers sold on discount, presented as a limited-time offer, and adds it to the basket even though it was not included on the shopping list. Consequently, the example demonstrates how unplanned meat purchases may be alarmed by in-store cues, promotional framing, and convenience, decreasing the likelihood of extended evaluation and shifting choice toward affect driven responses. Finally, variety-seeking decision-making can be observed as intentional switching among choice options (e.g., smoked, spicy, herbal, traditional) within a familiar category (e.g., sausages), to maintain novelty and prevent repetition fatigue. In this case, switching reflects consumer preference for diversity within a stable and low-risk set of options, instead of a response to dissatisfaction. In total, meat purchase cannot be explained adequately via a single decision model, but depending on the settings and consumer preferences, it may be justified through different decision-making patterns.

32.6 Modeling Consumer Behavior: Factors Affecting Decision-Making

As analyzed before, consumer decision-making is a process of selecting, interpreting, and responding on information under constraints of knowledge, motivation, and attention. It can be shaped by both internal and external influences, with internal factors being linked with dispositions within the consumer, involving perceptions, exposure, attention, interpretation, motivation, learning, personality and self-concept, age group and lifestyle, which determine how acquired information is "translated" into preferences. These factors may define what individuals notice, how they comprehend it, and which goals and identities are prioritized during the choice process. On the other hand, external factors arise from the surrounding settings and include situational influences concerning the physical and the market environment, time pressure, and social influences entailing culture and subculture, social class, group participation, opinion leaders, and gender roles, which structure the alternative option availability, and specify which norms and cues have become salient (Solomon, 2023). Both these influences interact and affect consumer responses, goal formation, alternatives' evaluation, and choice enactment, as explained by Solomon (2023). Figure 32.8 presents the internal and external factors affecting consumer decision-making process.

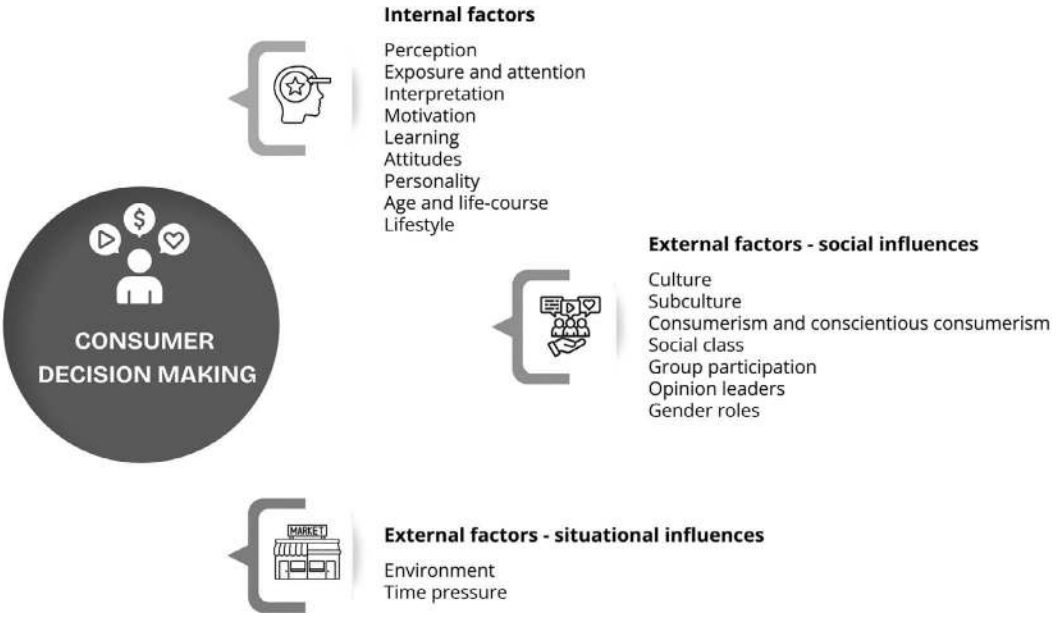

FIGURE 32.8 Internal and external influences of the decision-making process. (Adapted from Solomon, 2023.)

32.6.1 Internal Factors

32.6.1.1 Perception

In consumer behavior theory, perception is the process through which individuals select, organize, and interpret information from their surroundings in order to achieve a meaningful understanding of products, brands, price, and marketplaces. Perception structures the decision environment prior to deliberation, as consumers do not respond to the objective product attributes directly, but to their subjective assessment of price, quality, value, and risk. The perceptual processes are shaped by thresholds defining which stimuli are noticeable, the categorization of stimuli in brands or product types, and the reference points related to prior experience. Therefore, different consumers may evaluate the same set of options in nonidentical ways, perceiving different quality or price standards (Solomon, 2023).

32.6.1.2 Exposure and Attention

Exposure and attention determine which stimuli become input when consumers form judgments. Since in everyday life, individuals present multitasking behaviors (e.g., the consumer sends emails, while at the same time watches TV and send messages with his/her smart mobile), attention may be "fragmented", and hence decisions mostly rely on salient and easy-to-process cues. In such cases, individuals are more likely to weight signals, such as familiar brands, more heavily and give less importance to information that requires effort to process (e.g., risk information).

In a thorough review, Orquin, Lahm, and Stojić (2021) explored how visual attention operates in decision-making when information has to be acquired visually, as in shopping shelves, menus and digital platforms. The authors argued that a great body of the literature on decision-making has considered attention as mainly endogenously driven, caused by the decision-maker's goals, preferences, and perceived relevance, and has undermined the fact that exogenous factors of information presentation (position, size, and salience) can shape what people see, and consequently what information enters the decision process (e.g., Gluth, Spektor and Rieskamp, 2018, 2020; Krajbich, Armel and Rangel, 2010).

32.6.1.3 Interpretation

Interpretation refers to the process through which consumers assign meaning to stimuli by relying on prior associations, existing beliefs, and assumptions (Solomon, 2023). Previous research showed that children aged 3–5 years old overwhelmingly reported that fried potatoes tasted better when they were served in a McDonald's branded package than the identical fried potatoes served in a plain white package, indicating that branding can shape perceived sensory experience through interpretive processes (Robinson *et al.*, 2007; Solomon, 2023). Therefore, interpretation has a crucial role in whether marketing claims are incorporated into the decision-making process or rejected as noise.

32.6.1.4 Motivation

In decision-making, motivation refers to the internal forces that activate, direct, and sustain behavior toward specific goals. It explains why a person takes the decision to engage with a choice, rather than ignore it, which outcomes he/she gives priority, and how much effort he/she invests in searching for information and evaluating alternatives. Motivation has a major impact on the depth and the direction of the decision process. In particular, when consumers' involvement is high (e.g., high cost, high risk), they tend to increase search and systematic comparison among alternative options. On the contrary, in case of low involvement, they conserve effort by relying on habitual purchases, affect, and heuristics.

Chen (2024) examined the determinants of consumers' willingness to try plant-based meat in Taiwan, motivated by sustainability, health, and animal welfare concerns. Using a quantitative approach, this study modeled the willingness to try plant-based meat as a function of attitudes, subjective norms, and perceived behavioral control, while also incorporating food choice motives as antecedents of attitudes. The main findings showed that food choice motives significantly shaped consumer attitudes toward plant-based meat and also highlighted meat attachment as a key influential condition in plant-based meat acceptance. Under the same prism, Jahn, Furchheim, and Strässner (2021) provided a narrative review on why plant-based meat alternatives are characterized by low adoption rates despite the increasing sustainability and health concerns about conventional meat consumption. The authors made a clear distinction between structural (i.e., limited availability in food stores, low exposure, persistent price premium) and motivational adoption barriers (e.g., neophobic reactions, social norms, and rituals), noting that the latter may persist even if the structured ones improve.

32.6.1.5 Learning

Learning constitutes the process through which consumers' past experiences and acquired information are converted into expectations and preferences that guide future choices. Therefore, it comprises a key "mechanism" linking outcomes to subsequent behavior. Satisfactory outcomes tend to reinforce existing preferences and consumption patterns, strengthening brand loyalty and habitual purchasing patterns. On the other hand, negative experiences, such as poor performance, disappointment of perceived risk, are likely to prompt behavioral "adjustment", including product avoidance, brand switching, and more extensive informational research in subsequent decisions. Besides experiential learning, consumers can also become informed indirectly through external information sources, like online reviews, interpersonal communication, and mass media coverage.

Solomon (2023) underlines the crucial role of learning theories in marketing communication, providing an in-depth analysis of behavioral (classical and operant conditioning) and cognitive learning theory (observational learning). In particular, behavioral learning theories seek to explain how consumer preferences and purchase trends can be shaped through associative processes, rather than through deliberate reasoning. Therefore, learning occurs when repeated connections and consequences affect the probability that a stimulus (e.g., a brand package) will elicit a specific response (e.g., liking, avoidance).

Classical conditioning describes learning through association, in which a stimulus that initially elicits negligible response (i.e., the brand) can develop an affective meaning in case it is repeatedly paired with a stimulus that already educes a positive or a negative response (e.g., social approval or fear-evoking content). In time, the brand itself may evoke a similar reaction, influencing consumer attitudes and shaping

behavior (Webb, 1999). A comprehensible presentation of the classical conditioning theory is provided by Niosi and Chung (2025), noting how it is related to the development of brand affect, image, and evaluation, particularly in case choices are low-involvement and consumers lack strong prior preference. Under the classical conditioning mechanism, repeated pairing can shift familiarity and loyalty level, which subsequently may impact the product assessment and consumer final choice (Pornpitakpan, 2012).

On the other hand, operant conditioning explains the learning process through consequences (Niosi and Chung, 2025). Thus, behaviors followed by rewarding outcomes are more likely to be adopted, whereas behaviors linked with unpleasant situations have an increasing likelihood of being rejected. Brand loyalty and purchase repetition can be reinforced through recurring positive outcomes, whereas repetition is discouraged in case negative experiences arise, such as poor performance, inconvenience, or unforeseen costs. Operant conditioning theory is widely observed in loyalty schemes, price discounts, and promotion strategies, where rewards are designed to encourage purchase routines.

A different standpoint in the learning process is provided through the cognitive learning theory, in which consumers are portrayed as active information processors who develop knowledge, expectation, and decision forms through comprehension and interpretation rather than reinforcement. In contrast to behavioral learning schemes, in which learning is explained via stimulus, response associations, and reinforcement, the cognitive approaches emphasize how consumers encode information, integrating it with past knowledge in order to shape future evaluations and choices (Batkoska and Koseska, 2012; Rajagopal, 2021; Solomon, 2023; Niosi and Chung, 2025).

Cognitive learning refers to the learning procedure accomplished through mental processes, such as attention, comprehension, memory, and inference (e.g., the consumer reads labels, or interprets product certifications), or through observation. Repetition in information exposure can build product familiarity, improve consumers' ability to assess product attributes, and reduce perceived risks. On the other hand, observational learning is defined as knowledge acquisition derived from the observation of other people's behaviors and outcomes, rather than from direct personal experience. This information is encoded and retained in individual's memory, where it can be later retrieved to guide the formation of behavior patterns. Individuals acquire information through interpersonal networks, social media, opinion leaders and influencers, consumer reviews, and broader cultural narratives that define what is desirable, effective, or socially approved. Figure 32.9 summarizes the key points of both behavioral and cognitive learning theories.

32.6.1.6 Attitudes

In consumer behavior, an attitude is commonly defined as a relatively constant evaluation toward an object (e.g., a brand, a product category, a retailer, in issue or behavior). Attitudes organize consumers' assessments and can also predispose intentions and choices. In the ABC Theory of Attitudes, attitudes are conceptualized as a composition of three interrelated components, namely, affect, behavior and cognition.

32.6.1.6.1 The ABC Theory of Attitudes

This model is widely used in consumer behavior research because it clarifies that an evaluation of a product brand does not merely reflect "what a person thinks", but also constitutes an integrated structure of feelings, beliefs, and action that may align or diverge. In particular, the affective component refers to the emotions and the feelings associated with an object and may include liking, pleasure, comfort, excitement, or disgust. Furthermore, affect may be elicited through direct experience (e.g., taste), through symbolic meanings (e.g., status), or through associations that are shaped via repeated marketing cues. The cognitive component comprises beliefs and knowledge about the object, including perceived attributes and expected consequences. For instance, beliefs on meat products may concern quality and safety, price level and stability, environmental impact, health concerns, and animal welfare. Finally, the third component of the ABC Theory encompasses consumer's behavioral intentions or predispositions to act in certain ways toward the object, such as purchasing, recommending, avoiding, or seeking additional information. In consumer research, the behavioral component is often identified with purchase intention, willingness to choose and to pay, or purchase repetition.

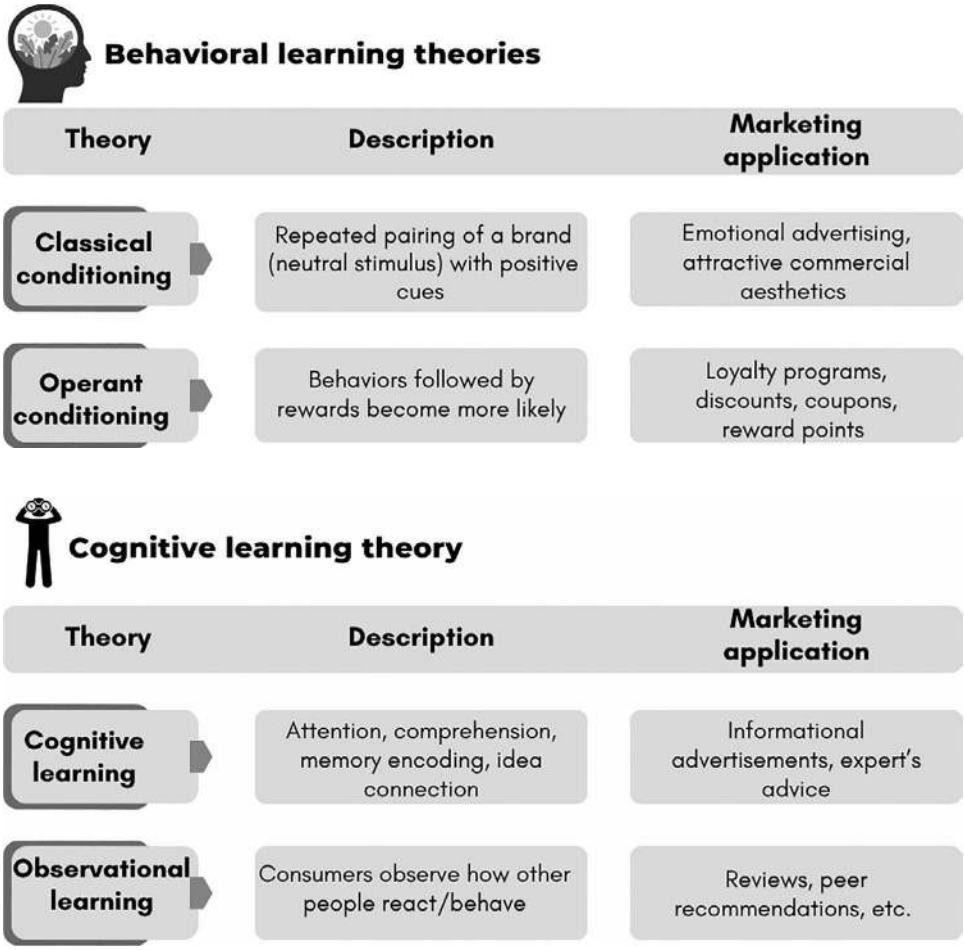

FIGURE 32.9 Behavioral and cognitive learning theories. (Adapted from Solomon, 2023.)

However, a clear distinction should be drawn between behavior and the affective and cognitive components, since even in case positive feelings and favorable beliefs may be held, purchase process may not be enacted or completed because of constraints, such as income, availability, or household preferences. On the other hand, purchases may be enacted despite mixed feelings due to habit formation or necessity (Lau *et al.*, 2023; Solomon, 2022, 2023; Gidaković *et al.*, 2026). Figure 32.10 presents an empirical application of the ABC model in the meat industry, and particularly in the decision-making of animal welfare chicken meat. This example illustrates how an overall attitude toward a meat product can reflect the interaction of affective reactions, cognitive beliefs, and behavioral predispositions, which may converge to support consistent ethical purchase patterns, or conflict to result in consumer ambiguity and subsequent compensatory reactions.

32.6.1.6.2 The Fishbein's Multi-Attribute Model

While in the ABC Theory attitudes are shaped by interconnected affective responses, cognitive beliefs, and behavioral predispositions, the structure of the cognitive component and its integration into the evaluation process are not clearly specified. To extend this analysis, the Fishbein's multi-attribute model comprises a classical theoretical framework considering attitudes as the outcome of beliefs about salient characteristics and the value attached to each one. More specifically, this approach explains individual's (overall) attitude toward an object (e.g., product, service, idea), assuming that consumers' beliefs about the object's attributes and their evaluation are integrated to form an overall attitude (Hovorushchenko,

FIGURE 32.10 Attitude toward higher animal welfare chicken versus conventional (ABC Theory of Attitudes). (Created by authors.)

Glukhov and Hovorushchenko, 2020; Varadzhakova *et al.*, 2025; Wassenaar, Kempen and van Eeden, 2019). The mathematical expression of the Fishbein model is specified below:

$$A_o = \sum_{i=1}^{n} b_i e_i$$

where A_o corresponds to individual's attitude toward the object, b_i denotes the strength of the belief that the aforementioned object has the attribute i, and e_i presents the evaluation of this attribute i. Under this framework, attitudes are perceived as the aggregated outcome of multiple considerations rather than as an undifferentiated evaluation.

In practical terms, the Fishbein model presents explanatory strength since it can distinguish two sources of a weak attitude. In particular, either the object may be considered of poor performance on a relevant criterion, or that criterion may be assigned limited importance. In both cases, targeted interventions could boost the overall attitude toward the object by reinforcing beliefs, evaluations, or both. For instance, when retailer's claims are distrusted and consumer's beliefs are weak, credibility enhancing strategies are required, whereas in case of weak evaluations, persuasive techniques could be more effective to increase the object's attractiveness. Although the Fishbein's model constitutes a structured representation of how attitudes can be shaped from beliefs and evaluations, in realistic market settings, consumer choice may deviate from its logic, since environmental constraints, strong emotions, or habitual purchase behavior may prevail over attribute integration.

32.6.1.6.3 Fishbein's Multi-Attribute Model Application: The Case of Animal Welfare Certified Pork

This case concerns consumer's attitude toward purchasing animal welfare certified pork. Assume the consumer evaluates the aforementioned meat type on five attributes, namely, animal welfare, taste, antibiotic usage, environmental impact, and affordability, measured on a 7-point Likert scale ranking from 1 to 7, with higher values signifying stronger belief and higher desirability (or importance). Table 32.3 presents consumer's scores for each attribute, as well as the final aggregated score.

The overall attitude is equal to 123, with animal welfare being evaluated as highly important (7) and performing strongly on this criterion (6). On the contrary, affordability presents a minor contribution in the total attitude score, since it seems that the consumer believes that the product is rather expensive compared to other alternatives (2), although affordability is highly valued (6). This pattern seems to be consistent with a common outcome in ethical food choice, in which a favorable attitude toward certified meat coexists with purchasing constraints, and it is often expressed through reduced meat quantities or less frequent purchases.

32.6.1.7 Personality

Personality and self-concept substantially affect what consumers value and how consumption functions in the environmental settings (Solomon, 2023). In consumer behavior, personality refers to a psychological disposition that differentiate individuals in their typical patterns of thinking, feeling, and behaving.

Therefore, as an internal factor, personality helps explain heterogeneity in consumer decision-making, including the appropriate information, which cues are trusted, how risk is perceived, and whether choices are influenced by affect, deliberation, or habit formation. Since personality traits can influence the decision-making process, as they shape motivation and consumer involvement, it is expected that individuals with more distinct traits related to curiosity and openness are more likely to explore unfamiliar products and engage in variety-seeking, whereas anxious or less confident consumers may engage in predictable and more "risk-free" behaviors, such as relying on familiar brands and retailers. Responsiveness to social and symbolic cues may also be affected by personality traits. Greater weight

TABLE 32.3

Fishbein's Multi-Attribute Model Application in Animal Welfare Certified Pork

Attribute	Belief (b_i)	Evaluation (e_i)	$b_i x e_i$
High animal welfare standards	6	7	42
Good taste	5	6	30
Lower antibiotic usage	4	6	24
Lower environmental impact	3	5	15
Price affordability	2	6	12
Overall attitude (A_o)			**123**

Source: Created by authors.

may be placed on distinct brands as identity symbols for gaining social approval when a more socially oriented disposition is present, resulting in increased responsiveness to reference-group norms and opinion leaders' influence. On the other hand, in case of a more self-directed disposition, alternative options are evaluated independently, and functional attributes or consumers' values are more likely to be given priority over social conformity.

In an analytical review, Esposito, Ceresa, and Buoli (2021) provided a structured synthesis linking personality traits to dietary preferences and food related behaviors. The authors showed that extraversion was found to be associated with increased sweet beverage portions, higher meat intakes, and augmented consumption of vegetables and fruits, whereas neuroticism presented links to sweet and salty foods and reduced fish and vegetable intake. The review also provided evidence that vegetarians and vegans differed from omnivores on personality traits, such as openness and neuroticism, and emphasized the heterogeneity in the personality–diet association. With respect to potential linkage between personality and meat consumption, Pfeiler and Egloff (2018a, 2018b)) demonstrated that lower openness and agreeableness were related with higher overall meat intake, further arguing that red and white meat consumption were driven by different psychological traits (e.g., disgust reactions, masculinity symbolism, and perceived health implications).

Besides personality traits, self-concept also has a crucial role in decision-making process. Self-concept refers to the set of beliefs and evaluations, which individuals hold about who they are, who they wish to become, and how they would like to be perceived. In consumer research, self-concept has a key role since many purchases may function as symbolic acts through which identity is expressed and communicated. A common distinction is between the actual self, reflecting the "picture" which consumers have created for themselves, the ideal self, portraying how they would like to be, and the social self, referring to how they believe others see them (McLeod, 2023). Overall, the self-concept can link consumption to identity goals and social contexts, shaping what consumers value and how preferences are enacted in everyday life constraints.

32.6.1.8 Age

Age comprises a significant determinant of decision-making process since it is associated with resource availability, role adaptation, and goal accomplishment. For instance, younger consumers may give priority to experimentation, identity and symbolism, and conformity to peer norms, and have also to deal with tighter budgets. On the other hand, middle-aged adults have to face time scarcity and coordination, whereas older individuals may emphasize risk reduction and usability. Furthermore, across the life course, shifts in health, income, family life, and technology usage can redefine priorities and constraints.

Regarding meat consumption, recent research showed that consumers' age influences meat intake through two pathways (Grasso *et al.*, 2021; Ritzel and Mann, 2021; van den Berg *et al.*, 2022). First, meat intake varies across the life span due to gender socialization and masculinity norms. Second, meat intake is reshaped with life-course transitions that alter habits and redirect motivation for dietary change. It should be noted that age effects on meat consumption are mostly attributed to identity shifting, household settings, and decision environments that become evident at different life stages rather than biological factors (Grasso *et al.*, 2021; Ritzel and Mann, 2021; van den Berg *et al.*, 2022). In particular, Ritzel and Mann (2021) concluded that there are also notable gender differences, which although not observed in infancy, become evident after early childhood, implying that the gendered consumption patterns are unlikely to encompass early preference differences. Instead, they seem to be shaped through socialization as gender identity becomes increasingly salient and as culturally embedded associations between meat and masculinity begin to influence food-related practices. In later life stages, Grasso *et al.* (2021) showed gender differences in meat consumption, underlining that heterogeneity in motives (i.e., health and sustainability concerns versus sensory appeal and familiarity) determine meat attachment and openness to alternatives. In an empirical study in young Dutch adults, van den Berg *et al.* (2022) found that life-course transitions were more often perceived to reduce than increase meat consumption, with "moving house" being most frequently identified as a "window to opportunity" due to changes in social environment and increased independence. The authors also classified the obstacles and enablers toward meat reduction, with taste, the perceived high price of plant-based alternatives, and habits being the most prominent barriers, whereas environmental and animal welfare concerns, enjoyment of smaller portions, and potential cost-savings constituting the major facilitators.

32.6.1.9 Lifestyle

As Solomon (2023) noted, demographic characteristics may reveal to marketers what products are preferred and purchased by consumers, but they cannot demonstrate the mechanisms underlying the consumption patterns. For this reason, marketers may profile individuals according to their lifestyle, since it comprises a significant determinant of how money and time are allocated, and also indicates preferences and consumption trends. In consumer research, lifestyle is considered as a patterned incorporation of activities, interests, and opinions (AIOs) that segment consumers based on their psychosocial and behavioral similarities. These patterns shape both opportunities and motivation by classifying product categories, consumption goals (convenience, health, status, etc.), and by determining which trade-offs are regarded as acceptable. For instance, individuals with time-constrained lifestyles may give major importance to convenience and reduce extensive information search, mostly relying on familiar brands and heuristics.

Recent research has highlighted the lifestyle influence on meat and meat alternatives' consumption. Tschanz *et al.* (2022) employed representative data from Switzerland and examined how consumption varies across lifestyle groups. The authors noted that smoking status and increased BMI were positively associated with total meat intake, suggesting that meat consumption may cluster with less healthy-oriented behaviors. In addition, white meat consumption was increased among respondents following a weight loss diet, implying consumers' shift toward poultry products in healthy and weight-management eating routines. In another study, Żakowska-Biemans (2025) examined heterogeneity in plant-based meat alternatives' adoption using cross-sectional data from a sample of Polish adults and via a food-related lifestyle framework. The main findings showed that the most frequent plant-based meat alternative purchases were reported by the "conscious food enthusiasts", combining high food involvement and innovativeness with high environmental responsibility. On the other hand, "tranditionalists" and "careless food lovers" were characterized by skepticism and weak sustainability-oriented responsibility and were less likely to adopt plant-based meat alternatives. In both research studies, lifestyle is treated as a "set" of everyday practices, orientations, and constraints linking fundamental values and goals with eating patterns, food perceptions, and behaviors (Tschanz *et al.*, 2022; Żakowska-Biemans, 2025).

32.6.2 External Factors of Consumer Decision-Making

Besides the internal factors, external influences have a crucial role in consumer decision-making, as they can affect which norms apply, which cues are prominent during the process, and product availability. They are distinguished in social and situational influences and are analytically presented below.

32.6.2.1 Social Influences

32.6.2.1.1 Culture

Culture constitutes a significant contributor in consumer decision-making by providing the shared meanings and norms that define needs, interpret options, and evaluate choices. Consequently, consumer decisions are shaped not only by individual preferences, but also by culturally shared expectations regarding the products and the consumption patterns that can be appropriately adopted in everyday life. Solomon (2023) have noted that marketing managers should recognize that consumers often choose brands which reinforce their cultural identity, underlining the importance of building customer relationships that respect family and religious values.

Cultural influence in consumer decision-making is expressed through several dimensions. First, culture can shape consumers' goals and motives by defining what is valued, such as health, status, tradition, and moral responsibility. For instance, in Greece, the consumption of spit-roasted lamb on Easter Day constitutes a widely established cultural practice. Second, it can influence perceptions and their interpretation by creating norms that guide how brands, prices, and symbols are decoded. In many European food markets, a "PDO/PGI" designation (e.g., feta cheese) is culturally perceived as a marker of authenticity and tradition. In such cases, the label is often interpreted as a signal of superior quality, justifying a premium price relative to noncertified alternatives. Third, culture may organize normative pressures by

establishing what is socially approved within groups. For instance, in social settings in which norms of hostility emphasize generosity, serving meat-based dishes at family or friend gatherings may be considered as the socially appropriate standard.

Therefore, culture influences food decisions by sharing ideas and perceptions about what counts as "appropriate" and "good" to eat. People learn these standards through everyday life, so choices are guided not only by internal factors but also by culturally shaped meal routines, such as what foods should be consumed, when they should be consumed, and how meals should be prepared and shared (Axelrod, 1997). Culture is expressed both through specific "traditional" dishes and through broader food practices that organize daily eating, including cooking methods, family and shared meals, and food-related rituals (Fardet *et al*., 2021; Jayasinghe, Byrne and Hills, 2025; Sproesser *et al*., 2022). Cultural values also structure food choice through rules of permissibility and avoidance, including religious dietary prescriptions and stereotypes that define what may be consumed and under which conditions (Arslan and Aydın, 2024). Furthermore, culturally embedded practices, such as food sharing enhance social belonging and influence food choices, especially in family and group settings (Jayasinghe, Byrne and Hills, 2025; Ratner and Hamilton, 2015).

32.6.2.1.2 Subculture

In consumer behavior, the subculture is a distinct group within a larger society whose members share specific values, norms, symbols, and practices (e.g., the members of a religious group) (Solomon, 2023). These frames can structure decision-making process by challenging problem recognition, defining desirable product attributes, and presenting normative expectations for the final consumption.

In specific subcultural groups, brands and symbols may acquire particular significance, increasing the perceived credibility or desirability of specific options, while at the same time reducing the acceptance of others. Furthermore, consumption may be regarded as a marker of belonging and identity consistency, with decisions being formed by the desire to maintain social approval. Previous evidence showed that consumption patterns can serve as a means of expressing religious identity, whereas commitment and religiosity may also shape food-related choices and evaluations (Coşgel and Minkler, 2004; He and Tian, 2023). He and Tian (2023) demonstrated a negative and statistically significant association between religious participation and food consumption, emphasizing religion as an informal regulation that promotes self-discipline and frugality. In an empirical study conducted in UK, Larcom, Panzone, and She (2024) investigated the reinstatement of meatless Fridays for Catholics and its impact on meat consumption, indicating that religious rules can measurably reduce meat intake, but compliance is partial and heterogeneous. In particular, the survey results illustrated that approximately 30% of the study participants adjusted their dietary habits after the reinstatement. Within this subgroup, more than half of participants reported a decrease in meat consumption, whereas a significant proportion stated complete abstention from meat on Fridays.

32.6.2.1.3 Consumerism and Conscientious Consumerism

Consumerism is perceived as a sociocultural phenomenon, in which consumption is positioned as a crucial means of achieving well-being, expressing identity and participating in social life. Within consumer decision-making, consumerism contributes to the expansion of wants beyond basic need satisfaction by elevating the symbolic, the hedonic, and the status-related motives. Therefore, consumer choices extend beyond functional performance and are often evaluated according to their meaning, self-presentation, and social comparison. Decision processes under consumerism may be characterized by increasing attention to novelty and differentiation, higher sensitivity to consumption trends, and peer influence. It mostly takes the form of overconsumption, driven by psychological, social, and political demands, and supported by the belief that consumption promotes economic growth and individual well-being (Lage, Lins and Aquino, 2022). Under the consumerism prism, products are treated as identity symbols and also as self-protective resources, with the buying process serving compensatory functions when the self is "threatened" (Lage, Lins and Aquino, 2022; Sivanathan and Pettit, 2010).

Following consumer' concerns for environmental sustainability, animal welfare, labor conditions, fair trade, and corporate responsibility, the conscientious consumerism concerns "framed" consumption decisions as moral and evaluated under ethical, environmental, and social objectives. From this

perspective, decision-making is influenced by expanding the options considered to include "responsible" options and by increasing the importance of cues that enhance consumers' trust, such as certifications, transparency, and traceability. Watkins, Aitken, and Mather (2016) examined conscientious consumerism as a "form" of sustainable consumption and political expression, arguing that sustainability-focused choices incorporate moral and ideological commitments besides "green preferences". The authors noted that the label "conscientious consumer" may be preferred to the label "ethical consumer" for individuals who act both privately and publicly on sustainability concerns. In addition, they identified a classification in sustainable practices, ranging from "light green" actions, such as recycling, to "deep green" actions, such as vegetarianism according to their level of commitment, suggesting that consumers' engagement could develop progressively.

Further research also noted that rising consumer concern about health, environmental, and social issues has increased the demand for information about food origins, production methods, and ethical practices, making transparency and traceability prominent in food markets (Jin *et al.*, 2025; Nguyen, Yeh and Huang, 2022; Nguyen and Nguyen, 2025). Since many ethically relevant attributes, such as pesticide usage, cannot be directly verified, consumers have to deal with information asymmetry by relying on the information provided by the suppliers and third-party governance. Since conscientious consumers require information for making ethical choices, the transparency in supply chains is frequently considered as a prerequisite for achieving sustainable agri-food management (Bastian and Zentes, 2013; Nguyen and Nguyen, 2025). Recent research explored whether digital systems could enhance conscientious consumerism by making traceability more "robust", with several studies discussing blockchain as a mechanism to connect transparency and traceability in supply chains (Centobelli *et al.*, 2022; Min, 2019).

32.6.2.1.4 Social Class

Social class can influence the decision-making process by shaping the interpretation cues, the constraints, and the resources through which consumers perceive the different options and evaluate their outcomes (Solomon, 2023). Furthermore, it can affect the set of feasible options, the perceived risk of each outcome, and the appropriateness of the decision strategies. Many markets also involve status symbols, where products and brands function as markers of distinction. In such cases, the evaluation process includes social visibility and symbolic value, and consumers may pay premium prices for products that communicate success, membership, or refinement.

In consumer research, social class is commonly described by income and education (Hollingshead, 1975) and considered as a source of shared experiences that structure information systems, perceived control, and habitual responses (Kraus, Piff and Keltner, 2009; Kraus and Stephens, 2012). This framing denotes that decision-making differences across various social class segments may be attributed to differences in alternative option feasibility, information availability, and social meanings attached to options, besides differences in consumer preferences. Monterrosa *et al.* (2020) linked food choice to social identity, connoting that individuals' choice can express "what they are", routines, social membership, and social norms. The authors underlined that social class and income can also modify household food labor, with higher-income households using paid staff, resulting in time burdens and decision authority change.

Previous literature has supported social class effects on food decision-making, with structural factors stating constraints, affordability, and access (Darmon and Drewnowski, 2015; Burgoine *et al.*, 2017). In addition psychosocial approaches have indicated that social class also shapes the evaluation mechanism through which options are assessed, including beliefs about taste and health (Manstead, 2018). Pivecka, Kunz, and Florack (2023) demonstrated using both cross-sectional and longitudinal data that socially patterned health–taste relationships in meal evaluation partially explain social class differences in food choice. In another research, Han and Lee (2022) explored organic food consumption in Seoul using data on the location of organic food stores and national survey data. The authors defined social class via education and income strata and showed that organic stores cluster in districts with higher income and education levels, indicating that consumer access and opportunity to purchase are socially patterned. However, in behavioral models predicting actual organic purchases, the main findings noted that lifestyle variables can be more predictive compared to sociodemographic indicators alone, suggesting that social class impact mostly concerns self-presentation and consumption orientations (Han and Lee, 2022).

Evidence from the meat industry regarding the impact of social class on meat consumption is provided by Hase Ueta *et al.* (2023), who analyzed data from Brazil by income level and underlined that purchasing power is strongly associated with meat intake across social segments. In particular, low-income consumers would have to spend 17 times more on buying beef (comparing the lowest to the highest income segment), implying that purchasing power and prices can also affect and alter diet composition. When beef meat absorbs a much higher share of the low-income budgets, consumption patterns are expected to shift due to affordability constraints, stating that the observed behavior may be the outcome of limited feasibility.

32.6.2.1.5 Group Participation

Group participation can shape decision-making by altering the informational environment and the incentives attached to particular options. Group participation can influence consumer decision-making through the structure of the information encountered, the determination of social "appropriateness" and reward, and the formation of identities. Tindale and Winget (2019) reviewed in depth group decision-making with the premise that decisions are socially incorporated through advice, ratings, and committees, and can vary according to the extent of interaction and information exchange among group members. Research on group decisions is based on the observation that group participation can alter both the informational basis and the social dynamics through which choices are formed. Participation in groups increases exposure to shared information and interpretations, and it also filters information perceived as credible. Furthermore, it reduces consumers' uncertainty via the formation and dissemination of heuristics (e.g., "what people would do in that case"). Therefore, decision quality can be improved via group-based information.

At this point, it should be noted that many decisions are taken under uncertainty, in which individuals have to evaluate the reliability of the relevant information sources and the risks associated with that choice. Group participation can affect this process through information distribution, and by also shaping the information level and its credibility. Moreover, in case groups bring together members with different experiences, the shared information can improve decision quality providing insights into a more complete understanding of the options available and reducing consumers' uncertainty (Tindale and Widget, 2019; Larrick, Mannes and Soll, 2024). On the other hand, the same information process can also decrease decision quality if a group circulates biased beliefs, which may become compelling through repetition and endorsement. Thus, specific conditions that could improve group decisions extend from openness to diverse perspectives to strong accuracy through shared information by experts, whereas biased representations, self-interested incentives, and skewed information exchange could undermine decision quality (Brodbeck *et al.*, 2007; Tindale and Winget, 2019). Consequently, group-based information can function either as a resource for improved assessment or as a channel through which misinformation may be reproduced, depending on the group's characteristics.

Besides information processing, group participation may create expectations about "appropriateness" and even attach social consequences to either compliance or deviation, with these consequences including approval and reputation for the first case, and criticism, exclusion, or loss of status for the second case. Therefore, groups membership can either enhance cooperation and collaboration among its members, encouraging collective action, or discourage disagreements by increasing the social cost of deviation. Furthermore, group participation may also provide identity to its members, implying goals and standards of evaluation. Toward this direction, reference groups have a crucial role since they are employed as a standard for comparison when individuals express preferences and make decisions (Solomon, 2023).

A great body of literature has stated that shared eating comprises a key social practice as it produces belonging and indicates membership (Fischler, 2011). Concerns about dietary individualization have raised the question if the practice of "common meal" has been weakening in the modern society and have urged investigation of how commensality changes across various settings (Jönsson *et al.*, 2021). Using data from the Netherlands, Veen *et al.* (2023) investigated how young adults manage shared meals, in which co-reside omnivores and vegetarians, noting that although meat consumption remains culturally dominant, at the same time meat reduction and vegetarianism are increasingly normalized. The main findings showed that shared meals usually continue and people eat together despite dietary differences and the household members eat at the same table through practical coordination. Thus, they may adapt

meals by making vegetarian dishes the default when a vegetarian is present, or by cooking a shared meal and adding meat separately for omnivores, or by preparing two different dishes (Salmivaara *et al*., 2022; Veen *et al*., 2023). Socially, they also keep a pleasant atmosphere through "agree to disagree", under which diet is perceived as a personal matter and debate about meat is avoided.

32.6.2.1.6 Opinion Leaders

Opinion leaders have a crucial role in consumer decision-making by acting as credible sources who interpret products and trends for others. An opinion leader can be defined as an active and highly engaged media user who mediates between mass communication and everyday assessments by interpreting media messages for less active users. Beyond simply repeating information, the opinion leaders translate content into meaningful evaluations, with their influence being mostly contributed to the esteem and credibility they inspire among others, which lead other consumers to regard their interpretations as trustworthy guidance in shaping judgments and directing choices (Morini, 2014). The concept of opinion leadership originates in the two-step flow of communication, which proposes that mass media rarely influence individuals directly. What happens is that media content first reaches a subset of more informed people, and these individuals then shape other's opinions through interpersonal interaction (Katz, 1957; Morini, 2014). Their engagement in decision-making include the uncertainty reduction, the introduction and legitimization of innovations, and the attention direction toward specific brands or product categories (Wang, Ting and Wu, 2013). In this sense, opinion leadership can influence the decision-making by altering the information inputs that consumers have to consider and by shaping the interpretive frames through which these inputs are evaluated (Farivar and Wang, 2022).

In contemporary settings, opinion leadership has been extended with online opinion leaders (influencers), whose influence is exercised through digital platforms and content creating, enabling them to act as mediators between consumers and brands (Tafesse and Wien, 2018). Influencer marketing research has perceived opinion leadership as a key driver of consumer responses, with a significant body of evidence noting that influencer characteristics, including opinion leadership, attractiveness, credibility and trustworthiness, can shape purchase intentions and affect final decisions (Belanche *et al*., 2021; Schouten, Janssen and Verspaget, 2020; Sokolova and Kefi, 2020; Farivar and Wang, 2022). Farivar and Wang (2022) investigated how influences shaped followers' purchase intentions, while situating opinion leadership into a broader social context, in which influencer marketing functions as a community-based form of communication. Based on the social identity theory, the main findings showed that follower decision-making is shaped not only by interpersonal sources like opinion leaders, but also by identification with the influencer's community. Therefore, although opinion leadership seems to have a major influence on consumers' decision-making, its persuasive strength is somewhat interrelated with the identity dynamics of influencer communities and on narrative forms that increase heuristics' processing.

With respect to the impact of opinion leaders in eating habits, Schulze, Spiller, and Jurkenbeck (2022) examined opinion leadership in food choices among young consumers, seeking to confirm whether influencers also exhibited distinctive patterns of meat consumption and policy-oriented attitudes. Their main results indicated that opinion leaders are more likely to follow dietary styles with decreased meat consumption and show higher openness to protein meat alternatives, such as plant-based alternatives.

Concerning the role of influencers as information "providers" about innovation, Specht, Rumble, and Buck (2020) depicted that attitudes and choices regarding food technologies are increasingly formed within networked channels in which influential factors shape what information is encountered and how it is interpreted. As social media has become a significant source of news and public discussions or controversies, influencers' role in driving decision shaping has expanded. Substantial proportions of adults use social media, with a very high share reporting that they receive news and information through these platforms (DataReportal, 2025). Besides "consuming information", these media are also employed for publicly expressing opinions, discussing topics of interest, and attempting to influence other people's views (Velasquez and Quenette, 2018). Specht, Rumble, and Buck (2020) analyzed how cultures meat was discussed on Twitter and showed that conversation volume was driven by specific events, with spikes being linked to policy and industry news. It was also noted that cultured meat interpretation was perceived as an emerging issue, although it still remains in an early stage of public debate. Furthermore, the authors identified the main themes triggering consumer discussions, such as regulation/labeling,

sustainability acceptance, business, animal concerns, and scientific and technological innovations, and noted that influencers can help shape the criteria and narratives through which consumers evaluate novel technologies in the food sector.

32.6.2.1.7 Gender Roles

Gender definition differs from sex definition because the latter is identified with biological characteristics, whereas gender include the culturally and psychologically constructed aspects of expression that vary across time and context (Holmes, 2007). Gender roles can influence decision-making process by assigning expectations about products, responsibilities, and identities. In particular, they can shape who performs shopping tasks in the households, which product categories are gender-coded, and how products are evaluated and interpreted. Marketing communication has a significant effect on the establishment of gender roles since it often preserves well-established beliefs about how women and men should behave and react, and how they should adapt their behavior according to gendered norms and expectations (Solomon, 2023). Based upon the social identity theory, people may conform to group stereotypes to reinforce identity, and in such case food choices can comprise the means through which masculinity and femininity are portrayed and socially evaluated (Young *et al*., 2009).

In a thorough review, Rodrigues, Goméz-Corona, and Valentin (2020) noted that biological differences may be interpreted socially and used to justify stereotypes, resulting into the "transformation" of physiology into public opinion. The authors reviewed evidence that foods operate as symbols employed to express identity and group membership, with meat usually being associated with masculinity and power, whereas fruit and vegetables being linked with femininity and health, although these relationships may vary across countries and subcultures (Pavan *et al*., 2017; Rodrigues, Goméz-Corona and Valentin, 2020). Concerning the role of media in producing gendered classification of food practices, recent evidence showed that platforms, such as television, social media, blogs, and cookbooks, use to address food-related symbolic meanings, in which everyday household cooking is considered as feminine, whereas professional culinary knowledge and "chef" identity are perceived as masculine (Contois, 2018; Lepkowska-White and Kortright, 2018; Rodrigues, Goméz-Corona and Valentin, 2020).

Research on demographic characteristics and meat consumption association has consistently identified gender as a main dimension with which both dietary behavior and attitudes toward meat production and livestock production have been differentiated. More specifically, recent research noted that males consumed more meat compared to women and were less likely to be proponent of vegetarianism or dietary patterns with lower meat consumption. On the other hand, their female counterparts were more likely to express environmental and ethical concerns regarding livestock production practices and reduce meat consumption to follow more sustainable eating patterns (Lombardo *et al*., 2020; Predanócyová, Kubicová and Pindešová, 2023; Rosenfeld, 2018; Rosenfeld and Tomiyama, 2021; Fantechi *et al*., 2024; Hopwood *et al*., 2024; Wiesli, 2025). Previous literature has sought to explain gender-specific meat consumption patterns by emphasizing the symbolic association between meat and masculinity. In particular, large-scale survey data underlined that males showed a stronger preference to beef, pork, and poultry compared to females, and they also seemed more critical toward plant-based nutrition, although overall willingness to consider veganism was statistically unrelated to gender (Love and Sulikowski, 2018; Rosenfeld and Tomiyama, 2021).

32.6.2.2 Situational Influences

32.6.2.2.1 The Environment

The physical environment constitutes a significant determinant of consumer decision-making, as it structures the conditions under which attention, evaluation, and choice occur. The retail setting with its design, its sensory cues, and the navigation potentials can shape what consumers notice and how they interpret the alternatives options, affecting final decisions by altering both the available informational inputs at the point of choice and the cognitive effort required to process them (Bawa, Sinha and Kant, 2015; Khan *et al*., 2023). Situational conditions like the layout, the shelf position, and the product visibility can affect which products gain consumer's attention with products placed at eye level and near checkout desks

being more likely to get noticed and perceived as more popular or desirable. Furthermore, the role of physical environments in influencing consumer preferences extends beyond information cues and visibility to sensory stimuli, with enjoyable settings encouraging the visitation repetition.

Visual merchandising may also have a considerable effect on consumer decision-making. Conceptualized as the strategic presentation of products and store spaces to support brand positioning and improve the service experience, it can reduce the search efforts, define the perceived range of options, and structure in-store exposure, so that certain options are easier to compare and choose (Iberahim *et al*., 2019; Florea *et al*., 2025). Toward this direction, sensory cues, such as music and lighting, can influence shopping experience through mood arousal and perceived product quality, with music characteristics (e.g., tempo, loudness) shaping time spent in-store and customer expenditures (Spence *et al*., 2014).

In a recent study, Khan *et al*. (2023) investigated how retail atmospherics and store design features can influence purchase decisions in Delhi chain stores. In order to account for combined effects and not rely on single-cue influences, the authors modeled window display, mannequin display, visual merchandising, lighting, music, and signage as predictors of purchase decisions. The main findings showed that visual cues strongly influence choice since they affect shoppers' behavior by capturing attention and encouraging store entry. Window displays create first impressions indicating what the retail store offers, whereas mannequin displays help customers imagine products on themselves, triggering the potential of impulse buying (Khan *et al*., 2023; Tantanatewin and Inkarojrit, 2016). The window display and the mannequin display showed positive associations with purchase decisions and store design and atmosphere, indicating that strong visual presentation cues can influence choice both directly and by contributing to the broader evaluation of the store. In addition, visual merchandising exerted a positive effect on purchase decisions and on store atmosphere, reinforcing the view that decision outcomes are partly contributed to external factors, besides customer preferences. On the other hand, lighting and signage influences were negligible, showing that cues may differ in their effectiveness to capture consumers' attention at critical moments and reduce cognitive effort in information search and alternatives' comparison.

Besides, the physical environment, the market environment may also shape decision-making by structuring both information and the choice process. Strategies, such as assortment, pricing regimes, promotion intensity, product placement, and platform environment in digital markets can affect both consumer attention and evaluation. Furthermore, competitive conditions can also have an impact on credibility and the prevalence of qualitative "warranties", such as certifications and return policies, as well as the extent to which consumers can reduce uncertainty through comparison. In digital markets, algorithm rankings have been incorporated in the market environment to help marketers understand consumers' preferences and their post-purchase expectations. Overall, the impact of the physical environment on consumer decision-making mostly concerns the organization of products' exposure, consumer's cognitive effort, affect, and action costs at the point of purchase, being even stronger when decisions are taken under time pressure, when products are almost similar, and opportunities for product differentiation are limited, and when consumers rely on habitual decisions or heuristics.

32.6.2.2.2 Time Pressure

Time and mostly time pressure comprise significant explanatory factors of the decision-making process by altering the cognitive effort for the evaluation of the alternative options and by changing the relative weight which consumers assign to purchase speed, convenience, and error avoidance. In case time pressure is high, consumers use to compress or bypass stages of the decision-making process, resulting in a rather weaker information search, the consideration of fewer alternatives, and an evaluation mostly based on heuristics, such as brand familiarity and price. Therefore, choices under time pressure tend to be more habitual to nuanced product attribute differences, especially in low-involvement decisions.

In addition, time pressure may also increase consumers' reliance on situational cues and the choice environment. When consumers have to make fast decisions, easily accessible options due to notable placement or options framed as "recommended" or "best value", or "limited time offer" are more likely to be selected since they decrease the need for comparison, especially at the point of purchase. In association with time pressure, emotional or physiological states can elevate consumer stress and anxiety resulting in consumers' turn to options that minimize effort or reduce uncertainty, and a stronger avoidance of unfamiliar products whose outcomes are less predictable.

Previous research has underlined a correlation between time scarcity and dietary patterns. Purchasing, preparing, and cleaning up meals require substantial non-market time, and time constraints may be more tight than financial constraints in household food production (Bencsik, Lusher and Taylor, 2025; Davis, 2014). For instance, Heuvinck and Li (2024) argued that time scarcity contributes to unhealthy eating practices since it increases consumers' willingness to choose fast food meals, identifying "fast meals" with "fast food". In a recent study, Bencsik, Lusher, and Taylor (2025) noted that higher traffic increases visits to fast food restaurants and reduces supermarket visits, with stronger effects being prevalent during afternoon rush hours. The authors highlighted that time pressure effects may operate through multiple ways. According to previous evidence, stress can increase preference for high-fat or high-sugar foods, whereas traveling between home and the workplace has been linked to stress, and separately to obesity correlates (Barrington *et al.*, 2014; Bencsik, Lusher and Taylor, 2025). Therefore, congestion may generate both time loss and stress, positioning time pressure as a broader situational condition, which can shift choice through interrelated constraints (time, effort, affect). Time and time pressure may systematically affect consumer choice and purchase behavior by reallocating cognitive effort, increasing reliance on heuristics, and elevating the importance of convenience.

Based on the foregoing discussion of the internal and the external determinants of the decision-making process, it becomes evident that these factors should be considered interactively, rather than in isolation. External environments determine which options and cues are encountered, whereas internal factors define how these cues are selected, interpreted, and "converted" into choice. Thus, consumer decision-making emerges from the interaction of cognition, culture, personal goals, environmental settings, and social structure.

32.7 Implications for Marketing Meat Products in the Food Industry

Marketing strategies for meat products can be analyzed as coordinated systems for managing demand in a product category marked by sensory importance, credence attributes, and strong ethical and regulatory scrutiny. Unlike many packaged products, meat is evaluated through a combination of sensory expectations (taste, tenderness, etc.), functional performance in preparation methods (i.e., ease and time for meal preparation), and socially mediated influences about safety, animal welfare and environmental impact. Besides communicating product and service value, the marketing strategy can structure how consumers interpret quality under uncertainty, how they justify purchases, and how they navigate the decision environment (both internal and external factors) during the decision-making process. Therefore, affective marketing strategies in meat industry may be perceived as strategic tools that differentiate products, reduce the perceived risks and ethical ambivalence, and increase convenience and habitual purchases and repurchases through marketing channels.

32.7.1 Product Differentiation

A crucial strategic challenge in meat marketing is the limited capacity for differentiation during the retail presentation, where products are often encountered as similar cuts, whose quality cannot be fully assessed prior to preparation. For many consumers, meaningful pre-purchase comparisons are difficult to accomplish because key attributes, such as tenderness, flavor, safety, and welfare, remain observable until the product has been cooked and consumed. Under these circumstances, market competition is shaped less by verified product differences, and more by credibility cues that represent those differences, with labeling and branding assuming a substantial role in structuring perceived quality and purchase justification.

32.7.2 Market Segmentation

A "concrete" consumer-oriented marketing strategy should be focused on market segmentation and positioning, and identify the mechanisms by which the brand's practices could be translated into superior outcomes and occasion-specific positioned products. Segment needs tend to diverge through multiple

dimensions to cover intersecting aspects related to consumer's price sensitivity, convenience orientation, culinary involvement, health-related goals, ethical concerns, and openness to innovation and novelty. Consumers oriented toward premium consumption are often more responsive to narratives, sensory attribute superiority, and origin labeling, prioritizing reliability and an acceptable price-quality trade-off. In addition, time-scarce households place greater weight on the ease and the efficacy of the preparation and cooking methods, whereas ethically motivated consumers demand verified animal welfare and environmental sustainability assurances. Therefore, the meat industry has to interpret the heterogeneity in consumers' needs, while avoiding ambiguous positioning.

Portfolio designs should connect segment expectations and product-line roles, distinguishing the needs, preferences, and affordability variations among various consumer groups. More specifically, value lines should be appropriately designed to deliver broad availability, minimal complexity, and affordability, whereas mid-range product lines should be designed to provide performance and convenience through specifications and functional packaging. On the other hand, premium product lines should be positioned to convert credence attributes, such as origin, welfare standards of production practices, into price premiums.

32.7.3 Product Positioning

Meat products may be positioned through culinary performance (e.g., tenderness), origin by marking either their regional identity or single-farm identification (e.g., MIMIKOS chicken), animal welfare (e.g., higher welfare lamb), or sustainability claims (e.g., lower-impact production methods). However, the efficacy of the positioning technique depends on the reliability and the validity of the claims stated, since meat products constitute a category characterized by credence attributes, which cannot be easily confirmed prior to purchase, and in some cases can remain unverified, even after consumption. In such cases, marketing claims can operate as signals for underlying attributes, rather than statements which consumers verify through experience. Therefore, the credibility of marketing claims mostly depends on institutional support measures, such as certifications or traceability systems, to reduce information asymmetry. At this point, it should be noted that positioning strategy may be more effective when the claims focus on a small number of highly informative cues, which are usually communicated through packaging, retail shops, and digital channels. This is highly important for welfare and sustainability claims, where higher public awareness has increased sensitivity to greenwashing and welfare-washing and consumers are alert to misleading messages. Thus, marketing messages should be aligned with institutional authorities, and communicate claims supported by transparent reports.

32.7.4 Branding

Besides brand positioning, brand architecture also comprises a key factor for product differentiation in meat markets, as many purchases are completed under limited deliberation, with consumers being unwilling or unable to conduct extensive pre-purchase comparisons. Under these circumstances, brands are required to act as cognitive signals that "compress" the evaluation task by concentrating multiple assessed attributes into a single trusted cue. Therefore, a meat business may adopt a "branded commodity" positioning strategy orientated toward the assurance of safety, consistency, and performance to reduce consumers' perceived risk and enhance repeated purchases. Furthermore, the business may adopt a differentiation strategy, in which brand meaning is built through narratives of expertise, husbandry practices, and tradition. In premium product marketing, meat businesses should seek to link product's sensory attributes with production practices and sensory outcomes. In such case, narratives that provide causal reasoning explaining how feed regimes, breed characteristics, aging processes, and handling practices influence the product characteristics tend to enhance the perceived authenticity by making quality claims intelligible. Also, storytelling could help product communication, constituting a risk-reduction tool to further support consumers' confidence in their purchase decisions.

32.7.5 Packaging Design

Marketing strategies in meat retailing should also place special emphasis on packaging since it is encountered at the point of purchase, where consumers usually have to deal with time constraints and make quick decisions. In such settings, packaging may form an information source to "translate" unobservable attributes into perceptible cues through visual signals. Packaging can also operate as a practical component for product supply, with implications for convenience, perceived value, safety, and waste. In modern food markets, where time pressure constitutes a basic constraint, packaging designs that embed convenience, as in ready-to-cook marinated products and ready-to-eat meals, can reframe the criteria by which consumers evaluate meat options. This reframing is especially important since it shifts competition from commodity price comparisons toward differentiated performance on convenience, preparation efficiency and ease, and occasion-specific suitability, enabling firms to build consumer loyalty and encourage constant purchases in time-pressured consumption environments. Nowadays, besides meeting consumer needs, meat businesses have to face competition with convenience foods and alternative proteins in sensory attributes, such as taste and convenience characteristics, as the overall ease of producing a meal. Tools, such as meal kits and bundled packages (e.g., meat plus barbecue sauce) and merchandizing with complementary items can reduce the cost of meal planning. Rather than "assembling" a meal through multiple and separate decisions, the consumer receives a "constructed" and time-saving choice unit.

32.7.6 Merchandizing

The retail environment can also affect consumer decision-making since visibility and availability may delimit the alternative options, which consumers may experience as available within the choice set at the point of purchase. In in-store environments, meat products compete within a constrained space in which consumers often rely on noticeable cues rather than making detailed comparisons. Consequently, merchandizing variables, such as shelf placement and in-store signage, operate as strategic tools that can alter purchase likelihood by influencing consumers decision-making through attention stimulation. Thus, products that are "easier to see and reach" are more likely to be chosen, especially under time pressure. Cross-merchandizing, through organizing complementary items, such as placing marinades or grilling equipment close to meat products, activates meal occasion scripts, while at the same time reducing the search and the costs associated with complementary product purchases.

32.7.7 Price Strategy

With respect to the pricing strategy, it must compromise price volatility with consumer price-sensitivity by also considering the signaling function of product price for brand equity and perceived quality. Although deep and frequent discounting may augment sales volume, there is increased risk that consumers will treat the product as a commodity, undermining premium cues. A solid price strategy should treat promotions as differentiated "instruments" with distinct behavioral purposes, distinguishing between promotional tools used for trial, those intended to encourage stock-up and increase usage, and those employed for loyalty reinforcement. Introductory offers can encourage trial of new cut or value-added product lines, whereas multi-buy offers could increase household usage, and loyalty-linked promotions could allow value to be targeted to relevant consumer segments. Price framing further shapes how consumer interpret monetary values, as consumers frequently rely on heuristics, such as "price per serving", implying that communication that translate price into meal outcomes can justify consumers' willingness to pay, particularly for premium product lines. At the same time, pricing and promotional communications are embedded in wider normative environments due to consumers' ethical and health concerns associated with meat consumption. In such cases, aggressive messaging can conflict with expectations about responsible production and consumption and impose increasing reputational risks to meat businesses. Therefore, pricing strategy should align sales volume goals with business reputation and consumer trust, avoiding mechanisms that may undermine both brand equity and long-run credibility.

32.7.8 Product Communication

Since advertising and communication tools for meat products increasingly operate in a turbulent cultural environment, meat business should take into consideration that although "conservative" appeals to taste, family meals, tradition remain effective, ethical concerns regarding animal welfare, antibiotics, and climate preservation have contributed to more ambivalent consumer evaluations, especially among specific consumer segment (e.g., younger or more sustainability-oriented consumers). Under these conditions, communication strategies cannot be restricted to demand increase, but they also have to manage credibility by addressing uncertainty and providing consumers with reasons for purchase. Therefore, meat businesses are confronted with a crucial choice about whether and how to engage ethical concerns, because in case of employing defensive claims that deny responsibility (e.g., "we are not the problem"), consumers may react with increased skepticism. Content marketing can contribute to this direction by providing accessible explanations of welfare standards, feed programs, and sustainability initiatives.

The digital environment also provides new opportunities for product communication in the meat industry, extending beyond the above-mentioned functions, by combining consumer persuasion with relationship-building. More specifically, social media platforms allow businesses to spread storytelling, provide cooking guidance and recipe education, and normalize specific preparation practices that reduce perceived effort and improve cooking skills. Influencer partnership becomes of great importance because many consumers appraise culinary experts, with chefs, food creators, and nutritionists operating as opinion leaders who translate product claims into practical scripts about cooking methods, products fitting to different occasions and price evaluation. The effectiveness of such partnerships is affected by the influencer' perceived authenticity and the "alignment" between the influencer' identity and the product's positioning. Therefore, a premium meat line benefits from associations with culinary skills, whereas a convenience product line benefits from creators who specialize in quick meals.

Besides influencer partnerships, foodservice partnerships and communication through restaurant menus can constitute strategically powerful tools for building brand name and generating experiential evidence of product quality. Since restaurant menus operate as curated assortments of products, consumers' taste experience in food service can shape retail preferences. Co-branding with restaurants, highlighting origin or welfare standards on menus, and supporting chef collaborations can position a meat brand as premium and trustworthy, with such strategies being especially effective for marketing meat cuts, which consumers are hesitant to cook at home. Favorable experiences can motivate consumers to replicate them in domestic contexts, creating a pathway from foodservice trial to household adoption. Furthermore, habit formation could also be generated and supported through sales promotion tools, as repeat purchase often comprises the central profit driver. In such cases, loyalty programs, subscriptions, and direct-to-consumer (DTC) channels may increase both consumer demand and lifetime value by reducing switching, stabilize purchasing and embedding the brand within the recurrent household dietary patterns. Subscriptions and curated-box models also operate as mechanisms of guided exploration, helping consumers try new cuts while lowering the cognitive and practical effort associated with experimentation. In addition, DTC channels enable data selection on consumer preferences and purchasing patterns, supporting more precise segmentation and personalization.

Promotional tools that stimulate trial and repeat purchase are most effective when they are complemented by consumer education, as informational and instructional supports reduce preparation-related uncertainty and increase the likelihood that initial promotional uptake results in satisfactory usage experiences and sustained repurchase. Consumer education is similarly consequential because meat is a technically demanding category, in which perceived cooking skills strongly shapes willingness to experiment. When consumers lack confidence in preparing specific cuts, perceived risk increases, and therefore demand concentrates on a small set of "safe" options. In such cases, instructional tools like recipes, cooking times and temperatures, and occasional usage recommendations can widen consumers' feasible choices by decreasing preparation anxiety and augmenting behavioral control.

Finally, contemporary meat marketing strategies must account for the increasing competition between meat and alternative proteins, as well as consumers' health, environmental, and ethical concerns. Meat

businesses can respond through quality strengthening and responsible production claims, by innovating toward "better meat" product designs (e.g., higher animal welfare standards, reduced antibiotic usage), and by offering convenience and culinary advantages. It should be ensured that meat remains an option that fits consumers' practical constraints and symbolic meanings, engaging sustainability, heath goals, and ethical legitimacy in the view of the emerging demand for responsibility and morality in the food chain.

In summary, marketing strategies for meat products operate more effectively when they are treated as an integrated system, incorporating four different domains: (i) the value framing through product differentiation and positioning, market segmentation, branding, and storytelling; (ii) the uncertainty reduction through certification, traceability, and credible claims, (iii) the decision-environment through packaging, placement, merchandising, and convenience formats, and (iv) habit formation through product trial, consumer loyalty, and foodservice experience. Afterall, the success in meat marketing depends on an integrated and consumer-oriented business plan, which will enable individuals to select, evaluate, and repurchase under real-world constraints of time, budget, and moral considerations.

32.8 Ending Notes

Consumer's perceptions toward meat increasingly reflect a multidimensional evaluation under conditions of uncertainty, and budget, time, and convenience constraints. Meat remains strongly embedded in sensory appeals, culinary familiarity, cultural symbolism, and established household practices, whereas at the same time, consumers express concerns about food safety, animal welfare, the environmental impacts of the meat industry, and the associated health risks. A key implication is that mixed or contradictory attitudes constitute a recurring feature of the meat markets with many consumers acknowledging negative externalities while maintaining meat purchases, as they weigh competing motives through decision trade-offs.

A further implication is that the observed discrepancy between values and behavior cannot be adequately explained by the lack of information, as psychological and moral mechanisms help stabilize consumption, even when ethical and sustainability concerns are strong. For instance, the meat paradox and the 4Ns rationalizations delineate how consumers protect their self-image and preserve culturally endorsed eating identities, even in case they have to deal with salient environmental, ethical, or health concerns. In addition, consumer decision-making models indicate that meat purchases occur through different levels of cognitive effort, ranging from habitual and low involvement choices to more extensive evaluations, in which individual's involvement is higher. This implies that the factors shaping choice vary with the purchase context, the consumption occasion, and the level of perceived risk.

In addition, many valued meat attributes may constitute credence characteristics, so consumer evaluations rely on the perceived trustworthiness of signals that represent claims which remain difficult to verify directly, such as provenance, animal welfare, food safety, and environmental performance. Therefore, effective market and policy responses depend on credible institutional infrastructures, including transparency standards, traceability systems, and certification labeling. The heterogeneity in consumers' priorities remains decisive, since segments that emphasize price, convenience, health, ethical and environmental considerations, as well as innovation receptivity respond differently to the same messages and product cues. This implies that commercial strategies and public interventions are more likely to be effective when they adopt segmentation approaches that adapt the proposed changes to the actions that consumers can undertake within everyday purchase and consumption routines.

Finally, the protein market is increasingly shaped by direct comparison between animal-based and alternative protein options. Plant-based and other alternative proteins comprise substitutes in specific settings and also redefine the criteria through which meat is assessed, since sustainability and health have become more salient attributes in consumer evaluation. Under these conditions, consumption shifts are likely to depend on combined approaches, including product and process improvements, that strengthen consumer's confidence in product attributes, as well as market environments that reduce barriers to change and innovation. Future research would benefit from linking self-reported attitudes to

observed behavior across diverse contexts to indicate how moral and health claims interact with identity and social belonging, and test interventions that combine information, experience, and support. Overall, consumer choices regarding meat and protein emerge from the combination of affect, cognition, cultural norms, and market conditions, unveiling important implications for marketing strategies and for the public acceptance of meat production systems.

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The Rise of Plant-Based and Cultured Meat: Consumer Perspectives

Neda Sattarzadeh, Szymon Wojciech Lara, and Amalia Tsiami

33.1 Introduction: Food Security Concerns

Despite a recent increase in global food insecurity, holistically, humanity has achieved the highest levels of food security ever recorded in history (Akbari *et al*., 2022). These achievements have been enabled by a range of technological and cultural advancements, including the transition from pastoralism to settled agriculture, mechanization, industrialization, and computerization of food systems. More recently, attention has turned to the potential role of digitalization and artificial intelligence in supporting further developments across food systems worldwide, from both global and local perspectives (Leeuwis, Boogaard and Atta-Krah, 2021).

According to the most recent evidence from the Food and Agriculture Organization (FAO), food security has declined globally since the COVID-19 pandemic, and scenario-based projections suggest that elevated levels of food insecurity may continue for several years (UNICEF, 2025). Food insecurity is predominantly attributed to challenges in production and distribution, particularly in parts of the Global South where food surpluses are often limited or unavailable (Falcon, Naylor and Shankar, 2022). In contrast, in many regions of the Global North, food insecurity is increasingly characterized by the overavailability of energy-dense, nutritionally poor diets rather than absolute scarcity (Van Dijk *et al*., 2021).

Current debates on food security highlight several interconnected areas of concern, including crop failure driven by climate change and disease (Hasegawa *et al*., 2021). Furthermore, environmental pollution, biodiversity decline, and dietary patterns characterized by high consumption of HFSS (high fat, salt, and sugar) foods and, increasingly, meat, particularly red meat (Ambikapathi *et al*., 2022; Scherer *et al*., 2020). Importantly, animal feed production, especially the large-scale cultivation of feed crops such as soy and maize, is closely linked to land-use change and habitat conversion and is therefore a significant driver of biodiversity loss (Antonelli, Fry and Villaverde, 2023). Meat has become a focal point of food security, sustainability, and health discussions due to its complex role within globalized food systems (Bonnet *et al*., 2020). Poultry, lamb/mutton, beef, and pork are traded as commodities across long and interconnected supply chains, making consumers more globally connected than ever, while simultaneously increasing vulnerability to supply disruptions (Henchion *et al*., 2021).

The ever-growing environmental concerns are attributed to meat production, notably greenhouse gas emissions, water and land use, and antimicrobial resistance (González *et al*., 2020). These impacts are not uniform across meat commodities or production systems. For example, water stress associated with free-range poultry or pasture-based beef can be lower than that of intensified systems due to differences in blue and green water use, while methane emissions may be higher in grass-fed cattle in the absence of methane-reducing feed additives (De Vries, Van Middelaar and De Boer, 2015; De Vries and de Boer, 2010). Despite this variability, global concerns regarding the sustainability, health implications, and resilience of meat supply chains continue to intensify.

Plant-based foods, particularly those emerging from food reformulation initiatives, have experienced substantial growth in both supply and demand in recent years (Alae-Carew *et al*., 2022). Within this

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category, meat analogues aim to replace or substitute animal-derived protein products. In parallel, there is growing interest in revolutionary technologies to produce cultured meat (Lewisch and Riefler, 2023). More precisely referred to as cultivated or cell-cultivated (cell-based) meat, these products fall within the field of cellular agriculture, where animal cells are expanded in vitro and directed to form muscle and fat tissues under controlled conditions (Mattick, 2018). Alongside this, 3D food printing and bioprinting technologies are being explored to create more structured, animal-like products by depositing cell-containing or protein-rich edible materials in defined architectures to better mimic the texture and structure of animal flesh (Chen *et al*., 2022; Handral *et al*., 2022). Innovation is also accelerating in the area of cultivated seafood, including fish products, reflecting sustainability concerns around overfishing and supply volatility, although environmental concerns are also attributed to these new technologies (Tuomisto and Teixeira de Mattos, 2011). Because these technologies are highly novel and, in some cases, politically and culturally contested, transparent regulation and clear public communication are likely to play a particularly important role in shaping trust and consumer confidence (Andreani *et al*., 2023).

From a public health perspective, it is also important to acknowledge that "plant-based" does not automatically mean "healthy". Furthermore, a proportion of meat analogues and other plant-based substitutes are criticized for being ultra-processed. Concerns have been raised regarding salt content, saturated fat profiles depending on formulation, and potential dietary displacement effects if these products replace minimally processed foods (Alcorta *et al*., 2021; McClements, 2023). At the same time, nutritional quality varies widely across the category, and health implications are not uniform across products.

33.2 A Short History of Plant-Based Foods, Meat Analogues, and Cultured Meat

Plant-based protein foods have been part of human diets for millennia. Legumes, cereals, nuts, seeds, and fermented products such as tofu and tempeh have long provided essential nutrients in diverse cultural contexts. In many regions, these foods were not perceived as substitutes for meat but as integral components of local foodways shaped by ecological conditions, religious beliefs, and culinary traditions (Poutanen *et al*., 2022).

The conceptualization of plant-based foods as alternatives to meat is a relatively recent phenomenon, particularly in Western contexts. During the nineteenth and early twentieth centuries, vegetarian movements in Europe and North America promoted meat avoidance for ethical, religious, and health-related reasons (Marsh, Munn and Baines, 2012). Early industrial meat substitutes, often based on soy or wheat gluten, emerged during periods of scarcity such as wartime rationing. These products prioritized protein provision rather than sensory similarity to meat and were frequently framed as utilitarian or moral choices rather than desirable food (Thakur *et al*., 2024).

From the late twentieth century onward, advances in food science and processing technologies enabled more sophisticated meat analogues. The development of texturized vegetable proteins, extrusion technologies, and flavor chemistry allowed manufacturers to better replicate the fibrous structure, juiciness, and aroma of meat (Kołodziejczak *et al*., 2021). These technological advances coincided with growing public concern about environmental sustainability, animal welfare, and health, creating a receptive context for innovation (Andreani *et al*., 2023; Zioga *et al*., 2022).

The early twenty-first century marked a shift toward plant-based meat analogues explicitly designed to appeal to mainstream consumers. Products were marketed not primarily to vegetarians but to flexitarians and omnivores seeking to reduce meat consumption without abandoning familiar dishes. Branding strategies emphasized similarity to meat, convenience, and alignment with sustainability goal (Arora *et al*., 2023). As a result, plant-based burgers, sausages, and mince alternatives gained substantial market visibility, moving from niche health stores to major supermarket chains worldwide (Boukid, 2021).

Cultured meat represents a more radical departure from conventional food production. Situated within the field of cellular agriculture, cultured meat involves the cultivation of animal cells in controlled environments to produce edible muscle and fat tissue (Reiss, Robertson and Suzuki, 2021; Mattick, 2018; Post *et al*., 2020).

Despite its technological promise, cultured meat remains at an early stage of market introduction. Regulatory approval has been granted in only a limited number of jurisdictions, notably Singapore,

reflecting ongoing uncertainty regarding safety assessment, labeling, and public acceptance (Bakhsh *et al.*, 2025). Compared with plant-based meat analogues, cultured meat challenges deeply held assumptions about food production, raising distinctive questions about naturalness, ethics, and trust (Bryant, 2020).

The expansion of plant-based diets has coincided with the rapid growth of companies such as Beyond Meat, Impossible Foods, and GOOD Meat. These firms have responded to rising consumer concerns about health, sustainability, and animal welfare by developing meat alternatives that closely resemble conventional products. Their success has helped normalize plant-based and cultivated meats within mainstream food markets, signaling a broader shift in consumer protein preferences (Ali and Bharali, 2025). At the same time, similar companies have been observing recent decline in revenue due to factors such as loss of consumer trust.

33.3 Trends in Hybrid Proteins and Their Acceptance in Relation to Consumer Needs

The alternative protein sector continues to evolve, with several emerging trends shaping its future trajectory. One notable development is the rise of hybrid protein products that combine plant-based ingredients with animal-derived components or cultured cells (Kaplan and McClements, 2025). These products aim to reduce the environmental footprint of meat while retaining sensory characteristics associated with conventional animal products (Alam *et al.*, 2024). Hybrid approaches may be particularly attractive to consumers who seek incremental dietary change rather than complete substitution.

Consumers choose to reduce meat consumption, and their acceptance of hybrid proteins has been noted due to their importance of balanced diet. The study from Raptou *et al.* (2024) indicated that Gen Z perception is that meat has better quality than other sources, although many reported about plant proteins, specifically from proteins nuts (see Figure 33.1).

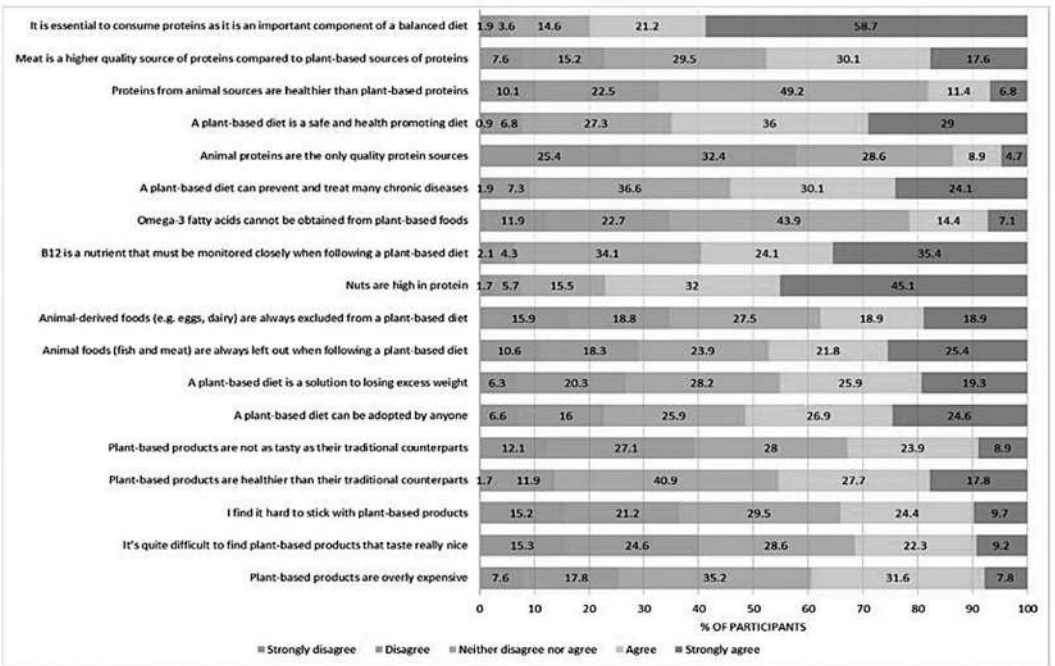

FIGURE 33.1 Distribution of participants' responses (%) to statements assessing knowledge, beliefs, and perceptions about protein quality, healthfulness, affordability, and acceptability of plant-based diets and products. Responses are shown on a 5-point Likert scale ranging from strongly disagree to strongly agree. (Reproduced from Raptou *et al.*, 2024, under the Creative Commons Attribution [CC BY 4.0] license.)

Hybrid products can also serve as transitional foods, lowering psychological and cultural barriers to reduced meat consumption (Hassoun *et al.*, 2022). By maintaining familiar taste profiles and culinary functionality, they may broaden appeal among consumers who are skeptical of fully plant-based alternatives. From an industry perspective, hybrid products may also offer greater flexibility in managing cost, supply stability, and sensory quality (Kaplan and McClements, 2025). Despite these anticipated benefits, hybrid products that incorporate plant proteins from legumes such as beans and peas are associated with noticeable sensory differences, particularly the release of off-flavors, which may limit consumer acceptance (Lara and Tsiami, 2024).

Another significant trend is the growing interest in personalized nutrition. Advances in nutritional science, digital health technologies, and consumer data analytics have increased attention to dietary individualization based on age, health status, lifestyle, and physiological needs (Ordovas *et al.*, 2018). Alternative proteins offer considerable formulation flexibility, enabling adjustments to amino acid composition, lipid profiles, fiber content, and micronutrient fortification. This adaptability may enhance relevance for specific population groups, including older adults, athletes, and individuals managing chronic disease (Ulhas *et al.*, 2023).

The food environment plays a critical role in shaping consumer acceptance. Retail placement strategies influence visibility, legitimacy, and perceived normality (De Koning *et al.*, 2020). Alternative meats positioned alongside conventional meat products may be perceived as more mainstream than those confined to specialized vegetarian sections. Price promotions, product sampling, and clear on-pack information further shape purchasing decisions (Alae-Carew *et al.*, 2022).

Hospitality settings represent both an opportunity and a challenge. Restaurants, workplace canteens, and institutional food services can normalize alternative proteins through menu integration and culinary creativity, following the nudging approach (Volgger *et al.*, 2026). However, food service operators face constraints related to cost, supply consistency, preparation methods, and consumer expectations. Sensory performance and reliability are particularly critical in these contexts and frequency of visits to specific restaurants is an important parameter to normalize use (Cai *et al.*, 2021).

33.4 Factors Affecting Openness to Meat Analogues and Plant-Based Meats

Consumer openness to alternative meats is a multidimensional process that extends beyond willingness to try a product. It encompasses awareness, initial trial, repeat consumption, and longer-term dietary integration within everyday food practices. Understanding openness, therefore, requires attention not only to individual attitudes, but also to the demographic, social, cultural, and structural conditions that shape how meat analogues and cultured meat are perceived, evaluated, and incorporated into daily life (Stubelj *et al.*, 2025).

Empirical research consistently demonstrates higher levels of openness toward plant-based meat analogues than toward cultured meat. This difference is largely attributed to variations in familiarity, perceived risk, and technological novelty, with plant-based products generally viewed as extensions of existing food technologies, while cultured meat is often perceived as more radical and uncertain (Lewisch and Riefler, 2023). These distinctions influence consumer expectations regarding safety, naturalness, and legitimacy, and help explain divergent acceptance trajectories for different categories of alternative proteins (Ungaro *et al.*, 2025).

Drivers of openness commonly include environmental concern, interest in reducing animal suffering, perceived health benefits, and curiosity about food innovation. Consumers who already incorporate plant-based foods into their diets are more likely to try meat analogues, suggesting that familiarity reduces uncertainty and perceived behavioral costs associated with dietary change (Ueland, Rødbotten and Varela, 2022). However, willingness to try does not necessarily translate into sustained consumption. Repeated adoption depends strongly on sensory satisfaction, price parity, convenience, and culinary compatibility. Products that fail to meet taste expectations or require unfamiliar preparation practices frequently remain occasional novelties rather than becoming embedded in routine diets (Amoneit, Gellrich and Weckowska, 2025). Consumers resist to adopt insect proteins despite high awareness—86% recognizing insects as nutritious and 58% linking them to sustainability—only 18.6% reported prior

consumption (Willeke, Tsiami and Lara, 2025). This awareness–behavior gap is substantially larger than that observed for other sustainable protein alternatives, such as pea-based meat substitutes, which have achieved wider consumer acceptance (Willeke, Tsiami and Lara, 2025).

At the same time, several barriers constrain openness to alternative meats. Perceptions of unnaturalness, particularly in relation to cultured meat, concerns about food safety, and skepticism toward highly processed products, are among the most frequently reported sources of resistance (Giacalone, Clausen and Jaeger, 2022). These concerns are often intensified by media narratives, misinformation, and polarized public debate, reinforcing uncertainty and distrust. As a result, credible communication, transparent information provision, and sensitivity to consumer values play a central role in shaping acceptance.

33.4.1 Demographic and Psychographic Segmentation

Demographic segmentation highlights population-level regularities in openness to meat analogues and cultured meat, while psychographic segmentation explains the mechanisms through which acceptance and resistance emerge (Abdul Kareem, Nicholles and Bryant, 2025). Moral and ethical considerations are embedded within psychographic dimensions, shaping how consumers interpret the legitimacy, desirability, and appropriateness of alternative protein products. Together, these perspectives demonstrate that consumer openness is socially patterned rather than purely individual.

Age remains one of the most consistent predictors of acceptance. Younger consumers generally display higher openness to plant-based meat analogues and cultured meat, a pattern associated with greater exposure to sustainability discourses, familiarity with technological innovation, and normative support for dietary change (Van Loo *et al.*, 2020; Verbeke *et al.*, 2015; Zhao *et al.*, 2023). While younger individuals are more likely to associate alternative proteins with environmental mitigation and animal welfare benefits, older consumers tend to emphasize concerns related to unnaturalness, food safety, and distrust in novel production processes (Siegrist, Sütterlin and Hartmann, 2018; Weinrich, Strack and Neugebauer, 2020).

Raptou *et al.* (2024) examined Generation Z's willingness to adopt plant-based diets among university students in Greece, India, and the UK, identifying clear attitudinal segmentation within this cohort (Table 33.1). The findings indicate that Gen Z individuals, who hold positive attitudes toward plant-based diets perceive them as healthy, and feel confident in their nutritional adequacy, particularly protein

TABLE 33.1

Summary of Key Findings on Gen Z Willingness to Adopt Plant-Based Proteins

Parameters	Key Finding	Implication for Plant-Based Protein Adoption
Consumer segments	*Two main groups identified*: proponents and opponents of plant-based diets	Gen Z is not homogeneous Targeted strategies are required
Attitudes	Positive attitudes toward plant-based diets significantly increased willingness	Attitude change is central to increasing uptake
Perceived health benefits	Belief that plant-based diets are healthy predicted adoption	Health framing is a strong motivator
Protein adequacy perceptions	Confidence in plant protein sufficiency increased willingness	Protein concerns remain a critical barrier
Lifestyle behaviors	Higher cooking involvement and healthy lifestyle behaviors increased openness	Skills-based and practical interventions may support adoption
Meat attachment	Strong attachment to animal-based proteins reduced willingness	Habitual meat consumption limits behavioral change
Sensory and familiarity concerns	Taste and unfamiliarity acted as barriers	Product development and exposure are essential
Cross-country comparison	Determinants of willingness were consistent across Greece, India, and the UK	Psychographic factors outweigh cultural differences

Source: Adapted from Raptou *et al.*, 2024.

sufficiency, demonstrate significantly higher willingness to adopt plant-based proteins. Engagement in food preparation, greater self-reported knowledge of healthy eating, and active lifestyle behaviors further increased openness to adoption. In contrast, strong attachment to animal-based foods, concerns about taste and familiarity, and doubts regarding protein adequacy emerged as key barriers. Notably, these determinants were consistent across all three countries, suggesting that psychographic and lifestyle factors play a more decisive role than national context in shaping Gen Z's acceptance of plant-based proteins.

Gender differences are similarly robust. Women consistently report greater willingness to reduce meat consumption and higher openness to alternative proteins, often driven by ethical concern for animals, environmental sustainability, and health considerations (Keller and Siegrist, 2015; Love and Sulikowski, 2018). Men, by contrast, tend to demonstrate stronger attachment to meat-centered diets, with meat consumption often linked to masculinity and social identity, contributing to resistance toward alternatives perceived as identity-incongruent (Keller and Siegrist, 2015; Love and Sulikowski, 2018; Verbeke *et al.*, 2015).

Socioeconomic status, encompassing income and education, further shapes openness through material and cognitive pathways. Higher income consumers are more likely to try and regularly consume plant-based alternative foods, reflecting reduced sensitivity to price premiums and greater access to novel products (Alae-Carew *et al.*, 2022). Education level is strongly associated with acceptance, as individuals with higher educational attainment tend to demonstrate greater trust in science, higher food literacy, and stronger alignment with ethical and environmental narratives surrounding alternative proteins (Verbeke *et al.*, 2015; Weinrich, Strack and Neugebauer, 2020). Experimental research indicates that information provision and framing can influence acceptance of cultured meat, with effects depending on message content and audience characteristics (Bryant and Dillard, 2019; Rolland, Markus and Post, 2020).

Religion represents an additional demographic dimension shaping openness through its influence on dietary norms, moral frameworks, and trust in food systems. Religious affiliations structure everyday food practices and often include explicit rules, taboos, and rituals related to meat consumption (Leroy and Praet, 2015; Sabaté, 2004). These prescriptions can either facilitate or constrain acceptance of alternative proteins, depending on how plant-based or cultured meat is interpreted in relation to religious doctrine. Beyond dietary rules, religion can also shape values, beliefs, and community belonging in ways that influence consumer judgment of novel foods (Mokhlis, 2009).

While demographic variables identify systematic differences across populations, psychographic segmentation provides deeper insight into how openness is constructed. Lifestyle habits, particularly dietary routines and food-related practices, strongly condition acceptance. Consumers who already follow flexitarian, vegetarian, or health-oriented lifestyles tend to perceive plant-based meat analogues as compatible with everyday routines, reducing perceived behavioral costs. In contrast, consumers whose lifestyles are organized around traditional meat-centered meals often perceive alternative proteins as disruptive or impractical (Żakowska-Biemans, 2025).

Moral values and ethical orientations constitute a central psychographic dimension shaping openness. Ethical concern for animal welfare, environmental protection, and broader societal responsibility is frequently cited as a motivation for interest in alternative proteins. For many consumers, reducing meat consumption or choosing meat analogues is interpreted as a morally meaningful practice aligned with universalistic values and ethical self-concept (Lewisch and Riefler, 2023). At the same time, ethical skepticism persists among other consumers, particularly in relation to perceptions of unnaturalness, distrust in scientific innovation, and concerns about food safety (Bryant and Barnett, 2020; Kantono *et al.*, 2022; Siegrist, Sütterlin and Hartmann, 2018).

Ethical considerations also influence consumer responses to marketing, labeling, and product positioning. Plant-based meat analogues designed to closely resemble conventional meat have attracted criticism regarding the ethical legitimacy of meat-related terminology. While some consumers interpret such terminology as misleading, others view it as a functional descriptor of culinary use rather than animal origin (Kołodziejczak *et al.*, 2021; Marshall, Bano and Banas, 2022). These divergent interpretations shape trust and acceptance and contribute to polarized responses within the same consumer segments.

Individual psychological traits further moderate openness. Innovativeness and openness to experience are positively associated with acceptance of cultured meat, whereas food neophobia and disgust

sensitivity represent strong barriers, particularly when attention is directed toward production processes rather than end products (Siegrist, Sütterlin and Hartmann, 2018; Wilks *et al.*, 2019). These traits help explain divergent responses among consumers with similar demographic profiles.

Finally, social class and symbolic capital shape how ethical food choices are interpreted. Meat consumption has historically functioned as a marker of economic power and social status, reflecting access to resources and cultural legitimacy. The societal centrality of meat has been linked to the economic, cultural, and symbolic capital represented by its consumption (Leroy and Praet, 2015). Within some social groups, reducing meat or adopting alternative proteins has become a form of distinction, signaling ethical awareness and cultural competence. In others, it challenges deeply embedded associations between meat, tradition, and social identity.

Taken together, demographic and psychographic segmentation demonstrates that openness to meat analogues and cultured meat is shaped by an interplay of social position, lifestyle, values, and ethical interpretation. Acceptance is therefore embedded within broader systems of meaning rather than driven solely by rational evaluation of product attributes.

33.4.2 Interactional Dynamics and Peer Influence in Alternative Meat Adoption

Openness to meat analogues and cultured meat is also shaped by social influence operating within everyday interactional contexts. Social norms provide informational cues about appropriate behavior by signaling what others do and what is socially approved (White *et al.*, 2009). In situations characterized by uncertainty, such as the introduction of novel food technologies, these cues can become especially influential, because consumers may treat the perceived behavior of relevant others as a proxy for safety, legitimacy, and social acceptability (Onwezen, Antonides and Bartels, 2013).

In practice, peer influence can function as both a barrier and a facilitator. Anticipated disapproval from family members or close social contacts may discourage individuals from trying alternative protein products, even when their personal attitudes are favorable. Conversely, visible adoption within social networks can reduce perceived risk and support normalization, particularly in shared eating contexts such as households, workplaces, educational settings, and hospitality environments. These social processes interact with other acceptance drivers, including trust in institutions, perceived naturalness, and sensory experience, influencing whether alternative meats remain occasional novelties or become integrated into routine dietary practices.

33.4.3 Cultural Contexts: Sensitivity and Traditions

Cultural contexts surrounding the consumption of plant-based foods and meat alternatives are highly diverse. In some regions, the avoidance of animal-derived proteins is culturally normative or widely accepted, while in others it may be viewed as socially or culturally inappropriate. High levels of meat consumption are deeply embedded in certain food cultures, such as those found in parts of sub-Saharan Africa and Scandinavia, whereas moderation in meat intake is more characteristic of dietary traditions in the Mediterranean basin (Sans and Combris, 2015; FAOSTAT, n.d.). Figure 33.2 underpins some of the common drivers of consumer behavior with psychological, social, and cultural aspects being of prime concern to the acceptance of new foods.

This diversity in food cultures, consumption habits, and foodways can function both as a barrier to and a facilitator of the adoption of novel meat-like products. Acceptance is more likely when innovations are introduced in ways that respect existing food traditions and cultural sensitivities (Alcorta *et al.*, 2021).

33.4.4 Sensory Experience and Sensory Limitations

Beyond cultural considerations, sensory and organoleptic properties represent a key arena in which traditional meat products and meat analogues are compared (Giacalone, Clausen and Jaeger, 2022). Manufacturers of plant-based meat analogues have sought to replicate the physicochemical properties of meat, including appearance, flavor, aroma, texture, mouthfeel, and cookability (Lewisch and Riefler, 2023).

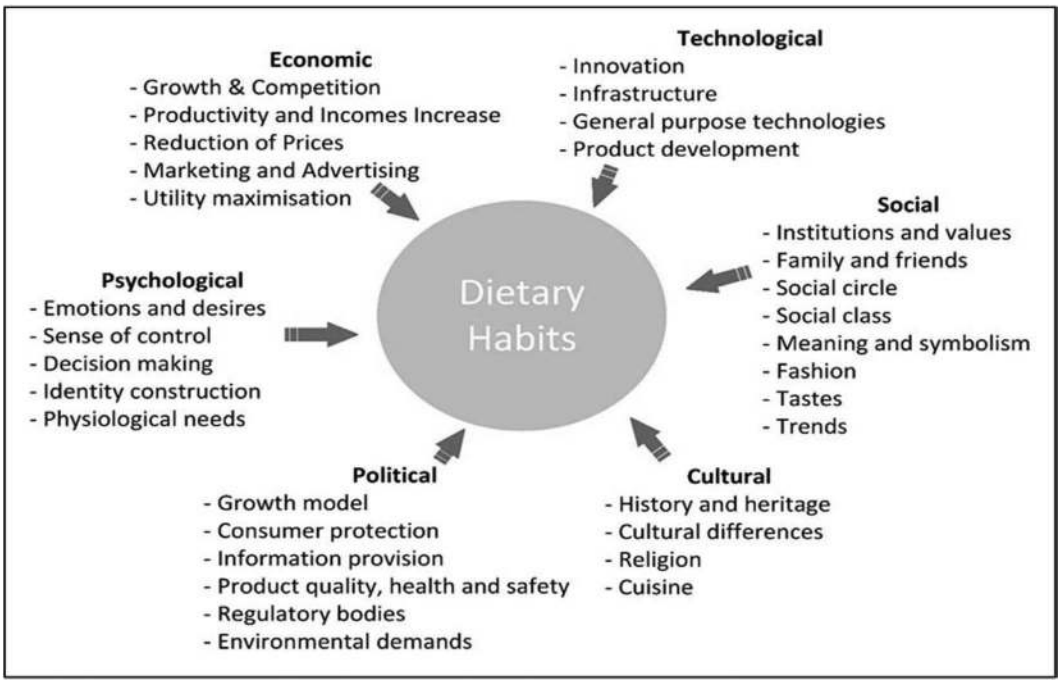

FIGURE 33.2 Diverse factors affecting consumer dietary behavior. (Adapted from Capone *et al.*, 2014.)

Nevertheless, meat analogues, particularly those derived from modified plant proteins, often exhibit unfamiliar textural or flavor profiles. While these products may closely resemble minced meat formats, detectable sensory differences are frequently identified by consumers, especially those with limited prior exposure. Such differences can discourage repeated consumption and limit broader adoption (Collier *et al.*, 2025). Although plant-based meat analogues may be more readily accepted in processed or composite products such as ready meals, their integration into food service environments, including restaurants, continues to present additional challenges (Juhrich *et al.*, 2025).

33.5 Trust, Consumer Confidence, and Transparent Regulation

Trust is a central determinant of consumer confidence in meat analogues and, in particular, cultured meat. Because these products rely on production processes that are technologically complex and largely invisible to consumers, acceptance is shaped less by direct sensory experience and more by perceptions of institutional competence, integrity, and transparency (Escobar *et al.*, 2025). Under such conditions, trust functions as a cognitive and social heuristic that enables consumers to evaluate risks and benefits in the absence of detailed technical knowledge.

Empirical research shows that distrust in scientists and biotechnology can reduce willingness to try cultured meat, although these effects vary across national contexts. Studies conducted in Austria and South Korea indicate that distrust in scientists and negative perceptions of biotechnology are associated with lower acceptance of cultured meat, whereas similar relationships are not consistently observed in the United States, where behavioral intentions appear less sensitive to such concerns (Hwang, 2020; Lewisch and Riefler, 2023; Wilks *et al.*, 2019). These differences suggest that trust operates in a context-dependent manner, shaped by cultural norms, political orientations, and historical relationships with scientific and regulatory institutions. Alternatively, Escobar *et al.* (2025) found marked cross-cultural differences in consumer acceptance of cultured meat in Belgium, Chile, and China. Acceptance was highest in China, where trust in science and regulation strongly influenced willingness to consume

cultured meat. Across all countries, perceived environmental and food security benefits supported acceptance, while concerns about unnaturalness and safety reduced it. The study demonstrates that attitudes toward cultured meat are culturally shaped, highlighting the need for context-specific communication and policy approaches.

Analyses of negative attitudes and intentions toward cultured meat further identify food neophobia, political conservatism, and distrust of food scientists as among the most powerful predictors of resistance (Wilks *et al*., 2019). Food neophobia and disgust sensitivity are well-established barriers to the acceptance of novel food technologies, including genetically modified foods and other unfamiliar products (Siegrist, 2008; Tuorila and Hartmann, 2020). When such affective responses intersect with skepticism toward scientific expertise or perceptions of excessive technological intervention in food systems, consumer confidence may be substantially undermined.

Trust is not a singular or undifferentiated construct. Research on risk perception demonstrates that how trust is conceptualized and measured has a significant influence on its explanatory power (Earle, 2010). General trust in science may be less predictive of acceptance of cultured meat than trust directed toward specific actors, such as food scientists, the food industry, or regulatory authorities. Evidence suggests that while general distrust in science does not always predict rejection of cultured meat, distrust of food scientists specifically is strongly associated with negative attitudes (Wilks *et al*., 2019). This distinction highlights that consumers differentiate between abstract confidence in scientific progress and trust in the actors responsible for developing, regulating, and commercializing novel foods.

Trust becomes especially salient under conditions of uncertainty. When consumers lack the knowledge required to independently assess a food technology, they may rely on the assessments of others, using trust to determine which sources of information are credible (Siegrist and Cvetkovich, 2000). Studies from related technological domains show that consumers who trust the food industry are more likely to accept foods and food packaging produced using nanotechnology, even when their personal understanding of the technology is limited (Siegrist *et al*., 2007). These dynamics are directly relevant to cultured meat and advanced meat analogues, where production processes are distant from everyday consumer experience.

Within this context, transparent regulation plays a critical role in shaping consumer confidence. Regulatory frameworks serve not only as mechanisms for ensuring food safety, but also as symbolic signals of oversight, accountability, and procedural fairness. Clear approval pathways, robust safety assessments, and consistent regulatory communication can reduce perceived risk and support trust, particularly among consumers who are otherwise skeptical of novel food technologies. Conversely, regulatory ambiguity or inconsistency may reinforce distrust and heighten perceptions of risk.

Marketing and labeling practices operate at the interface between regulation and consumer perception and therefore play a pivotal role in mediating trust. Food labeling schemes have been widely advocated as tools for communicating unobservable or credence attributes, enabling more informed consumer choices in contexts where direct evaluation is not possible (Ardeshiri and Rose, 2018; Van Loo *et al*., 2014). In the context of meat and alternative proteins, labeling can communicate information related to production methods, sustainability credentials, and ethical attributes that are otherwise inaccessible to consumers.

The concept of consumer empowerment is particularly relevant in this regard. Within meat consumption, empowerment encompasses both meat eaters who seek to purchase more sustainable products and meat reducers who aim to consume less but better meat (Apostolidis and McLeay, 2016; de Bakker and Dagevos, 2012). At the same time, a growing group of meat anti-consumers abstain from consuming meat or specific meat products altogether (Armstrong Soule and Sekhon, 2019). In several countries, including the United Kingdom, an increasing number of consumers are reducing meat consumption or adopting vegetarian or vegan diets, reflecting broader shifts in ethical concern, health orientation, and environmental awareness (Rosenfeld, 2019).

Product labeling can support these diverse consumer strategies by communicating credence attributes that individuals consider important, such as sustainability, ethical production, or technological processes. When aligned with regulatory standards and perceived as transparent and credible, labeling may reinforce trust and facilitate informed choice. However, when marketing or labeling practices are perceived as strategically ambiguous or misleading, they may undermine confidence and intensify ethical skepticism, particularly for highly novel products such as cultured meat.

From a policy perspective, these dynamics underline that trust and consumer confidence are shaped through the combined effects of regulation, marketing, and communication. Regulatory oversight alone is insufficient if it is not accompanied by labeling and marketing practices that consumers perceive as honest and informative. Conversely, even well-designed labeling schemes may fail to build trust in the absence of credible regulatory governance. Coordinated approaches that align regulatory design, marketing standards, and transparent communication are therefore essential for supporting informed acceptance of alternative proteins.

Taken together, trust in meat analogues and cultured meat emerges from a complex interaction between psychological dispositions, trust in specific institutional actors, and the regulatory and communicative environments in which these products are introduced. Recognizing trust as a differentiated and context-sensitive construct provides a foundation for the policy and industry implications discussed in the final section of this chapter, particularly with respect to governance, consumer communication, and market development.

33.6 Implications for Policymakers, Industry, and Public and Private Sectors

The preceding analysis demonstrates that consumer acceptance of meat analogues and cultured meat is shaped not only by product attributes, but also by broader systems of trust, regulation, and communication. These dynamics have important implications for policymakers, industry actors, and public and private institutions involved in the governance, production, and promotion of alternative proteins.

From a policy perspective, trust emerges as a foundational condition for acceptance. Evidence indicates that distrust in science and scientific institutions can be associated with lower willingness to try cultured meat in some contexts, and that distrust directed specifically toward food scientists is linked to negative attitudes (Wilks *et al.*, 2019). Policymakers, therefore, face the challenge of designing governance frameworks that not only ensure food safety, but also actively signal institutional competence, independence, and transparency. Regulatory processes that are perceived as opaque or overly politicized risk reinforcing skepticism rather than alleviating it. Finding of Donato (2024) is that political decision-making around meat-substitute denominations in the European Parliament is driven more by political compromise and stakeholder power than by consumer evidence or popularity. Specifically, the study shows that debates over whether plant-based products can use terms such as *burger*, *sausage*, or *steak* were not primarily informed by evidence of consumer confusion, which research consistently finds to be low. Instead, decisions reflected competing economic interests, particularly pressure from conventional livestock and agricultural lobbies, alongside concerns about cultural tradition and rural livelihoods within the European Parliament.

Public institutions have a particularly important role to play in this regard. When information about novel food technologies is provided by actors perceived as independent and oriented toward public interest, such as public health authorities or regulatory agencies, trust is more likely to be established. This highlights the importance of separating regulatory communication from commercial promotion and ensuring that public-facing information is framed as educational rather than persuasive.

Variation across national contexts further underscores the need for policy approaches that are sensitive to institutional trust landscapes. Differences between countries in baseline trust and in the perceived credibility of information sources imply that strategies effective in one jurisdiction may not translate directly to another. Policymakers should therefore avoid one-size-fits-all approaches and instead tailor governance and communication strategies to national and cultural contexts.

For industry actors, these findings imply that market success depends not only on innovation and product quality, but also on alignment with trusted institutional frameworks. Industry communication that bypasses or contradicts regulatory guidance may undermine consumer confidence, particularly for highly novel products such as cultured meat. Collaboration with regulatory bodies, public health institutions, and independent experts can help reinforce credibility and reduce perceptions of self-interest. Industry actors should therefore view transparent engagement with governance structures not as a constraint, but as a strategic asset for long-term market development.

Marketing and labeling practices also carry significant implications for both public and private sectors. As discussed in the previous section, labeling functions as a key interface between regulation and consumer interpretation. Clear, standardized, and enforceable labeling requirements can support informed choice and reduce confusion, while inconsistent or ambiguous practices may exacerbate skepticism. Policymakers and regulators should ensure that labeling frameworks are designed to communicate credence attributes effectively, without overstating benefits or obscuring production processes. For industry, adherence to such standards can support trust and mitigate reputational risk.

Public and private sector collaboration is particularly important in addressing consumer uncertainty associated with novel food technologies. Joint initiatives involving regulators, public health bodies, and industry can facilitate coherent communication and avoid contradictory messaging. Such coordination is likely to be especially important during early market introduction phases, when consumers rely heavily on external cues to form judgments about safety and legitimacy.

Finally, the findings suggest that efforts to promote acceptance of meat analogues and cultured meat should focus less on persuasion and more on enabling informed evaluation. Trust is more likely to develop when consumers perceive that they are being provided with balanced, transparent information rather than targeted marketing messages. Policymakers and industry actors alike should therefore prioritize openness, clarity, and responsiveness to public concerns.

Taken together, these implications indicate that the successful integration of alternative proteins into food systems depends on coordinated action across governance, industry, and public institutions. Building and maintaining trust requires transparent regulation, credible information sources, and responsible marketing and labeling practices. Without such alignment, technological innovation alone is unlikely to translate into sustained consumer acceptance.

33.7 Conclusion

Future consumer trends indicate that plant-based and cultured meat will increasingly move from niche alternatives to mainstream food choices. Normalization through retail, hospitality, and institutional settings is expected to reduce novelty and increase everyday acceptance, while the growth of hybrid protein products may support gradual dietary transitions among flexitarian consumers. Sensory quality, particularly taste, texture, and cooking performance, will remain central to sustained adoption, alongside transparent regulation and trusted certification to build consumer confidence. Importantly, culturally sensitive communication and culinary innovation will shape how these products are integrated into diverse food traditions. Collectively, these trends suggest that long-term success will depend less on ethical positioning alone and more on delivering familiarity, trust, and high-quality eating experiences.

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34

Case Study: Engineering Aspects of Meat Products and Equipment

Abeera Moin and Shahzad Umer Sama

34.1 Introduction

A variety of meat such as bovine, goat, poultry, and aquatic are consumed by human beings with varying preferences (Font-i-Furnols and Guerrero, 2025). The meat is either available fresh, cured, fermented, ready-to-eat, frozen convenience food, and coated products. Each type of meat is processed before it reaches the plate of a consumer. From carcass chilling and deboning to high-value portion cutting, trimming, comminution, emulsification, cooking, and packaging, each meat processing step is underpinned by engineering. Moreover, behind every product attribute such as bite of a nugget, juiciness of a stake, and texture of a sausage, there are engineering principles at work. For instance, the mechanical processing systems determines particle size, shear forces, and structural development while thermal processing determines microbiological lethality and moisture content of meat products. Furthermore, fluid dynamics influences batter adhesion and cleaning in place (CIP) efficiency of processing equipment. Whereas, the oxidative stability of meat and its shelf life are governed by packaging engineering. These operations are carefully integrated to ensure a consistent product, microbiological safety, and economic efficiency.

The goals of a food processor include yield maximization, safety maintenance, consistency and efficiency improvement, extended shelf life, waste reduction, and energy consumption optimization (Alam *et al.*, 2025). To successfully achieve these goals, it is critical to understand the linkage between equipment, engineering principles, product attributes, and safety controls. Therefore, this chapter approaches meat processing as a multidisciplinary engineering system, highlighting how thoughtful equipment selection, process optimization, and hygiene considerations could contribute to the production of safer, high-quality, and economically feasible meat products. Moreover, by positioning nuggets as a model system, this chapter aims to provide transferable engineering insights which are applicable to a broad category of processed meat products, including patties, formed meat portions, and emulsified meat products such as sausages, bologna, and frankfurters etc.

34.2 From Slaughter Room to Primal Cuts

The primary processing of meat occurs in the slaughter house and comprises a series of unit operations that convert a dressed carcass into primal or subprimal cuts, which are suitable for retail or further processing (Figure 34.1). It refers to various stages: animal handling, stunning, bleeding, hides or feathers removal, evisceration, carcass splitting, washing, trimming, and chilling (Matarneh *et al.*, 2017). From an engineering perspective, the primary processing represents the first point at which the biological variability is translated into a controlled industrial system. Notably, the primary processing of ruminants, birds, and fish differs. The equipment used at this stage are stunning devices, scalders, defeathering machines, evisceration tools, and chilling systems. These equipment are designed to achieve repeatable

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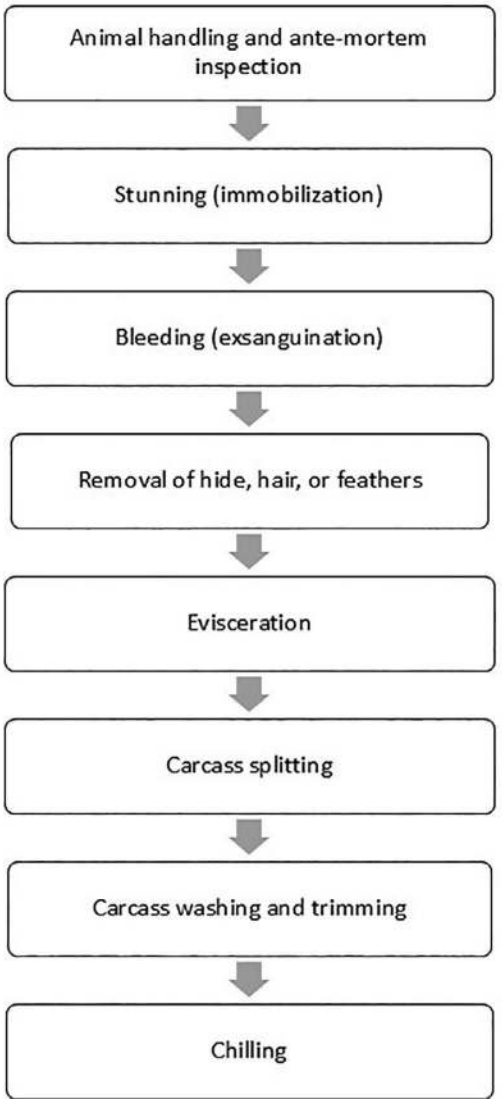

FIGURE 34.1 Meat primary processing.

outcomes under high-throughput conditions while minimizing the physical damage and microbial contamination. The performance of these systems directly influences carcass integrity, temperature control, and surface contamination levels with fecal material, stomach and gut content, bile, hairs, feathers, and blood. Therefore, primary processing is critical not only for humane and regulatory compliance but also for downstream meat quality and microbiological safety. Inadequate bleeding, improper evisceration, or ineffective chilling could lead to elevated microbial load, compromised shelf life, and reduced functional performance of muscle proteins during secondary processing. For instance, in comminuted meat products, such inadequacies can cause inconsistent texture and increased safety risk during further processing.

The primary operations also form the foundation of food safety management systems implemented downstream. The control measures established during slaughter and carcass handling such as hygiene equipment design, controlled product flow, and rapid chilling can reduce the hazard burden entering the secondary processing lines and enhance the overall robustness of meat production system.

34.3 Cross-Cutting Engineering Considerations in Processed Meat Manufacturing

34.3.1 Raw Material Variability and Engineering Implications

Meat is a biologically variable raw material and its inherent heterogeneity presents a fundamental engineering and automation challenge in industrial processing (Olaniyi and Kucha, 2025). For instance, poultry muscle differs in composition depending on anatomical location, age of bird, feeding regime, and postmortem handling (Ayaz *et al*., 2024;Goraya *et al*., 2025). Variations in moisture, fat, and connective tissues content present in the different muscles of same bird are also observed (Ali *et al*., 2025). The variability directly affects the grinding behavior, protein extraction efficiency, lipid oxidative stability, water-binding capacity, and final product texture as extensively reported in meat science literature.

From an engineering perspective, processing equipment and operating conditions are designed to accommodate the biological variability of meat. For instance, grinders, mixers, and formers must operate reliably across a range of raw materials characteristics without affecting the yield or required end product. Moreover, the temperature control system during handling and comminution is particularly critical (Sun *et al*., 2022). The elevated temperatures can accelerate denaturation of protein and fat smearing, thereby impacting functional performance (Hernández and Mojica, 2025; Hugo and Roodt, 2007). Hence, the management of raw materials is both quality and engineering constrain that dictates the robustness and consistency of a process.

34.3.2 Particle Size Reduction and Structural Development

Particle size reduction is a fundamental process in meat processing and a defining operation in comminuted meat products. It converts raw materials into specific shapes and particle sizes to facilitate downstream processes and meet diverse product requirements. The mincing and chopping operations subject muscle tissues to mechanical shear and compression, leading to extraction of soluble myofibril proteins. These proteins act as a functional binder within the meat system (Witte *et al*., 2022). Studies on mechanically minced meat indicate that progressive particle size reduction is associated with increased fragmentation of muscle fiber and connective tissues resulting a homogeneous meat matrix with improved structural integration. The structural refinement enhances cohesion and binding capacity which are critical for the formation and stability of restructured meat products such as nuggets, meatballs, patties, and sausages. However, the control of particle size is critical because intensive mechanical input adversely affect meat structure, reflecting over disruption of meat tissue (Kabulov *et al*., 2019). Moreover, excessive mechanical energy input can lead to undesirable temperature rise which consequently damages proteins while insufficient comminution could lead to poor binding property of meat and structural weakness. Some studies show change in color due to variation in minced size. The increased surface exposure of finer mince accelerates myoglobin oxidation leading to darker color, while course ground retain lighter color (Abdul *et al*., 2025). Therefore, selection of comminution equipment such as saw blades and knives and the number of fringes on each blade, balanced mechanical energy, and thermal control are critical for size reduction of meat.

Previously, cutting methods relied extensively on manual labor workforce posing many challenges: hygiene, safety, precision, skilled labor recruitment, training etc. Now, the emergence of intelligent cutting systems employing artificial intelligence (AI), computer vision system (CVS), and robotics to automate the unit operation offers a promising solution to address these limitations (Sun *et al*., 2025).

34.3.3 Thermal Sensitivity and Cold Chain

The meat proteins are thermally sensitive and even moderate temperature increment during mechanical processing can alter their functional properties. For instance, Tornberg (2005) reported that sarcoplasmic proteins aggregate at 40–60 °C, myofibrillar proteins unfolding begins at 30–32 °C, and collagen denatures at 53–63 °C. Heat generated through friction in grinders, choppers, homogenizers, and mixers

poses a significant processing challenge, particularly in high-throughput industrial systems. Therefore, cold chain is integral to processed meat manufacturing so that raw materials and intermediate products remain within safe temperature ranges that preserve protein functionality and inhibit microbial growth. Chilled processing rooms, controlled defrosting stations, precooled raw materials, and equipment design that minimize frictional heating can help mitigating the challenges arising from thermal sensitivity of meat. Furthermore, intelligent time–temperature indicators are developed that report real-time temperature profiling based on molecular and color changes (Yar *et al*., 2025).

34.3.4 Hygiene and Sanitary Design

Hygienic design and maintaining hygienic environment in meat processing serves as the foundation for quality enhancement, food safety, and effective microbiological, chemical, and physical risk management (Synytsia *et al*., 2025). The hygiene design applies to both equipment and processing area. The hygienically designed gear maintains sanitary conditions during the processing. The examples include smooth surfaces, hygienic welds, and drainable geometries to ensure effective cleaning and sanitation. The systemic measures to apply hygienic design for equipment and food processing plant include good hygienic practices for food handlers, cleaning and sanitization, integrated pest management system, waste disposal mechanism, chemical and microbial hazard assessment, proper floor drainage to prevent water ponding in processing area, maintenance, etc. Pakdel *et al*. (2025) studied integration of hygiene design and sustainability and reported that conveyor belts, motors, and deboning machines are the most mentioned and discussed equipment with respect to hygienic design in Norwegian meat processing facilities. Furthermore, CIP and pulsed flow are also introduced for cleaning and sanitization of processing units. These processes employ the principles of fluid dynamics, chemical action, and automated control (Silva *et al*., 2023).

34.3.5 Process Flow of Nuggets Manufacturing Operations

A nugget is a meat-based reconstituted, battered, and breaded product, manufactured with minced meat (Mazumder *et al*., 2024). Unlike whole muscle products, the texture and quality attributes of nuggets are engineered through mechanical and thermal processes rather than anatomy of muscle. The generic nugget production system beings with chilled boneless meat that is subjected to size reduction and mixing to create a homogeneous meat matrix (Figure 34.2). The homogenized minced mass is then shaped using mechanical forming equipment for consistent and uniform portions. Afterward, the shaped units undergo sequential battering and breading, which apply liquid and coatings that contribute to texture, appearance, and final product yield. Then, thermal processing is typically applied through pre-frying or full-cooking steps. It is designed to stabilize the finished product texture and microbiological safety. Subsequent freezing and storage at cold temperature preserves quality and extend shelf life by reducing biochemical and microbial activities. Lastly, the nuggets are packed using systems that limit oxygen exposure and protect against physical and microbial contamination during distribution and storage. Each step of this process flow represents a discrete unit operation governed by engineering principles related to mass transfer, heat transfer, fluid mechanics, and material science.

34.3.6 Nugget Manufacturing Operations

Mincing and mixing unit operations form the foundation of nuggets manufacturing as these operations determine the rheological behavior of meat mass and structural integrity of the final product. Mincers reduce the muscle tissues into smaller particle sizes, while the mixing stage homogenizes fat, moisture, and functional proteins throughout the meat matrix. The effectiveness of this process depends on controlled application of mechanical energy. Therefore, it is emphasized that comminution must achieve sufficient protein extraction without excessive temperature rise which could impair protein functionality and, consequently, destabilize meat matrix. As a result, micing equipment is designed to balance cutting efficiency with thermal control, often through optimized blade geometry, rotational speed, and processing time. Similarly, for stable matrix development by protein–protein interaction and uniform

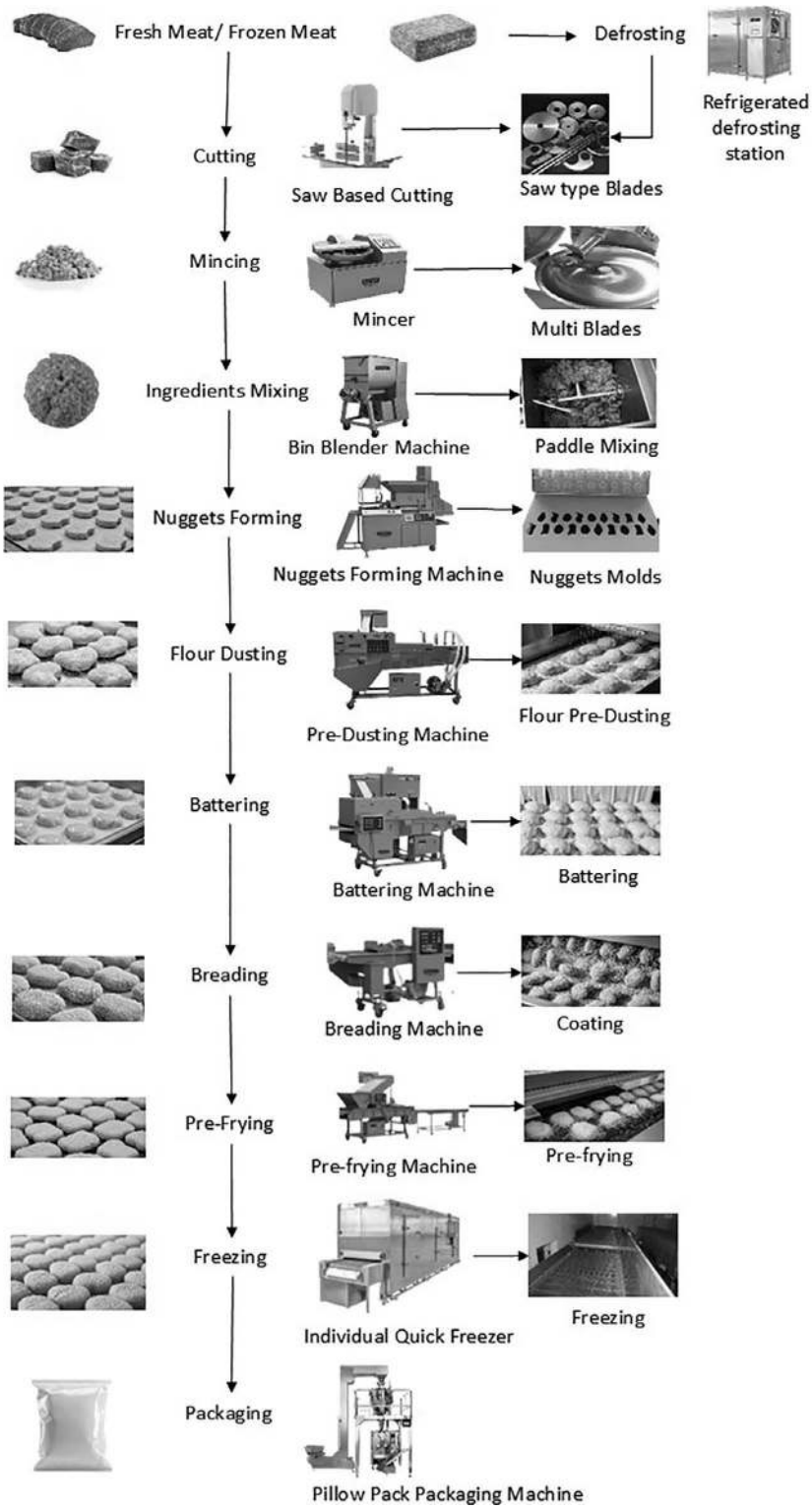

FIGURE 34.2 Nuggets process flow diagram.

TABLE 34.1

Mechanical Risks Mapping across the Nugget Manufacturing Operations

Unit Operations	Major Equipment	Key Mechanical Risks	Controls
Primary processing (slaughter to primal cuts)	Stunning systems, knives, deboners, saws	Kinfe lacerations, saw contact, pinch/crush injuries	Ergonomic knife design, blade guards, interlocks, 360 guarding, LOTO system, operator training
Comminution	Meat grinders, mincers	Blade contact during feeding or cleaning, entanglement, overload failure	Fixed guards, interlock covers, controlled feed rate, sensor interlocking
Mixing	Ribbon mixers, paddle mixers, vacuum mixers	Entanglement and shear injuries	Enclosed mixer designs, safety interlocks, emergency stop and controlled rotational speed
Forming	Extruders, molders, and forming plates	High-pressure release, pinch/crush injuries	Pressure sensors, guarded dies, ergonomic design
Batter and breading	Coaters, conveyors, tumblers	Conveyors nip point, rotating drum contact	Conveyor guarding, speed control
Thermal processing	Continuous fryers, ovens, conveyors	Conveyor entrapment, electrical failure at high temperature, high evaporation and oil sparkle, spillage	Heat-resistant guarding, proportional integral deviation (PID) control heat system, upper-limit temperature control
Freezing	Blast freezers, individual quick freezers, spiral freezers	Temperature and interlocking system malfunctioning	PID control, temperature sensors, installation of dehumidifier
Packaging	Flexible packing machine, vertical form fill seal (VFFS), horizontal form fill seal (HFFS)	Exposure to mechanical parts, sealing jaw injury	Interlocked lids, pressure relief valves, automatic sealing cycles

distribution of components, controlled mixing operation is required. Undermixing of mince lead to poor cohesion, crumbly texture, and inconsistent forming behavior in nuggets, while overmixing could cause excessive protein breakdown and textural defects such as pasty or rubbery texture. Ribbon or paddle mixers, planetary mixers, and high-shear homogenizers are widely used in nugget lines to homogenize comminuted meat with functional ingredients while maintaining controlled shear (Szpicer *et al.*, 2025). The mixing performance could be optimized through blade configuration, tool design optimization, and process and structural parameters adjustment (Zuo *et al.*, 2023). The mechanical risks involved in nugget manufacturing are closely interlinked with nugget quality, process yield, and operational safety as they often arise from deviations in mechanical energy input, equipment loading, and process control (Table 34.1).

The next stage is forming that converts the minced meat matrix into discrete nugget shapes with consistent mass and geometry. Mechanical forming system apply pressure to the meat mass, forcing it into the molds or dies. Here, the applied pressure and residence time influence product density, surface smoothness, and structural stability. Uniform pressure distribution is decisive to prevent defects such as cracking or weak interfaces. The equipment must accommodate variations in mince matrix consistency without compromising portion accuracy. Forming of nuggets is treated as a critical control point linking upstream comminution to downstream coating operations.

Battering and breading are coating operations governed by principles of fluid mechanics and adhesion. Batter is a suspension of solid particles in liquid system, usually water, that forms outer coating of the mince and serves as a binding layer between meat matrix and the subsequent layer of breading (Varela and Fiszman, 2011). Battering system in the nugget manufacturing line must maintain appropriate flow behavior to ensure even coverage of the formed nugget surface. The breading system relies on controlled particle deposition and retention. The challenges at these stages are maintaining consistent batter

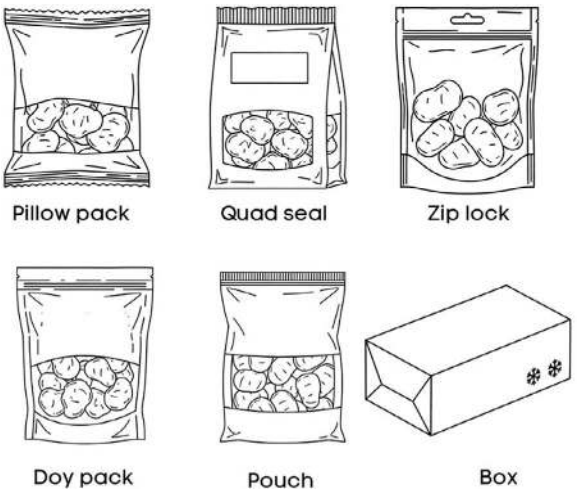

FIGURE 34.3 Packaging designs for nuggets.

viscosity, managing excess coating material removal, and minimizing product loss. From an engineering perspective, coating systems are designed to synchronize conveyor speed, batter flow, and mechanical agitation to achieve reproducible coating thickness. Ineffective control at coating stage of nugget leads to variability in yield, appearance, and thermal processing performance.

Thermal processing of nuggets is carried through a deep fryer or continuous oven and it serves two primary objectives: achieving microbial safety and stabilization of nugget structure. Heat transfer during the cooking process must be sufficient to inactivate pathogenic microorganisms while avoiding excessive loss of moisture or surface damage (Cui *et al.*, 2024). Engineering analysis focus on heat penetration to the core of nugget, surface heat flux, and residence time within the cooking equipment. Thermal processing is considered as a critical control step where deviation in cooking temperature and duration can compromise both safety and quality of nugget. Consequently, fryer design and pre-frying process monitoring are decisive to ensuring consistent lethality and product integrity. The cooked nuggets are subjected to freezing by using blast freezers or individual quick freezing (IQF).

Packaging represents the final barrier of the processed nuggets and the external environment. It plays a critical role in shelf life extension and safety assurance. The packaging systems are designed to control gas exchanges, limit moisture migration, and protect the product from cross-contamination during distribution and storage. Vacuum packaging and modified air packaging (MAP) are commonly employed. Moreover, the selection of packaging material is equally critical. Usually, clear food grade polymers that provide visibility, mechanical integrity, and barrier performance suitable for frozen or chilled distribution are used. Moreover, to obtain the desired package design, as shown in Figure 34.3, different packaging equipment are employed.

34.4 Hazards Identification and Controls

Like all processed food products, the nugget processing is also susceptible to biological, physical, and chemical hazards. These risks could be mitigated through equipment design, process control, and system integration, rather than end product testing alone. The biological deterioration of meat and meat products could be caused by *Acinetobacter*, *Enterobacter*, lactic acid bacteria, *Escherichia coli* O157: H7, *Bacillus cereus*, *Clostridium botulinum* spores, and *Staphylococcus aureus* (Guo *et al.*, 2024). The spoilage of poultry meat particularly is linked with *Salmonella* spp. and *Listeria monocytogenes* (Pegueros-Valencia *et al.*, 2025). In nugget manufacturing, these hazards are primarily managed through process controls rather than reliance on raw material microbiological quality alone. Thermal processing steps, including cooking or pre-frying, are engineered to deliver sufficient heat transfer to kill the pathogenic

microorganisms, while freezing and cold chain management inhibit subsequent microbial growth. Post-frying contamination represents a critical risk, particularly during cooling, freezing, and packaging. Therefore, hygienic equipment design, controlled product flow, and segregation of raw and cooked zone are emphasized.

Bone fragments or metal pieces could be the possible physical hazards at the nugget processing line due to mechanized deboning of meat and intensive equipment use in the manufacturing process. The control for physical hazards includes detection of foreign materials by integration of metal detectors and X-ray inspection systems within the processing line. Use of food-grade cleaning chemicals with correct dosage and quality of water used for cleaning also prevent possible chemical and microbiological hazards.

34.5 Sustainability and Process Efficiency Considerations

The sustainability of nugget manufacturing could be framed in terms of process efficiency, resource utilization, and waste reduction, rather than isolated environmental claims. From an engineering standpoint, the efficiency of process is closely linked to yield optimization, energy consumption, and performance of equipment across the production line. Energy-intensive operations in nugget manufacturing include mincing, thermal processing, freezing, and packaging, all of which contribute to overall economic and environmental footprint of the process.

Optimization of these steps to reduce energy input while maintaining safety and quality are critical for sustainable operations. For instance, efficient heat transfer during cooking step, controlled freezing rates, and high-quality insulations not only contribute to product stability but also reduce energy demand and operational costs (Howard *et al.*, 2023). In addition to energy efficiency, material loss and rework streams represent critical sustainability challenge in nugget manufacturing. Batter and breading losses and off-specification products generated during forming and coating directly reduce yield and increase waste-handling requirements. Addressing these losses through process synchronization, strict operational controls, and improved equipment design could enhance both resource efficiency and sustainability of overall nugget manufacturing process.

34.6 Conclusion

This case study has presented nugget manufacturing as an integrated engineering system where equipment design, process control, and safety management are inseparably linked together. The example of nuggets serves as representative of minced meat product and could be used for other processed meat products, including burger patties, sausages, and other restructured meat products. The interdependence of meat processing unit operations is highlighted and the role of engineering controls to achieve safe, consistent, and sustainable product is discussed.

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Conclusions

Slim Smaoui and Theodoros Varzakas

This book offers an organized and multidisciplinary inspection of the meat production system, exploring animal welfare science, meat quality, processing technologies, food safety, sustainability, and consumer-driven market dynamics. The collective chapters prove that contemporary meat science must interchange beyond production efficiency alone and implement a systems-based perspective that looks for ethical responsibility, technical progression, regulatory compliance, and societal prospects.

The section dedicated to animal welfare principles, evaluation methods, and livestock management found animal well-being as a foundational component of sustainable meat production. Stress, pain, and poor management throughout rearing, transport, and even during the action of killing have profound impacts on animal health, carcasses, in addition to meat quality features, namely, pH values, color traits, water retention, and textural properties of meats.

Advances in precision livestock farming and welfare checking technologies have meaningfully enhanced the capacity to measure animal status in real time. The employment of sensors, automated imaging, data analytics, and decision-support systems allows early detection of stress, disease, and interactive anomalies, thus assisting evidence-based management and decreasing the production damages.

Chapters addressing meat science fundamentals focused on the importance of animal genetics, nutrition, and controlling the meat quality determination, and sustainability consequences. The information specified in the sections concerning the structure and organization of muscular and adipose tissues, and the nutritional anatomy of meats, represents a scientific explanation for thoughtful advantages and drawbacks of consuming meats. At the same time, the need for food safety concerns such as microbiological risks, bovine spongiform encephalopathy (BSE), and emerging risks and trends in food safety highlights the need for existing systems for prevention and control.

The section dedicated to meat products and by-products established the substantial progress in handling, preservation, and product novelty. Tools such as chilling, freezing, thermal processing, smoking, fermentation, pasteurization, and aging are obtainable as vital tools for quality retention, guarantee of security, and shelf life delay. Corresponding growths in packaging systems, processing equipment, and manufacturing solutions assist to enhance operational efficiency, product consistency, and sustainability implementation.

Another key issue within the chapters of this book is the considered role of by-product utilization in circular bioeconomy. The upgrading of meat by-products to valuable materials, ingredients, or functional compounds supports the mitigation of waste generation, the more rational usage of resources, as well as the sustainability of the environment. Systemic innovation, including the optimization of the entire supply chains and digitalization, can offer an additional level of robustness and economic sustainability. The application of computer vision, artificial intelligence, as well as cybersecurity seems to have come into the land of the meat industries.

The final sections addressing consumer perspectives, ethics, and market trends highlight the increasing effect of public values on meat production and consumption. Ethical considerations, transparency in labeling, health perceptions, and environmental concerns are progressively shaping purchasing behavior and industry strategies. The emergence of plant-based and cultured meat alternatives highlights shifting consumer preferences and technological divergence within the protein sector.

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In summary, this book validates that the future of the meat industry be influenced by an integrated framework that combines animal welfare, scientific innovation, food safety, sustainability, and consumer trust. Talking global challenges such as food security, climate change, and public health will necessitate synchronized exertions across research, industry, and regulatory domains. By supporting technological development with ethical responsibility and evidence-based policy, the meat sector can progress toward more hardy, well-organized, and socially acceptable production systems.

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