

Food Engineering Series

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C. Nickhil

A. K. Haghi *Editors*

Engineering Solutions for Sustainable Food and Dairy Production

Innovations and Techniques in Food
Processing and Dairy Engineering

 Springer

Food Engineering Series

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Editors

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ISSN 1571-0297

Food Engineering Series

ISBN 978-3-031-75833-1

<https://doi.org/10.1007/978-3-031-75834-8>

ISSN 2628-8095 (electronic)

ISBN 978-3-031-75834-8 (eBook)

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Preface

The global food and dairy industries are undergoing rapid transformation, driven by the need for sustainable practices, technological advancements, and the rising demand for safe, high-quality products. With growing concerns around food security, climate change, and resource efficiency, there is an urgent call for innovative engineering solutions that can enhance productivity while ensuring environmental sustainability. In response to these challenges, this book, *Engineering Solutions for Sustainable Food and Dairy Production*, aims to provide a comprehensive exploration of the key engineering principles and emerging technologies that are shaping the future of food and dairy processing.

This edited book is part of the Advances in Food Engineering Series and brings together the expertise of researchers, academics, and industry professionals to offer insights into a range of critical topics. The chapters cover both fundamental concepts and cutting-edge innovations, offering a balance of theoretical understanding and practical applications. From the basics of food and dairy process engineering to the latest advances in sensory assessment, packaging preservation, and shelf life extension, the book addresses the entire spectrum of the field.

The chapters are designed to provide a detailed exploration of the challenges and opportunities facing food and dairy engineers today. Topics such as fluid mechanics, heat transfer, pasteurization, fermentation, and separation technologies are discussed in depth, along with the critical aspects of quality assurance, regulatory compliance, and food safety standards. Special attention is given to the growing role of biotechnology, enzyme applications, and novel extraction technologies in food processing, as well as the importance of consumer preferences in shaping future product development.

This book also highlights successful case studies on by-products utilization, offering valuable lessons on how food waste can be minimized and repurposed, contributing to a more sustainable food system. The final chapters delve into future trends, providing a forward-looking perspective on how the field of food and dairy process engineering will evolve in the coming decades.

We hope this book serves as a valuable resource for students, researchers, engineers, and professionals in the food and dairy industries, offering both foundational

knowledge and insights into the latest technological developments. By fostering a deeper understanding of these critical topics, we aim to contribute to the ongoing efforts to create a more sustainable and efficient global food system.

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Chapter 1

Introduction to Food and Dairy Process Engineering



Raj Singh, Sankar Chandra Deka, C. Nickhil, R. Nisha, and A. K. Haghi

1 Introduction

Food and dairy process engineering comprises of a large number of methods and tools that are implemented to enhance the safety programs and the quality and efficiency of manufacture of dairy products. Membrane technologies are mainly implemented in the dairy industry to efficiently assess, concentrate, and purify dairy waste (Tayawi et al., 2023). These methods help in waste disposal, reduction on energy use, and maintain product quality. Additionally, membrane separation technologies have been used for purification of milk oligosaccharides from dairy byproducts solving the problem of digestible sugar recovery and target oligosaccharides (Wang & Hua, 2021). Measures that are applied to the dairy processing are central in determining its safety. Some approaches of coping with the problem define the ways of improving the customer security for dairy produce (Stabel, 2003). It is pivotal to assess possible microbial hazards in fermented dairy products, for creating prevention strategies during food production (Sayed et al., 2022). This encyclopedic plan contributes to the quality and safety of dairy products, no matter the phase of the processing. Stakeholders in the food and dairy processing industries apply concentration techniques with the aim of getting improved qualities of new

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products (Muñoz et al., 2018). Some of the methods include freeze concentration and membrane concentration that assist in achieving high dry matter content, added value, and longer shelf life. In addition, the application of progressive and block freeze concentration techniques in lactose-free milk makes it possible to develop milk products that satisfy protein requirements and other functionalities (Dantas et al., 2021). Currently, there is a constant search for new technologies and procedures intending to enhance dairy processing. Studies on the decrease of the polarization layer in buttermilk membrane concentration methods show the developments made on the improvement of the membrane. Besides, the employment of complex processing technologies as well as analytical methods significantly enhances the evaluation and determination of dairy product qualities and processing stages (Moschopoulou, 2021).

Security and availability of food in the world is very significant and it very much depend on food safety. Several research works indicate the challenges that occur in food supply networks (Oriekhoe, 2024; Hagenimana, 2022). The United Nations' Sustainable Development Goals indicate increased importance in the safety of foods to promote people's health as well as development. The COVID-19 pandemic has underlined the importance of updating global food safety risk management approaches (Luo et al., 2022). Advances in food processing sector are critical to improving the global food supply's sustainability, safety, and quality (Pokharel, 2023). Transparency and traceability are required to ensure food safety throughout the supply chain (Liu, 2018; Liu & Guo, 2016). To ensure that food is continuously safe and of high quality, supply chains must include risk assessment, quality management, sustainability, and traceability (Ren et al., 2013). A variety of factors influence fresh produce food safety, including international trade, globalization, government laws, and a lack of food safety knowledge (Boxstael et al., 2013). Intergovernmental organizations and international standard-setting agencies play a crucial role in coordinating effective activities for long-term consumer protection and equitable international trade (Quested et al., 2010). The Global Food Safety Initiative sets global food safety standards (Rao et al., 2021).

2 Principles of Food and Dairy Safety: Challenges and Opportunities

2.1 Key Principles and Practices for Ensuring Safety

Maintaining standards in the business necessitates a variety of factors, including the safety of food and dairy products. Education along with training are key to two important improving food safety procedures among food handlers (Abdu, 2019; Adesokan et al., 2015; Nawawi et al., 2022). Therefore, based on the literature, several factors such as supervision, availability of advice, positive attitudes, food

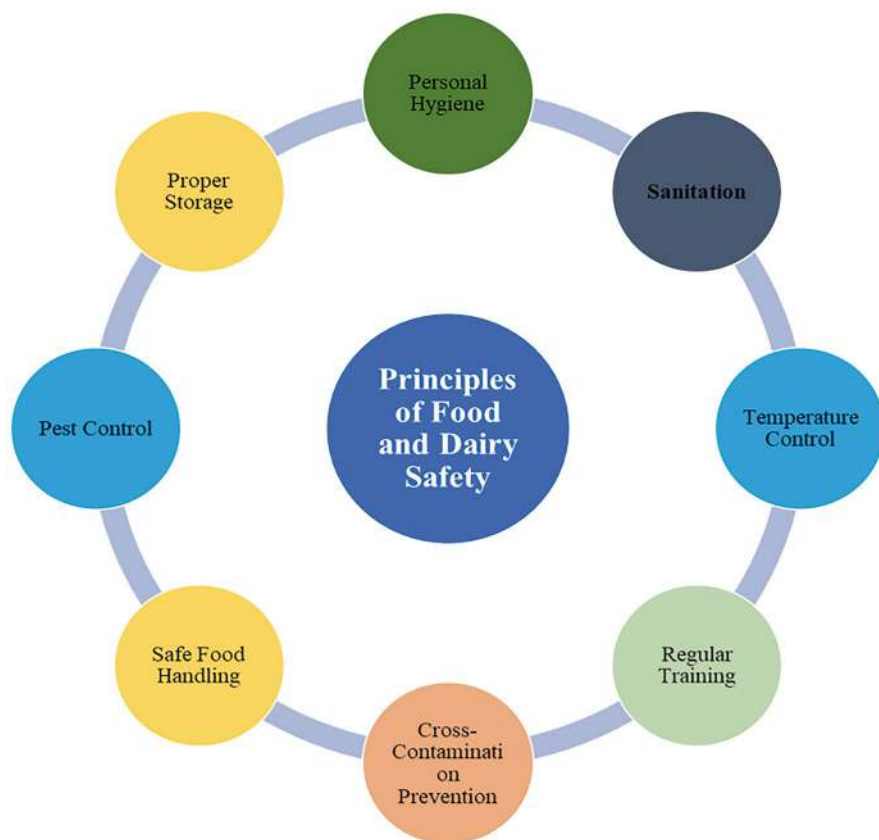


Fig. 1.1 Principles of food and dairy safety

safety training, and sufficient knowledge significantly determine the level of regulation of satisfactory practices in the food sector (Abdu, 2019). In addition, knowledge enhancement and skills update are effective in the observation of proper measures in food handling and comprehension (Adesokan et al., 2015; Nawawi et al., 2022). In as much as aiming at reducing dangers, there is necessity in establishing a personality of a food safety management system in businesses (Fig. 1.1). This methodical approach encompasses as many topics as sustainable farming, policies for animal treatment, labor rights, product ingredients' sourcing from reliable suppliers (Dahlal, 2024; Lee, 2023). It is well established that Hazard Analysis and Critical Control Points (HACCP) is one of the more effective approaches to maintaining the safety of foodstuffs (Raihanah, 2021). It helps in analyzing and sorting out risks that are bound to occur in the manufacturing of foods. Moreover, it cannot be overemphasized the need to have correct information with regard to food safety.

Studies have established that people who possess greater knowledge on food safety are usually inclined to handling food safely. Extending education is another factor that has been deemed necessary to enhancing the understanding of food safety among the food vendors leading to voluntarily good attitudes towards food safety and hygiene (Jores et al., 2018). Theory of Planned Behavior aims at identifying suggestions to encourage principles of food safety, for instance, hand washing, use of thermostats and proper control of food's interaction with food (Pilling et al., 2008).

2.2 Emerging Challenges and Potential Solutions

Challenges that relate to food and dairy safety are complicated issues that require the use of particular measures to solve them. One of the severe difficulties is to ensure food traceability to help identify acts of adulteration and contamination; at the same time, it is necessary to preserve the nutritive value of various dairy yields (Patel et al., 2023). Thus, to enhance the safety of structured dairy products, quality design, and food safety provisioning by means of quasimetrics forecasting are needed (Dunchenko et al., 2022). Opportunities to enhance safety of foods and handle industrial risks are presented by FDA's plan to employ applications for food safety (Deng et al., 2021). Assessing food safety hazards requires a significant resources and scientific skills, especially in high-risk commodities such as dairy products. This underscores the importance of a comprehensive methodology, such as Hazard Analysis and Critical Control Points (HACCP) (Manning & Soon, 2013). It is now critical to integrate blockchain technology into food supply chains to ensure global food safety and avoid foodborne illnesses and issues in contamination (Oriekhoe, 2024). Exposure to modern technology such as biometric and virtual reality tools can improve food safety training and research with a path for better improvement (Baldwin & Evans, 2020). Improvisation in Food safety can be implemented through real-time monitoring and control enabled by Internet of Things (IoT) technologies, allowing stakeholders to proactively manage food safety hazards and maintain the integrity of the food supply chain (Abass, 2024). As demonstrated in China, the creation of sophisticated monitoring systems for food safety emphasizes the need of international standards, transparency and effective supervision in for ensuring food safety. Creating a reliable traceability system is critical for efficiently resolving food safety issues, and it is dependent on incorporating IoT and big data into food safety traceability (Jabbar, 2024). Using essential oils as antimicrobial agents in biopolymer-based active packaging can enhance food safety by supplementing governmental regulations and training for food handlers (Tomić, 2023). Regulation bodies like public-private partnerships, offer opportunities for improving food safety practices (Martínez et al., 2007). The COVID-19 pandemic set as a better lesson about food safety in times of disaster (Lacombe et al., 2020).

3 Quality Assurance and Control in Food and Dairy Products

3.1 Methods for Ensuring Product Quality

The food and dairy sectors employ a multitude of measures in delivering quality and safety of products during the manufacturing process. Of these, HACCP is one of the key safety techniques that is preventive in nature that addresses assurance of quality and safety of the dairy products from the time of manufacturing up to the time they are consumed by the consumers. From the existing literature, it is evident that HACCP is obligatory to ensure the safety of dairy products as well as to halt the spreading of diseases (Bodyfelt et al., 2008; Papademas & Bintsis, 2010). In addition, the dairy industry has been the first to adapt quality assurance activities focusing on the uniformity of nutritional value, technology incorporation, and quality of the final product (Cattaneo & Holroyd, 2013). In addition to HACCP, other methods of modern technologies like Raman and near-infrared spectroscopy are employed in the quality control of the dairy industry (Zhang et al., 2019; Fysun et al., 2020). With these technologies, quality attributes and nutritional and additive profiles of dairy products may be determined, this greatly enhancing brand differentiation and quality rating outcomes (Fysun et al., 2020). Furthermore, approaches of real-time monitoring to detect and control fouling in real-time techniques; for instance, cyclic voltammetry has been used to control fouling in dairy processing, leading to an improvement in the quality of end-products (Upadhyay et al., 2021). Quality control in the dairy industry demands that certain legal requirement have to be met. These requirements that have been set in the regulation include; fat analysis, microbiological and organoleptic tests which have been set for milk and milk products in Nepal (Jh et al., 2008). Comparably, European law has emphasised the importance of regulatory compliance in ensuring product quality and recommended the use of HACCP as a quality risk management program for the entire dairy chain.

3.2 Common Quality Control Measures and Their Applications

Food and dairy products must be safe and of good quality, necessitating the use of quality control measures. Hazard Analysis Critical Control Points (HACCP), a technique, aims to prevent infections while maintaining product quality (Nasr, 2017). Another well-known yet effective quality control method is sensory analysis, which focuses on the final product's quality and ensures dairy products' safety, consumer acceptance, and consistent nutritional benefits (Bodyfelt et al., 2008) (Fig. 1.2). Other quality control methods, like as Raman and near-infrared spectroscopy, have also been developed to extract chemical features and differentiate brands in dairy products (Cattaneo & Holroyd, 2013; Zhang et al., 2019). Food safety management systems, such as HACCP, have become industry standard processes to assure the safe production and distribution of dairy products (Papademas & Bintsis, 2010).



Fig. 1.2 Applications of quality control measures

These helps in identification of proper points of control in activities like pasteurization, fermentation and packaging to minimize on contamination of the product for safety reasons. Moreover, bacteriophages have been used due to their efficiency in controlling pathogenic bacteria and increasing food safety in the dairy supply systems. Another factor that needs to be controlled in the production of dairy products is this legal working rules and regulations that have been set for a certain period of time. Some standards maintained for standardizing milk and milk products include testing for content of fat, microbiological presence, and organoleptic properties (Upadhyay et al., 2021). Blockchain technology may improve dairy product traceability, prevent adulteration, and retain nutritional value.

4 Fluid Mechanics in Food and Dairy Processing

4.1 Fundamental Concepts of Fluid Mechanics

Basic fluid mechanics concepts are important in many parts of food and dairy production. Understanding the behavior fluid during process such as pasteurization, homogenization, and the production of dairy products is critical in dairy processing (Mishra & Bindhani, 2022). The techniques in fluid mechanics are applied plate heat exchangers, to ensure efficient heat exchange without mixing among various fluid phases (Schaer et al., 2018). Furthermore, by altering factors such as

transporter activity, ion channels, and cellular connections, fluid flow management via the mammary gland of dairy cows has a direct impact on milk production (Cai et al., 2017). Furthermore, the cleanliness of processing equipment directly affects the safety and quality of dairy products. This means that to ensure that the quality of the dairy products are not compromised and to ensure that the raw milk is not contaminated by the processing equipment, the latter has to be cleaned and disinfected duly (Su, 2024). Another essential knowledge area relates to fluid mechanics in the context of dairy processing to maximize processes and minimize consumers' cost in urban areas by innovating and integrating automated dairy farms and plants (Meena et al., 2020). Besides, the trend of consuming dairy has also changed over the years from fluid milk products and the current market has a more processed milk products derived products as yogurts, ice creams and cheeses (Davis et al., 2011). HDF cuts, packs, and pasteurization processes all affect the customer interest and the preferences towards the dairy products such as the fluid milk and their substitutes from plants (McCarthy et al., 2017). Moreover, the knowledge of a label including the ingredients and the procedures used for producing dairy products is different; the elder as well as the literate customer is more conscious of these matters (Schiano & Drake, 2021).

4.2 Applications in the Design and Operation of Processing Equipment

Fluid mechanics is a crucial consideration in the manufacture of food and dairy processing equipment. A large number of technologies have been introduced to enhance the standard of the final product and the output of the procedure. For instance, practical treatment such as the use of UV light on milk alters the molecular attributes of proteins and hence leads to changes in viscosity coupled with syneresis. Concerning some details such as vibrational mixing and bubbling, it has also been discovered that it can enhance, the concentration of buttermilk membrane and present waste-free options for the process. An understanding of dielectric properties is vital to the food industry to developing procedures that include technological appliances like microwave (Gutiérrez-Cárdenas et al., 2022). Non-thermal atmospheric plasma has come out as a prospective food preservation method since it kills microorganisms while having a small impact on the quality of the food (López et al., 2019). Moreover, the enhancement of food processing activity is contingent on the thermal characteristic of food constituent including specific heat and thermal diffusivity (Ahmed et al., 2021). Therefore, some of the factors that influence the performance of the food processing equipment include food structure; food moisture content; food temperature; and the processing pressure (Smirnov & Abdilova, 2021). Increase in consumption of dairy products has been realized to have a positive effect in that it increases one's bone mineral density, indicating that dairy products play a crucial role towards the preservation of bones in regards to dairy processing (Mangano et al., 2019). Besides, attempts to mechanized and enhance

the production of dairy products are visible in the creation of advanced technologies in particular; a cheap paneer-making machine (Sivaranjani et al., 2021). To prevent the consumption of adulterated products, it is mandatory that the use of food additives should be given keen attention and the cleanliness laws also must be considered.

5 Heat Transfer and Pasteurization Techniques

5.1 Heat Transfer Mechanisms

Pasteurization procedures applied in the food industry for food safety and quality assurance mainly depend upon mechanisms of heat transfer. Pasteurization refers to the heating of foods to cause destruction of enzymes, spoilage organisms and pathogenic bacteria (Lepinard et al., 2019). The basis of this thermal process involves elimination of bacteria and denaturation of enzymes which are essential in preventing food decay (Shafiekhani et al., 2016). Several pasteurization techniques have been designed to cater for various food products and processing conditions such as high hydrostatic pressure, irradiation, pulsed electric fields, UV, cold plasma, ultrasound super critical gas and pulse light pasteurizations (Pawar, 2022). This included container orientation, among other variables that might affect heat distribution inside the product during natural convectional heating within pasteurization was investigated using computational fluid dynamics (CFD) analysis in relation to heat transfer mechanism (Lepinard et al., 2019). Moreover, CFD modeling has been employed to predict the loss of color and preservation of bioactive compounds in raspberry pulp during pasteurization, underscoring the importance of comprehending heat and momentum transfer in maintaining quality of processed products (Badin et al., 2022). To surpass inherent limitations associated with conventional heat treatments for food processing safety improvement, new pasteurization processes have been developed. On the other hand, Kavuşan and Serdaroglu (2019), suggest that modern methods aim at preserving items' microbiological safety as well as retaining their useful properties. Besides, Sentandreu et al. (2020) supported high-pressure homogenization as a sustainable approach to increase the bioavailability of beneficial components in mandarin juices. Pasteurization and preservation are mutually beneficial processes. Moreover, employment of such advanced technologies like microwaves, ultrasonication or HP-processing has shown promise in the process efficiency and effectiveness in regard to pasteurizing operations. One example of this is microwave pasteurization, which inactivates microorganisms faster at lower temperatures than conventional methods, thus shortening processing time and improving energy utilization. In the same way, the use of cold ultrasound in supercritical fluids provides an innovative route to fast food production with maintenance of product quality (Abramova et al., 2021).

5.2 *Various Pasteurization Methods and Their Impact on Product Safety and Quality*

5.2.1 *Pasteurization Methods and Their Effects on Product Safety and Quality*

Commonly, most food products are pasteurized by heating them to make them safer and last longer on shelves (Yilmaz et al., 2019). This requires such specialized machinery as heat exchangers which use energy-intensive resources like steam, hot water, and electricity (Yilmaz et al., 2019). Proper selection of pasteurization processes is vital for both microbiological safety and preservation of food quality during storage as noted by Inanoglu et al. (2022). Water bath, steam, vacuum steam, infrared heating, microwave heating, radio frequency heating LTLT i.e., low temperature long time), ultra high temperature UHT) and HTST i.e., high temperature short time are among the techniques used in pasteurization (Pawar, 2022). These methods are meant to kill dangerous bacteria and enzymes that may spoil food (Silva & Silva, 2000). Pasteurization processes can be customized to avoid any changes in quality while ensuring microbial destruction (Siguemoto et al., 2018; Silva et al., 2008) analyzed power absorption coefficient of microwaves and heat transfer coefficients during microwave-assisted pasteurization of liquid meals. Similarly, a successful application has been made of microwave pasteurization to low sodium diet preparation and intermediate moisture foods (Wang et al., 2023). Traditional thermal processing techniques including freezing, drying and cooling etc. are usually applied for food safety (Nayak et al., 2018). Internet of Things (IoT) is the emerging technology that pasteurization system can use to enhance real-time decision making for low temperature long time pasteurization strategy for example (Hadi, 2024). Besides that, as what Peng et al. (2015) have highlighted, thermal pasteurization is necessary to keep at par the high quality level expected by both food manufacturers and consumers on food products.

6 *Separation Technologies in Food and Dairy Process Engineering*

6.1 *Filtration, Centrifugation, Evaporation, and Concentration Methods*

Because of the availability of new dairy food ingredients, the membrane separation technology has shown a tremendous impact on the processing of dairy products (Muthukumarappan, 2013). This technique transformed the dairy sector by enhancing product quality and processing efficiency (Kumar et al., 2013). Furthermore, pressure-driven membrane separation techniques are frequently employed in the

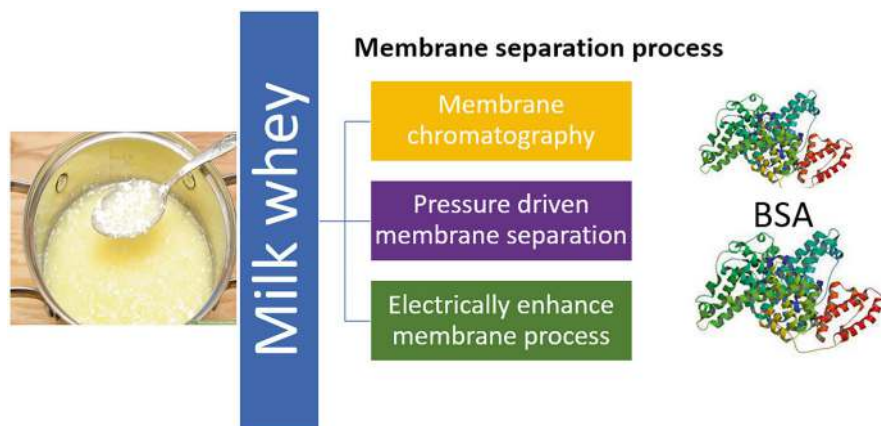


Fig. 1.3 Milk membrane separation process

dairy processing sector for commercial purposes, improving the safety and quality of the finished product (Fig. 1.3).

Centrifugation is important in dairy processing because it separates components such as cream from milk and reduces microbial contamination, as demonstrated by the possible application of centrifugation to minimize *Mycobacterium avium* ssp. *paratuberculosis* in raw milk (Grant et al., 2005). Furthermore, centrifugation is required for the creation of human lactoferrin and lysozyme in transgenic dairy cows, demonstrating its versatility in producing novel proteins in milk (Cooper et al., 2015). The use of proper centrifuge equipment is critical for successful separation procedures, as evidenced by a centrifuge selection methodology based on performance visualization (Salte et al., 2006).

Evaporation is another important procedure in dairy engineering, used to concentrate dairy products to increase shelf life and nutritional quality while maintaining their physicochemical properties (Gebeyehu, 2023). This method is critical for standardization in the dairy industry, notably cream separation operations (Bellassi et al., 2021). Furthermore, evaporation techniques are used to produce excellent biochar from algae culture for treating dairy effluent generated during cleaning processes (Dziosa, 2024).

Concentration procedures are essential in dairy processing for increasing the solids content of products such as milk and cheese (Fig. 1.4). These same requirements are necessary for the manufacture of recycled manure solids as bedding in dairy farms where screw separators are commonly used for solid-liquid separation (Fournel et al., 2019). In addition, full-scale recovery predictions of some dairy products such as ovine polyclonal immunoglobulins, use ultra-scale-down operations similar to those in large industrial centrifugation.

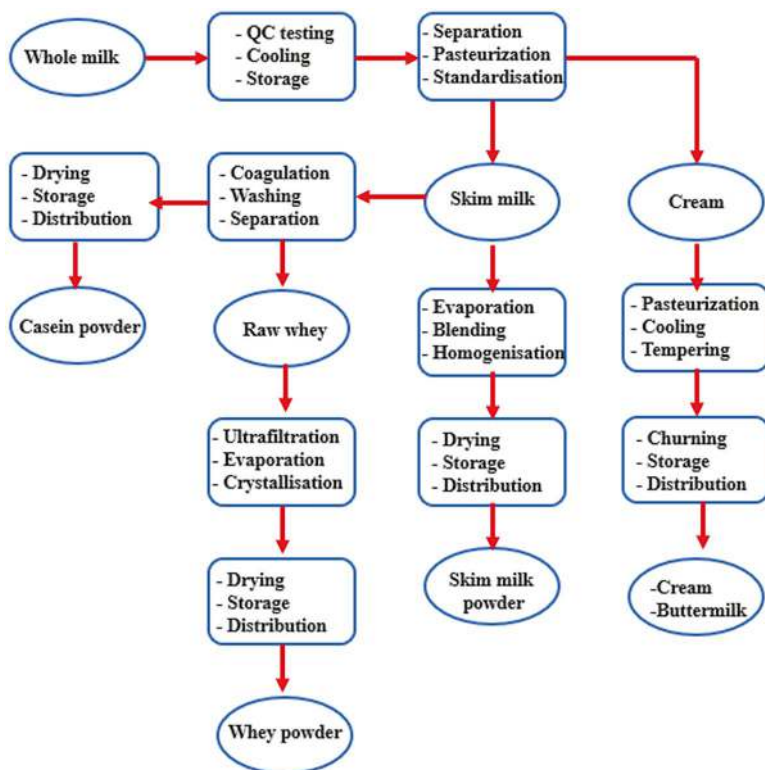


Fig. 1.4 Milk processing flow chart

6.2 Their Role in Product Purification and Concentration

Separation technologies are vital in product purification and concentration in the food and dairy processing industry. Membrane separation technology has been a major breakthrough in this aspect, especially, in the processing of dairy food (Muthukumarappan, 2013). This is because, it ended up changing the fractionation of dairy ingredients such as casein and whey which in turn led to the extraction of milk bio actives as well (Lin et al., 2021). Membrane separation processes have been deployed extensively by dairy industries for different purposes including component separation, filtration, removal of bacteria, and wastewater treatment (Chen et al., 2018a, b). These processes provide an effective way to separate, concentrate, and purify dairy wastewater with advantages such as reduced process steps compared to traditional methods used earlier (i.e. sedimentation), low effect on product quality; operational flexibility i.e. operating at ambient or low temperature without impacting the intrinsic values present in milk proteins; less energy consumption (Al-Tayawi et al., 2023). Secondly, pressure-driven membrane separation processes were found out as one among other trends that can be feasible for commercial

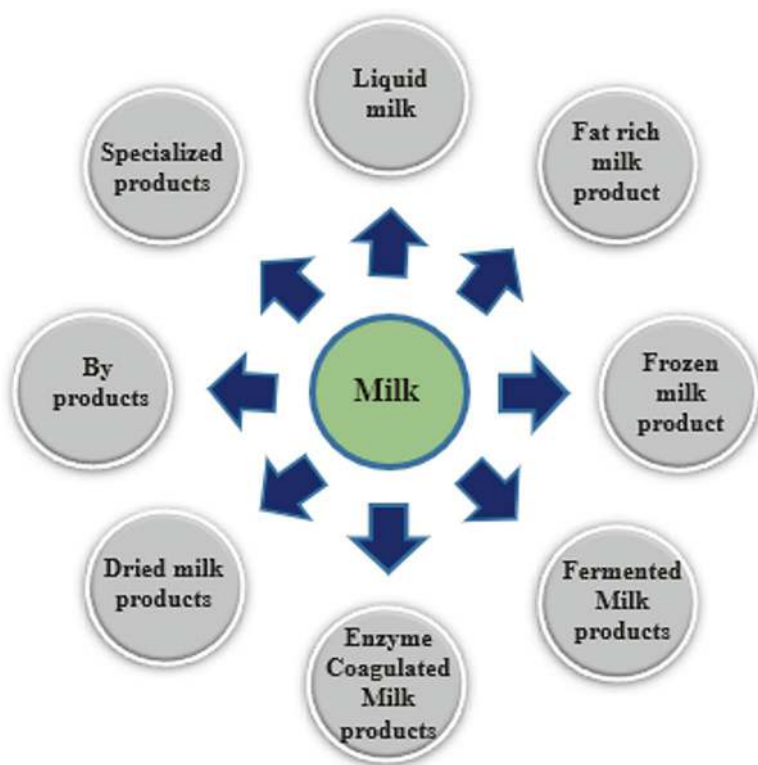


Fig. 1.5 Milk and its products

application in the dairy processing industry hence showing its relevance in this field. It could be noticed that ultrafiltration was adopted by the dairy industry for bacteria removal due to its efficiency and flexibility hence indicating how membrane applications can enable efficient unit operations such as pre-treatment i.e., bacteria removal from milk before entering other unit operations like heat treatment and pasteurization) during milk processing (Fig. 1.5) therefore enhancing product quality (Gebeyehu, 2023.) Technologically advanced concentration techniques such as freeze concentration and freeze-drying out compete with conventional ones on industrial level due to their improved energy efficacy nevertheless they impact negatively on food properties like quality. Consequently alternative advances techniques like membrane separation technology is being studied by most researchers who believes that it offers better characteristic advantages over conventional methods (Prestes et al., 2022). Nanofiltration and ultrafiltration are the membrane processes that generates high protein concentrations and separation in the dairy industry due to rise in global increase in demand on food processing technologies (Shabbir et al., 2021). This new dairy technology trend could indicate a global consumers' shift to a preference of minimal processed foods (Dj et al., 2019).

7 Food and Dairy Fermentation Processes

7.1 *Basics of Fermentation*

The process of fermentation is an elementary method that is widely being used for many years to produce various kinds of dairy products. Any modification in the milk products is achieved based on specific characteristics attributed to LAB including g acidity, flavor, aroma and texture of fermented milk products (Harper et al., 2022). From a technical standpoint, fermentation is one of the most widespread and oldest processes, the application of which for the production of a great number of dairy products has been discovered thousands of years ago. It is acknowledged that LAB is the agent that induces acidity, flavour/odor and texture in fermented milk products. These state that they are effective in explaining locational characteristics and, in turn, desired consumer behaviours, which supports the suggestions by Erkmen and Bozoglu (2016) and Ranadheera et al. (2017). Besides enhancing the nutritional value, fermentation also creates other useful compounds for the consumers' benefits such as vitamins, gamma-aminobutyric acid, and bioactive peptides (Zhang et al., 2018). Because of the fermentation process, fermented dairy products are known to be nutrient-rich and contain probiotics, as well as high-quality protein, bioactive compounds, vitamins, and other critical nutrients (Tapsell, 2015). Consuming dairy products that have undergone fermentation has been linked to possible health.

7.2 *Applications in Food and Dairy product Development*

Fermentation is one of the oldest methods used for developing food and dairy products, which has a broad spectrum applications in improving not only nutritive value but also flavor enhancement as well health benefits markers. Lactic acid bacteria (LAB) are one type of the important microorganisms in food fermentation and used for producing dairy product. These bacteria are in the category of probiotics type bacterias it improve gut health and welfare (Harper et al., 2022). The most commonly consumed fermented dairy products globally are yogurt and cheese, and it is well established that live bacteria contained in these food matrices (i.e., probiotics) exert cardiometabolic benefits as part of the functional profile fabricated during fermentation (Koskinen et al. 2018). Lactic Acid Bacteria (LAB) are the most abundant group of microorganisms in fermented foods, and play a major role during fermentation by developing characteristic flavours (Rezac et al., 2018). LAB are broadly used as starters for dairy fermentation that epifluorescence and starter bacteria were frequently linked to many fermented foods, particularly in the cheese industry (Velly et al., 2014). Over the past few years, fermented dairy products m such as yogurt and cheese have become more popular than ever. Being naturally rich in probiotics, calcium, high quality protein vitamins and bioactive molecules that are enriched through fermentation process (Zhang et al., 2018). To be more unique,

fermented foods are abundant sources of nutrients which could overcome a greater degree and availability of bioactive metabolites during fermentation process compared to nondairy raw material (Zhang et al., 2018). Moreover, fermented milk has been reported to possess potential health benefits such as the reducing symptoms of lactose intolerance; producing bioactives including vitamins and peptides; promoting gut function etc. (Erkmen & Bozoglu 2016). The nutritional characteristics of dairy products are increased due to lactic microbial metabolism during fermentation along with the addition of taste and different product extended self-life (Papadopoulou et al., 2023). The bioactive-enrichment of health-oriented dairy foods through natural fermentation processes is increasingly sought after, highlighting the demand for such functional foods (Linares et al., 2017).

8 Mixing, Blending, and Emulsification in Processing

8.1 Techniques and Equipment Used for Mixing and Blending

Blending also provides a means to composite material properties in various industries. Blending includes pre-blending and phase-mixing, including liquid mixing for the manufacture of polymer blends and liquid-liquid dispersions (Wijesinghe et al., 2021). A blending step is essential and, to enhance the blending, shear-based mixers for effective particle breakup and particle dispersion are used, including internal mixers, extruders and two-roll mills (Kaliyathan et al., 2019). Blending is a technique used to convert bulk material particles into an intimate mix or blend of on a consistent and unified characteristic (Boukouvala et al., 2011). It has several benefits, for example, mechanical reinforcement; excellent thermal stability of products from a homogenous mixture at high temperatures during cross-linking and processing; dimensional stability; reduced shrinkage; and improved wear resistance (Heino et al., 1994). Blending is one of the most cost-effective techniques in material development, and it allows for developing a wide range of polymer properties by combining different structural properties (Dündar, 2024). Blends such as NR- and butadiene rubber (BR) are compounded to achieve desired composite-like morphology with specific tensile and fatigue deformation characteristics (Moon et al., 2018). The mixing dynamics of these immiscible polymer blends critically depend on the gradual mixing performance with downstream characteristic variations in properties of the resulting blends (Sen et al., 2017). Blends that are not optimally mixed lead to a poor mechanical performance of the resulting immiscible polymer blends (Singkronart, 2024). Blending various biomass materials allows for tailoring the quality of feedstock to fulfil a predetermined conversion platform as well as can serve to expedite the fermentation processes to enhance its rate and efficacy (Eksioglu et al., 2021). For an improved dispersion in blends, compatibilisation provides high-quality, fine particle size with better shape and better interfacial adhesion for enhanced resin and polymer qualities (Kallel et al., 2002). However,

important considerations such as phase morphology during compound manufacturing critically depend on melt mixing and solution mixing techniques which have significant implications on the performance of the new material (Paleri et al., 2017).

8.2 *Emulsification Processes and Their Importance*

Emulsification techniques are critical in a variety of industries, including chemical engineering, increased oil recovery, medication delivery, and environmental cleanup. The process of emulsification is the dispersion of immiscible liquids in order to produce stable emulsions. These include; spontaneous emulsification, mechanical emulsification and membrane emulsification. Spontaneous emulsification can be useful for the production of oil-in-water vesicles with bilayer structures (Shahidzadeh et al., 2000). For pharmaceutical applications, this method contributes greatly to enhancing drug solubility and bioavailability (Staden et al., 2023). Emulsion is crucial in enhanced oil recovery where it helps mobilize residual oils in wells especially during chemical flooding operations (Gao et al., 2022). Examples of the mechanical method are mixing, colloid milling and homogenization which are commonly used to make micron-sized monodisperse oil-in-water microspheres (Kobayashi et al., 2001). These methods involve the use of shear forces to break up non-mixing fluids into smaller droplets leading to stable emulsion systems. Additionally, amphiphilic block copolymers provide a guide for nanoparticle formation through emulsifying them with solvent evaporation strategies (Fan et al., 2020 examples of techniques in membrane emulsification such as Shirasu-porous-glass membrane method (Chen et al., 2019). These approaches provide precise control over the emulsification process and are especially beneficial in applications that need homogeneous droplet sizes, such as). Shirasu-porous-glass membrane that results into monodispersed particles are among polymer particle manufacturing (Hosoya et al., 2005). In environmental remediation, oil emulsification in saltwater is critical for oil spill cleanup methods (Gong et al., 2015). Emulsification helps to disperse the oil, making it more susceptible to breakdown by microbes. Furthermore, hydrodynamic cavitation is an effective strategy for accelerating emulsification processes, resulting in size reduction, homogeneous dispersions, and better emulsion stability (Carpenter et al., 2022).

9 Zero Hunger: Food and Dairy Packaging Preservation

Food and dairy packaging can be used to preserve the food, reduce waste, and ensure the safety of food through the supply chain (Fig. 1.6). Eco-friendly packaging solutions are quite necessary to support the United Nations' Sustainable Development Goal to reduce food waste and loss. Since packaging containing

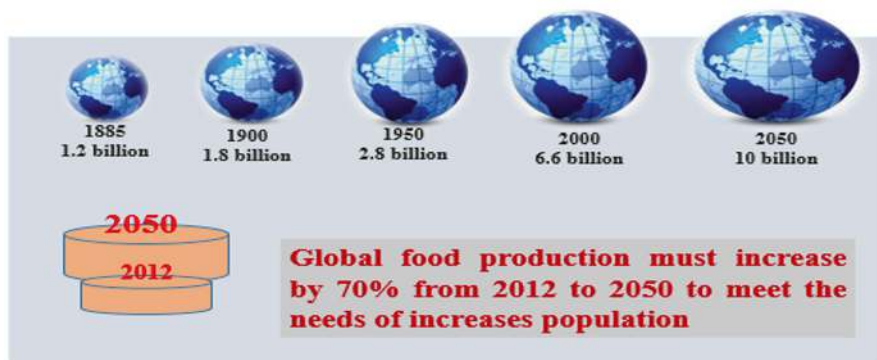


Fig. 1.6 Global food production

information on preserving food impacts per capita food waste in the retail and consumer stages, adequate packaging methods for preserving food can greatly lower the global food waste (Wikström et al., 2018). These tactics are in line with the stewardship of the environment and proved to be consistent with the customer values and preferences towards green goods (Zambujal-Oliveira, 2024). It has remained a major trend in the development of smart packaging technologies for ensuring long-term monitoring of quality and safety of foods. These enhance the shelf life of the food products and ensure they remain fresh during storage as well as during transit (Kaushani et al., 2022). Some of the stuff derived from seaweed for packaging have been identified to act as films, which serve as efficient ways of preserving fresh produce shelf life and enhancing the shelf life of dairy products (Waseem, 2023). In this case, packaging plays an essential role of enhancing the safeguard of the products from some extraneous conditions that may affect their quality in the sector of dairy products. Oxygen absorbers, carbon dioxide removers, antimicrobial packaging enhances the qualities of the perishable dairy product and minimizes the risky pathogens (Ščetar et al., 2019). In addition, antimicrobials have been formulated in nanostructures to enhance the safety and quality of the dairy products besides improving the properties of the packaging materials. The use of sustainable packaging is crucial in the circular food system since it affects the consumption of excessive packaging. These solutions also serve the purpose of food preservation and minimize food wastage and the use of resources (Cruz & Varzakas, 2023). Cible packaging presents by itself a concept that has elicited interest on the possibility of boosting the sustainability of the food manufacturing sector (Nair et al., 2023). In addition, the advanced application of biotechnology technologies in the process of making milk seeks to enhance the quality and safety of milk products, and also, the shelf life (Rodionov et al., 2021).

10 Advances in Food and Dairy Processing Technologies

The developments in food and dairy processing have benefited the dairy industry in the aspects of quality, safety and production. Perhaps the most important advancement is the application of various technologies of milk processing that enhance the preservation and safety of the dairy products' physicochemical characteristics and shelf stability (Gebeyehu, 2023). These technologies have enabled functional dairy products and other biotech products to be produced for the food and the pharma markets enabling dairy offers to be versatile. In addition, the strategies of the precision dairy farming through digitalization of the dairy farming and integration the movement sensors and milking parlor also enhanced productivity and good animal welfare (Schuetz et al., 2018). The modern trend of the dairy processing show highly development throughout history the advancement in milk pasteurization, cleaning and sanitizing technologies and the standard of the sanitary equipment during the processing were among the important factors that contributed to the Additionally, high-technology interventions in dairy farms, for example, dairy farm management systems, automated milking systems, IoT systems, etc., have led to greater efficiency in dairy farming, and at the same time has encouraged sustainable farming practices (Rajchamaha, 2023). The current trend towards embracing new techniques of processing and employing analytical methods has made enhancements on the dairy production activities and ways of evaluating the quality of the products (Moschopoulou, 2021). Advanced technologies in food processing have elicited concern on the effect on agriculture value addition raising concerns that require thorough study in order to establish impacts that are likely to affect future agricultural development and agriculture value addition chains (Neema, 2023). In addition, new technologies like high-pressure homogenization has enhanced the quality, shelf life and sensory characteristics of milk and milk products such (Massoud et al., 2016). These developments are in harmony with the increasing global market for premium processed dairy products and respond to key issues of the dairy chain which are sustainability, food quality, animal health, and welfare (Henchion et al., 2022).

11 Food and Dairy By-products Utilization

There are numerous works elaborating the role of food and dairy byproducts covering all aspects of it, including detailed information concerning the consumption process, nutritional value, responsible impacts, economic effects, and measures of protection. Milk and dairy products show benefits in increasing the child diet quality since it increases the nutrient density and reduces the density of food erosive to children's health (Rangan et al., 2012). In addition, findings have shown that the thick of low fat and fat free dairy products on obesity treatment in adolescents (Wrotniak et al., 2018). In terms of sustainability, all of the following foods have

been noted to be micronutrient-dense, cheap and visually appealing; milk and yoghurt. Economically, the increase in demand for dairy products has been looked at with the demand factor emphasizing issues like income effects and trends looked at in research (Irz & Kuosmanen, 2013). There is a push for partnership between the sectors to scale up production of safe and nutritious dairy products; at the same time reducing the impacts on the environment (Tricárico et al., 2019). Food safety is very important in milk production with some measures being recommended to be taken out in order to minimize food borne illness associated with the consumption of raw milk; pasteurization being one of the most common methods recommended (Ruegg, 2003). Concerning the utilization of probiotics in dairy and non-dairy products with a view of enhancing human health, particularly through the consumption of the beneficial bacteria through fermented dairy meals, research has taken place (Ranadheera et al., 2017). Other advancements have also been sourced to biotechnology on the grounds that the innovation has also provided the vantage to enhance the chances of making differentiated dairy products, according to the consumers' preference (Gebeyehu, 2023). Moreover, the more focused on functional products like dairy products with probiotics, added appetite corresponds to a growing recognition of the role of diet (Jang, 2024). Tomašević et al. (2016) found that the dairy business benefits from improved food safety management systems. Traceability in dairy supply chain networks has been identified as critical for addressing quality and safety hazards, particularly given the perishable nature of dairy products (Pant et al., 2015). Forecasting models predict an increase in dairy product consumption, implying possible business growth for industrial companies (Rana, 2021). Consumer behavior and preferences for milk and dairy products have been thoroughly examined, highlighting their popularity and importance in healthy human development (Constantinescu et al., 2018). Innovative dairy products have been investigated, with classic options such as butter, UHT milk, and cheeses being widely consumed (Rybowska, 2022). To prevent milk-borne infections, it is critical to ensure the safety of milk and dairy products through effective heat treatment.

12 Enzymes and Biotechnology in Food Processing

Enzymes play an important part in food processing within the field of biotechnology. They are applied for better the efficiency of countless food industries on the aspects of processing, product quality and energy consumption with less formation of waste. Enzymes are obtained from numerous origins and may be tailored to certain food processing usages via enzyme engineering (Chaudhry & Sagar, 2015; Simpson et al., 2011; Olempska-Beer et al., 2006; Abdullahi et al., 2021). Microorganisms and their metabolic products are mandatory for the existence of food biotechnology because microbial fermentations are crucial for food production. Preparative use of various active ingredients that affect producer microorganisms is a key element of food biotechnology (Dysin et al., 2023). Recombinant microorganisms used within food production are used to help synthesise food ingredients and to aid certain

aspects of food production. These enzymes are required for improving the production of cheap, tasty, and easily available food products (Abdullahi et al., 2021; Olempska-Beer et al., 2006). The assessments done on the safety of food enzymes are crucial for the consumer protection. Bodies that regulate the use of enzymes in food industries carry out tests that help them decide on the safety of enzymes in various processes in the food industry. These evaluations involve the following components: the source of the enzyme, its purpose, and the risks involved.

13 Recent Developments in Sensory Assessment and Consumer Preference Techniques

Recent advances in sensory evaluation and consumer preference approaches have had a substantial impact on a variety of industries, including food, cosmetics, and drinks. These advancements are critical for understanding consumer behavior and preferences, which in turn drive product development and marketing plans. Sensory evaluation is an important approach for identifying consumer preferences for various products. Studies by Lee and Lee (2008) and Pensé-Lhéritier (2015) highlight the significance of sensory data in understanding consumer preferences for products such as rice wines and cosmetics. Preference mapping techniques, as noted by (Simons et al., 2019), are useful in discovering sensory determinants of consumer liking, allowing businesses to optimize their products depending on customer segmentation. According to Ruíz-Capillas et al. (2021), sensory analysis is crucial in the food sector for developing new products and assessing quality. According to Thompson et al. (2004), preference mapping is the process of linking product sensory features to consumer preference ratings, which provides useful information for product development and marketing tactics. Ramírez-Rivera et al. (2019) demonstrated the use of novel approaches, such as the Analytic Hierarchy Process (AHP), for sensory characterization and consumer preference surveys. These technologies provide novel approaches to better understanding consumer preferences and enhancing product development processes. Consumer preferences are important not just for product creation, but also for making sound business decisions. Studies by Svec et al. (2012) and Giannoulis et al. (2013) highlight the necessity of matching consumer preferences with company strategy in order to create systems that effectively meet consumer requirements.

14 Food and Dairy Product Shelf Life Extension

Modern research has paid attention to some new ideas and technologies for the preservation of foods and dairy products. The former is achieved through the use of protective bacterial cultures or their metabolites, which is generally referred to as

biopreservation (Costa et al., 2018). Active packaging and nanomaterials are effective in the extension of shelf life in the dairy products by controlling permeability and other undesirable sensory characteristics (Ščetar et al., 2019). Other types of modified environment packaging techniques are used in packing such products as dairy products and this is through procedures like gas flushing with carbon dioxide among others has gained popularity in enhancing the quality and safety of dairy products which consequently leads to increase their shelf life (Singh et al., 2011). High-pressure processing (HPP) appears to be very effective in enhancing the shelf life of some perishable products like cream than heat pasteurization methods, (Machado, 2023). Additionally, the type of raw materials used can affect the quality of the dairy products though stressing the need to increase raw milk quality as a way of increasing shelf life (Yeung, 2012). According to Mancuso et al. (2014), it was suggested that bioactive packaging material containing antimicrobial peptides has to be used to prevent bacterial growth and spoilage of milk and dairy products. In addition, the interaction of inorganic metal oxide nanoparticles has also demonstrated a possibility of uplifting desirable qualities by decreasing the bacterial load like *E. coli* in raw milk and can enhance the shelf life of dairy products (Jalilzadeh et al., 2015). Antioxidant arising naturally include rosemary extract; they have been observed to prevent the breakdown of nutrients and enhance the longevity of dairy products (Gebeyehu, 2023). Moreover, the significance of electron-beam irradiation and high-pressure processing have equally been investigated on the abilities to enhance the safety of foods, minimize spoilage, and prolong the shelf life of dairy products (Hotchkiss et al., 2006; Nazem, 2024).

15 Regulatory Compliance and Food Safety Standards

Legal requirements and the quality of food products are fundamental foundations of the food industry that supply the populace with quality foods. The standards that constitute the industry are usually owned and pushed by retailers since they are the ones that ensure that all suppliers adhere to the laws regarding food safety (Havinga, 2015). Retailers' participation is driven by some factors like quality of the products they offer and the desire to build confidence in the buyers and protect their selves from claims of liability. Besides, the work indicates that high standards regarding food safety regulation will enable the sphere to develop the capacity in the public sector and make the government management roles less ambiguous. Several innovations of institutions relating to food safety as a public good have been developed that includes; private food safety assurance standards, the WTO's SPS Agreement and the foreign assistance towards better food safety management in developing nations (Unnevehr, 2007). These initiatives clearly signify that there is a need for international efforts and acclamation for the purpose of ensuring food safety on the global level. Out sourcing its function to supermarkets is becoming a common feature and many regulatory strategies are being applied ranging from public to private

and from minimalist to maximum regulation responsibilities. (Havinga, 2006). As this change in the private standard signifies, the various participants in the food supply chain have a major role in observing food safety standards. Specifically, the aspects of regulatory compliance in the United States are the strict and rigorous observance of the rules, regulations, and standard set down by the regulatory administrative bodies such as the US Food and Drug Administration (USFDA), to ensure the safe and effective utilization of the various products including drugs, medical devices as well as food and beverages circulating in the market (Sharma, 2023). This puts great importance on the requirement of regulatory compliance of business establishments in the promotion and sustenance of high standards of food safety and quality.

16 Novel Extraction Technology in Food Processing

Several new extraction methods have emerged including enzyme assisted extraction, microwave assisted extraction, ultrasound assisted extraction, supercritical fluid extraction and pulsed electric field assisted extraction. Compared to traditional methods these technologies provide benefits such as lower solvent consumption, shorter extraction time, higher yields and less energy usage (Diaconeasa et al., 2022; Gangopadhyay et al., 2015). The adoption of new extraction technologies coincides with the food industry's need for green and sustainable processing methods to eliminate the use of hazardous chemicals and increase overall process efficiency (Noor et al., 2021). Technologies such as ultrahigh pressure extraction (UPE) have been developed to use high pressure to extract valuable compounds from food sources (Zhang et al., 2007). Pulsed electric field assisted extraction (PEFAE) has shown potential in valorizing food processing waste by extracting bioactive compounds while reducing solvent and energy requirements (Velusamy et al., 2023). Incorporating new extraction methods not only enhances the extraction process but also promotes sustainable waste management. Technologies such as pulsed electric field (PEF) extraction is critical in managing food waste sustainably, reducing environmental impact and increasing bioactive compound extraction from waste materials (Chatzimitakos, 2023). Recovery of polyphenols from food byproducts using eco-friendly approaches shows the potential of mild extraction technologies to improve food processing sustainability (Ebrahimi & Lante, 2022). Adopting new extraction methods is key to increasing food value and meeting customer demand for clean label products made with natural ingredients. These technologies help preserve food ingredients while increasing extraction efficiency and product quality (Gopalan & Sharma, 2017). Furthermore, use of high pressure processing (HPP) technology and other emerging non thermal technologies in food processing ensures food safety and quality by retaining the molecular and structural properties of food (Chen et al., 2018a, b).

17 Future Trends in Food and Dairy Process Engineering and Business

A number of features have been identified in recent studies that would influence future trends in food and dairy process engineering and business. The changes being experienced in the dairy sector are vital for its long-term viability as well as meeting changing customer needs. Major among them is prioritizing innovation and R&D to introduce new dairy products that match consumer expectations (Hu, 2023). There is a change in regional production and consumption patterns, intensification of production goals, and higher recognition of environmental impacts caused by plant based or synthetic milks (Bojovic & McGregor, 2022). To enhance sustainability, dairy producers emphasize genetic enhancements and managerial developments aimed at increasing yields of fodder crops and cereals while minimizing carbon footprints (Martin et al., 2017). Modern processing technologies such as thermal and nonthermal processes are used to improve food safety while preserving quality (Roos et al., 2015). Automation technologies or robotization approaches are being widely embraced in dairy farming practices to enhance productivity efficiency levels (Yurochka et al., 2023). High-intensity pulsed electric field processing is being investigated to enhance the quality of milk and dairy products (Sobrinho-López & Martín-Belloso, 2009). Despite environmental problems, the dairy business continues to be critical to world food production. To increase sustainability, dairy farms are projected to become smarter, more profitable, and higher producing (Pulina et al., 2020). Digital solutions are being implemented to promote efficiency, sustainability, and transparency in food businesses (Raheem et al., 2019). Reproductive management approaches are emerging to improve dairy cow performance, health, and fertility (Crowe et al., 2018). Furthermore, emerging technologies such as artificial intelligence and blockchain are viewed as viable instruments for improving resource allocation and sustainability efforts in the dairy business (Atadoga, 2024).

18 Conclusions

In conclusion, the field of food and dairy process engineering is pivotal in addressing the growing demand for safe, nutritious, and sustainable food products. This book has explored diverse aspects, from fundamental safety principles to advanced processing technologies. Sustainable dairy farming practices, innovative raw material handling, and cutting-edge quality control methods ensure the integrity of food products. Understanding fluid mechanics, heat transfer, fermentation, and separation technologies enhances efficiency and product quality. Freezing, cooling, mixing, and emulsification techniques, along with sustainable packaging solutions, extend shelf life and reduce waste. Emphasizing quality assurance, biotechnology, and regulatory compliance is essential for maintaining high standards and consumer trust. Future trends point towards sustainability, precision agriculture, and digital

integration, necessitating interdisciplinary collaboration. By embracing these advancements, we can ensure a future where safe, nutritious, and sustainable food products are accessible to all, contributing to global food security and environmental well-being.

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Chapter 2

Principles of Food Dairy Safety: Challenges and Opportunities



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1 Introduction

Over the past 20 years, there have been more incidents of food hazards, which has led to consumers getting more and more concerned about food safety. Internationally, the food and dairy industries face both challenges and opportunities in terms of market prospects, production, and trading. Global demand for dairy products has been broadening consistently due to factors like changing dietary preferences, rising disposable incomes, and population expansion, particularly in emerging economies like China, Southeast Asia, and India. Consumers are increasingly seeking healthier and more natural dairy products, including organic, low-fat, and probiotic-rich options, creating opportunities for innovation and product diversification (Franco & Nagrale, 2020). There is growing awareness about the environmental impact of dairy production, leading to a demand for sustainable and ethically sourced dairy products. The hike in e-commerce platforms and digitalization has transfigured the way consumers purchase dairy products, presenting opportunities for companies to reach a wider audience and streamline distribution channels.

The food and dairy sectors are vulnerable to variations in production and distribution due to supply chain disruptions brought on by events like disease outbreaks, natural disasters, and geopolitical instability. Ensuring consistent quality and safety standards across international supply chains can be challenging due to differences in regulations, production practices, and infrastructure among countries. Dairy production requires significant resources, including water, feed, and land, which can be limited in certain regions. Maintaining the health and welfare of dairy animals is

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crucial for sustainable production. Challenges such as disease outbreaks, antibiotic resistance, and animal welfare concerns require proactive management and investment in veterinary care (Franco & Nagrale, 2020). International trade in dairy products is often subject to tariffs, quotas, and trade barriers imposed by governments, affecting market access and pricing dynamics. Meeting regulatory requirements for food safety, labelling, and certification can pose challenges for exporters and importers operating in different jurisdictions, requiring careful navigation of complex regulatory landscapes (Charlebois et al., 2021). Microbial contamination, such as pathogens like *Salmonella*, *E. coli*, and *Listeria* spp., poses a severe threat to public health and can lead to foodborne illnesses and outbreaks. Antibiotic-resistant bacteria are created as a result of the abuse and overdose of antibiotics in animal farming, which includes dairy production. This compromises the usefulness of antibiotics in medicine for humans as well as animals. Agencies closely monitor the emergence of new or previously unrecognized pathogens in dairy products, such as emerging strains of bacteria or viruses with potential public health implications. Rapid detection, surveillance, and response mechanisms are critical to addressing these emerging microbial threats (Feliciano et al., 2020). During the pandemic, there has been an increased emphasis on hygiene and sanitation practices throughout the food and dairy supply chain (Hamid & Mir, 2021). This includes rigorous cleaning and disinfection protocols in dairy processing facilities, transportation vehicles, and retail establishments to minimize the risk of virus transmission. Consumer behaviour has undergone significant changes during the pandemic, including shifts towards online shopping, increased demand for shelf-stable and long-lasting dairy products, and preferences for trusted brands with strong safety and quality assurances. Regulatory agencies have implemented additional measures to safeguard food and dairy safety during the pandemic, including guidance on COVID-19 risk mitigation strategies, temporary regulatory flexibilities to address supply chain disruptions, and increased monitoring of foodborne illness outbreaks (Acosta et al., 2021). The pandemic has accelerated the adoption of technology and innovation in the food and dairy sectors to enhance safety, efficiency, and resilience. Artificial Intelligence (AI), big data analytics, and the Internet of Things (IoT) are examples of Industry 4.0 technologies that allow for real-time monitoring and analysis of several factors across the dairy production process (Djekić et al., 2023). This data-driven approach allows for proactive identification of potential safety risks and opportunities for optimization. Automation and robotics systems can streamline dairy production processes, reduce human error, and enhance consistency and quality control. Blockchain technology, a key component of Industry 4.0, offers opportunities for improving back-tracing and transparency in the dairy supply chain. Smart packaging solutions, including Radio Frequency Identification (RFID) tags and Quick-response (QR) codes, can provide consumers with instant access to information about product ingredients, nutritional content, and safety certifications. Industry 5.0 technologies may enable greater personalization and customization of dairy products to meet individual consumer preferences and dietary needs. Industry 5.0 emphasizes sustainability and environmental responsibility, prompting the adoption of eco-friendly manufacturing processes and resource-efficient practices in the food and dairy industry (Lei

et al., 2022). This could include the adoption of renewable energy sources, waste reduction strategies, and circular economy principles to minimize environmental impact.

2 Safety Issues in Production, Processing and Supply Chain of Dairy and Food Sectors

Food that is safe and secure is crucial for human health. Every institution that handles food is concerned with food safety, which is closely related to food nutrition. Food that is unfit for human eating can be triggered by a variety of circumstances. The main issues regarding food threats that are explicitly raised include microbiological, chemical, and pesticide residues, as well as allergies (Morya et al., 2020).

2.1 Microbial Hazards

The primary health and safety risks facing food operations today are foodborne microorganisms, which might give rise to contamination and intoxication. Food safety and security regulations must be subsequently followed, and the ability to recognize and track harmful bacteria is essential to the safety and security of food products (Yamada et al., 2016).

Raw materials used in dairy and food production, such as milk, fruits, vegetables, and grains, can harbor harmful microorganisms like bacteria, molds, and yeasts. The quality and safety of raw materials through proper sourcing, storage, and handling practices are essential to prevent microbial contamination. The implementation of strict supplier qualification and verification processes can help ensure that raw materials meet microbiological safety standards before they enter the production facility. Poor hygiene practices during production, including inadequate hand-washing, improper cleaning of equipment, and cross-contamination between raw and cooked foods, can contribute to microbial contamination.

It is important to train and educate personnel on proper hygiene practices, including hand hygiene, sanitation procedures, and personal protective equipment (PPE) use, are essential to prevent microbial contamination in the production environment. Inadequate processing procedures, such as insufficient heat treatment, improper cooling, or inadequate preservation methods, can fail to eliminate or control microbial contaminants in dairy and food products. Hence, the implementation of validated processing techniques, such as pasteurization, sterilization, and thermal processing, can effectively kill or inhibit microbial growth in dairy and food products. Monitoring critical control points in the production process and implementing corrective actions when deviations occur can help ensure the microbiological safety of finished products. The risk of Cross-contamination between different production

areas, equipment, and surfaces can introduce microbial contaminants into dairy and food products. Implementing effective segregation measures, such as dedicated production areas for raw and cooked products, color-coded equipment, and sanitation protocols for shared equipment, which can help minimize cross-contamination risks.

Allergen contamination in dairy and food products can pose serious health risks to consumers, especially if cross-contamination occurs during production.

Emerging pathogens such as *Salmonella* spp., *Escherichia coli* O157:H7, and *Listeria monocytogenes* continue to pose challenges in food safety. Foodborne infections are a serious concern when it comes to antibiotic resistance, since the improper application of antibiotics in agriculture can lead to the emergence of resistant strains. Pathogenic bacteria come in many different varieties and can cause foodborne sickness. Consequently, a disease brought on by contaminated germs can be classified as a foodborne ailment (Morya et al., 2020). Many different kinds of microorganisms can cause food poisoning. These days, a wide variety of foodborne illnesses are common. Food poisoning produced by bacteria accounts for more than 80% of food poisoning cases, according to laboratory studies that demonstrate food consumption is the direct cause by breeding the pathogenic bacteria (Pepin et al., 2014).

The primary underlying cause of foodborne illnesses is bacteria. In 2000, the United Kingdom saw a 77.3% infection rate from *Campylobacter jejuni*, a 20.9% infection rate from *Salmonella* spp., and a 1.4% infection rate from *E. coli* O157:H7 and others accounted for less than 0.1% of the underlying causes of foodborne diseases (Aljamali et al., 2021).

The two main types of bacteria that cause food intoxication are *Staphylococcus aureus* and *Clostridium botulinum*. It is also known that *Clostridium perfringens* and *Bacillus cereus* may bring about food poisoning (Aljamali et al., 2021).

The effects of mycotoxins through food consumption are referred to as alimentary mycotoxicosis. Mycotoxins can occasionally have significant negative impacts on animal and human health. Illnesses brought on by dietary poisons and fungi contain Fumonisin, Aflatoxin, Patulin, and Tremorgenic mycotoxins. Good Manufacturing Practices (GMP) that are properly implemented and enforced, as well as food safety monitoring and surveillance, are crucial elements of contemporary food supply systems that are essential to the management of foodborne pathogens.

2.2 Chemical Hazards

Recent safety issues related to chemical contaminants in the manufacturing, processing, and supply chain of dairy and food sectors have continued to evolve with advancements in technology, changes in agricultural practices, and emerging regulatory concerns. Antibiotic resistance remains a significant concern in the dairy and food sectors, driven by the misuse and overuse of antibiotics in livestock farming. Regulatory agencies worldwide are increasingly focusing on monitoring antibiotic

residues in food products and implementing stricter controls to mitigate the risk of antibiotic resistance. Emerging research suggests that antibiotic residues in food products may lead to the spread of antibiotic-resistant bacteria and genes, creating a potential public health risk.

The use of pesticides and insecticides in agriculture continues to raise concerns about the presence of residues in food products. Consumer demand for organic and pesticide-free food products has led to increased scrutiny of pesticide residues in conventional farming practices and the adoption of alternative pest control methods.

Emerging chemical contaminants, such as per- and polyfluoroalkyl substances (PFAS), pharmaceuticals, and industrial chemicals, pose new challenges to food safety and environmental health. These contaminants can migrate into the food supply chain via various pathways, such as contaminated water sources, agricultural runoff, and food packaging materials. Regulatory agencies are exploring new monitoring methods and setting limits for emerging contaminants to protect consumers from potential health risks. Environmental pollutants, such as heavy metals (e.g., lead, cadmium, mercury), persistent organic pollutants (POPs), and industrial chemicals, can contaminate soil, water, and air, posing risks to food safety and environmental health. Contaminants may enter the food supply chain through uptake by plants or animals, bioaccumulation in the food chain, or direct contamination during processing or packaging.

Processing aids, additives, and packaging materials used in food processing and packaging may introduce chemical contaminants into dairy and food products. Contaminants can leach from equipment, containers, or packaging materials into food products, particularly under conditions of high temperature, acidity, or prolonged storage.

As industrialization and urbanisation expand, so does the amount of metals contaminating food. Harmful metals can find their way into a wide range of foods due to a number of causes, such as packaging materials, animal feed, agricultural soils, irrigation water, agricultural practices, and air pollution. Hazardous metals do not biodegrade, thermodegrade, or remain in the environment for very long. They accumulate quickly in a variety of foods. Metal contamination of various foods, including crops, meat, milk, fish, and eggs, puts food security and safety at risk. A major risk to human health arises from the introduction of contaminated plants, animals, irrigation water, agricultural soils, and plants into the food chain. The bulk of metals have negative effects on human health and accumulate in a number of organs, including the kidney, liver, spleen, and skeleton. Animal and plant productivity is negatively impacted by metals. As a result, several remediation techniques had to be used in order to reduce the amount of dangerous heavy metals that entered the human body and food chain. Metal nanoparticles have a wide range of applications, but they may also present significant risks (Abdel-Rahman, 2022).

If toxic metals are present in milk or milk products, it can be dangerous and detrimental to human health. Thus, milk and milk products become less safe as metal levels grow. The environmental state could be responsible for the majority of the variation in metal contamination in milk (Singh et al., 2020). The various fish absorbed harmful metals from the water either by drinking it directly or by

absorbing it through their skin, gills, and digestive systems (Marzouk et al., 2016). To improve food safety and preserve human health, it is vital to estimate the levels of heavy metals in animal muscle and offal. The age of the animal affected the amount of metals in the meat because as the animal became older, the amount of water and protein in the meat reduced while the amount of fat and ash increased. This resulted in an increase in the amount of metals in the meat (Darwish et al., 2015). Eggs are a cheap food source that is packed with nutrients essential to human health. However, eggs can acquire some harmful elements (Hussien & Nosir, 2017). When compared to fruit vegetables like tomatoes and cucumbers, leafy vegetables like lettuce, watercress, and potatoes had the highest concentration of harmful metals (such as lead, aluminum, arsenic, and mercury) (Eissa & Negim, 2018).

2.3 Safety-Related to Environmental Issues

Seasons and climate variables are expected to have a direct impact on the microbial ecology of raw milk, which in turn will affect the microbial profile of dairy products. These variables include variations in average temperature, relative humidity, average precipitation, and sunshine (Moretti et al., 2010). Through the induction of heat stress in nursing cows, climatic change indirectly affects the microbiological profile of raw milk by altering the microbiota, concentration, and kinds of microorganisms in raw milk, as well as their sensitivity to pathogenic microorganisms. Furthermore, the effects of heat stress on nursing cows include a decrease in milk production and modifications to the physicochemical characteristics of the raw milk produced by these animals.

The microbial ecology and variety of raw milk can be influenced by the seasons and climate, and the anticipated increase in the mean global temperature can promote the quicker growth of microorganisms and the microbial ecology of both raw and processed milk products. These modifications may take two forms. According to Marchand et al. (2009), they are the rise in the microbial burden caused by food-borne pathogens and/or food microorganisms. The most diverse microorganisms were found in the summer, followed by those found in the spring and fall. The least diverse milks were found in the winter months. Higher concentrations of microorganisms are found in the summer, and spore-forming bacteria like *Bacillus* spp. were the most often observed types.

During the winter, *Pseudomonas* species, lactic acid bacteria, and other psychrophiles were the most common microbes observed. Furthermore, seasonal parallels were noted, specifically between winter and spring and between autumn and spring. Climate change is expected to increase both the average temperature and the frequency of extreme weather events, such as droughts. This might impact the dairy industry by altering the health of nursing cows, which would subsequently have an impact on the raw milk's quality. Indeed, the consequences of rising temperatures (West, 2003).

The alterations in lactation cows can include decreased eating behaviours, oxidative stress induction, and immunological function degradation. These are linked to alterations in physiological circumstances, as well as an increased risk of infections and mastitis. The problem of preserving cow health in the face of climate change scenarios could, however, be compounded by the potential future appearance of novel infections and vector-borne illnesses. In the end, these modifications to the health status of cows may also result in modifications to the microbiology of raw milk, a decrease in raw milk yield, and modifications to the physicochemical characteristics of raw milk, all of which may impact the development of heat stress in cows.

Bacterial infections, including those from *Staphylococcus aureus*, *Streptococcus* spp. (*S. agalactiae*, *S. dysgalactiae*, and *S. uberis*), *E. coli*, and, less frequently, *Listeria* spp. (*L. innocua*, *L. monocytogenes*, and *L. ivanovii*), are the most common cause of mastitis in lactating cows. According to West (2003), heat stress in cows has an adverse effect on the physicochemical characteristics of raw milk as well as milk yield. When cows are lactating, the detrimental effects of heat stress may cause a decrease in milk production. The impact of hot, muggy weather on a cow's typical resting state, which leads to disruptions in its typical physiological or productive states, is known as heat stress.

Global warming and climate change have similar effects on food production efficiency and quality worldwide. The rise in global food production in recent years has mitigated these effects. At least half of the world's population gets its protein from fisheries, but they are currently under a lot of stress due to overexploitation, harmful environmental consequences, and alterations in the climate, which puts the food source at risk. Elevated temperatures, drought-related stress, or higher CO₂ concentrations can all lower crop and livestock productivity. These effects might happen suddenly or gradually. Droughts, floods, excessively high or low temperatures, and other extreme weather conditions can negatively impact a variety of crops, including maize, soybeans, wheat, rice, cotton, pasture, and fruit yields (Aryal et al., 2019).

According to Simpson et al. (2004), environmental factors, such as temperature, relative humidity, insect attack, drought, and plant stress, have a significant impact on moulds' capacity to produce mycotoxins. Additionally, the pathogenicity of different mould varieties may be partially additive, and the selective advantage of one over another may be temperature dependent. The species composition of Fusarium Head Blight (FHB) in wheat varies depending on several variables, chiefly temperature, and climatic circumstances.

The weather affects the infection cycle in different ways. For example, heavy rains during anthesis can effectively spread *Fusarium* inoculum to ears, and extended warm, humid periods are favourable for *Fusarium* spp. to infect cereal ears. The very poisonous trichothecene mycotoxins, like DON (Deoxynivalenol), are present in the low-quality grains that are harvested from *Fusarium*-infected ears. The formation of DON can also be significantly impacted by temperature fluctuations (Hope et al., 2005).

Climate change has been linked to an increase in bacterial contamination of food and water in relation to food and feed microorganisms. This could lead to a shift in

the hazards associated with foodborne and waterborne infectious diseases. Food- and water-borne bacteria can result in mild to severe gastrointestinal disorders in humans, as well as significant complications such as hemolytic-uremic syndrome (H7) or hemorrhagic colitis (*Escherichia coli* O157:H7), meningitis (*Listeria monocytogenes*), Guillain-Barre syndrome (*Campylobacter* spp.), and hemorrhagic colitis.

3 Safety Regulatory Framework Globally

3.1 Regulation of Food and Dairy Sector by FAO/WHO

Global food and dairy product safety and quality are regulated and guaranteed by the Food and Agriculture Organisation (FAO) and the World Health Organisation (WHO). Through the Codex Alimentarius Commission, FAO and WHO work together to create global food standards, guidelines, and codes of practice. These standards cover a wide range of food and dairy products, ensuring their safety, quality, and fairness in international trade. They conduct risk assessments on various foodborne hazards, including microbiological, chemical, and physical contaminants, and guide risk management measures to control these hazards and ensure food safety along the entire food chain. FAO/WHO assists countries in building their capacity to safeguard food safety and quality. This includes providing technical assistance, training programs, and expertise to improve food safety systems, laboratory capabilities, and regulatory frameworks. They collaborate with countries to establish surveillance systems for monitoring foodborne diseases and contaminants. This helps in the early detection of outbreaks and identification of emerging risks, allowing for timely intervention and control measures. They also provide support during food safety emergencies, such as outbreaks of foodborne illnesses or contamination incidents. They assist in risk communication, coordination of response efforts, and facilitating international cooperation to address the crisis. These agencies also work towards raising awareness among consumers about safe food handling practices, proper nutrition, and the importance of making informed food choices. This gives customers more power to defend themselves and their families against foodborne illnesses (Gandhi et al., 2020).

3.2 Regulation Related to Food and Dairy Sector by European Unions

The European Union (EU) has a comprehensive regulatory framework for ensuring food safety and quality standards within its member states. Regulation related to the food and dairy sector in the EU is extensive and covers various aspects, including

production, processing, labeling, and marketing (Sorbo et al., 2022; Tsaregorodtseva et al., 2020).

- (a) **General Food Law Regulation (EC) No 178/2002:** The present regulation establishes the fundamental tenets and prerequisites of EU food law, encompassing food safety, traceability, and risk assessment. It creates the European Food Safety Authority (EFSA) to offer unbiased scientific guidance on hazards associated with food.
- (b) **Hygiene Regulations:** The EU has hygiene regulations (Regulation (EC) No 853/2004 and Regulation (EC) No 854/2004) that set out defined hygiene requirements for food businesses, including those handling dairy products. These regulations cover aspects such as premises, equipment, personnel hygiene, and temperature control to ensure the safety of food products.
- (c) **Regulation (EU) No 1169/2011 on Food Information to Consumers:** This regulation harmonizes food labeling requirements across the EU, including mandatory information on allergens, ingredients, nutrition, and origin labeling. It aims to provide consumers with clear and accurate information about the food they purchase, including dairy products.
- (d) **Veterinary Regulations:** Veterinary regulations (Regulation (EC) No 853/2004 and Regulation (EC) No 854/2004) establish specific rules for the production and placing on the market of products of animal origin, including dairy products. These regulations cover requirements for official controls, labeling, and health certificates for dairy products intended for human consumption.
- (e) **Organic Production Regulation (EC) No 834/2007:** This regulation sets out the requirements for organic production and labeling of agricultural products, including dairy products. It establishes standards for organic farming practices, animal welfare, and the use of additives and processing aids in organic dairy production.
- (f) **Regulation (EU) No 1308/2013 on the Common Organisation of the Markets in Agricultural Products:** This regulation governs the common organization of agricultural markets within the EU, including measures related to the dairy sector such as production quotas, price support mechanisms, and marketing standards.
- (g) **Food Safety Authorities:** The national food safety authority of every EU member state is in charge of enforcing EU food safety laws inside its borders. To verify adherence to EU regulations, these authorities sample, examine, and audit food goods.

3.3 *Regulation related with Food and Dairy by South Asian Countries*

Regulation related to food and dairy varies across South Asian countries, but many have established regulatory frameworks to ensure food safety, quality, and standards. Here are some examples of regulations and authorities in South Asian countries:

3.3.1 India

The Food Safety and Standards Authority of India is primarily responsible for overseeing regulations pertaining to food and dairy products in India (FSSAI). Established by the Food Safety and Standards Act of 2006, the Food Safety and Standards Authority of India (FSSAI) is a governmental agency tasked with enforcing national regulations and standards pertaining to food products, particularly dairy. The following are some significant laws and programmes pertaining to food and dairy in India:

3.3.1.1 Food Safety and Standards Act, 2006

The legal foundation for governing food safety and standards in India is provided by this legislation. It creates the Food Safety and Standards Authority (FSSAI) and delineates its authority and duties, which include establishing guidelines for food items, controlling their production, storage, sale, and importation, and guaranteeing adherence to food safety regulations.

3.3.1.2 Food Safety and Standards (Food Products Standards and Food Additives) Regulations, 2011

These regulations says about standards for several food products, including dairy products such as milk, milk products, and dairy analogues. They specify requirements related to composition, labeling, packaging, and hygiene standards for dairy products.

3.3.1.3 Food Safety and Standards (Licensing and Registration of Food Businesses) Regulations, 2011

These regulations specify the licensing and registration requirements for food businesses, including dairy processing units, milk collection centers, and dairy farms. They outline the procedures for obtaining licenses and registrations from the FSSAI based on the scale and nature of the food business.

3.3.1.4 Food Safety and Standards (Packaging and Labelling) Regulations, 2011

This prescribes about the packaging and labelling requirements for food products, including dairy products. They specify mandatory information that must be displayed on the labels of dairy products, such as the name of the product, list of ingredients, nutritional information, batch number, and expiry date.

3.3.1.5 Food Safety and Standards (Contaminants, Toxins, and Residues) Regulations, 2011

These rules set maximum limits on a range of residues, poisons, and pollutants that can be found in food items, including dairy products. They establish guidelines to guarantee that dairy products are safe to eat and devoid of dangerous ingredients.

3.3.1.6 Surveillance, Enforcement, and Capacity Building

The FSSAI conducts surveillance, inspection, and enforcement activities to ensure compliance with food safety regulations. It also conducts capacity building programs, training workshops, and awareness campaigns to enhance the capacity of food businesses and enforcement authorities in ensuring food safety and quality.

3.3.2 Japan

In Japan, regulation related to food and dairy products is overseen by several government agencies, including the Ministry of Health, Labour and Welfare (MHLW), the Ministry of Agriculture, Forestry and Fisheries (MAFF), and the Consumer Affairs Agency (CAA).

3.3.2.1 Food Sanitation Act

The main piece of legislation in Japan establishing requirements for food safety and hygiene is the Food Sanitation Act. It lays up specifications for the production, sale, and distribution of food items, especially dairy. The Act establishes maximum residual limits for agricultural pesticides and pollutants in food, as well as hygienic criteria for food facilities and labelling specifications.

3.3.2.2 Standards for Milk and Dairy Products

MAFF sets standards for milk and dairy products under the Agricultural Standards Act. These standards include specifications for milk composition, hygiene requirements for dairy processing facilities, and labelling requirements for dairy products sold in Japan.

3.3.2.3 Food Labelling Regulations

The MHLW and the CAA regulate food labelling in Japan. Food labelling regulations specify requirements for labelling information such as product name, ingredients, nutritional information, expiration date, and allergen labelling. These regulations ensure that consumers have access to accurate and reliable information about the food products they purchase, including dairy.

3.3.2.4 Quota System for Milk Production

Japan operates a quota system for milk production to support domestic dairy farmers and ensure a stable supply of milk. Under this system, dairy farmers are allocated production quotas by the government, and any excess production is subject to penalties or restrictions.

3.3.2.5 Import Regulations

Japan imposes import regulations on dairy products to protect domestic producers and ensure the safety and quality of imported products. Imported dairy products are subject to inspection and certification requirements to verify compliance with Japanese standards and regulations.

3.3.2.6 Food Safety Monitoring and Surveillance

The MHLW conducts monitoring and surveillance programs to assess the safety and quality of food products, including dairy. This entails sampling and testing food products for pollutants, monitoring outbreaks of foodborne illness, and routine inspections of food processing plants.

3.3.2.7 Promotion of Food Safety and Consumer Education

Japanese government agencies promote food safety through consumer education and awareness campaigns. These campaigns aim to aware consumers regarding safe food handling practices, proper nutrition, and the importance of making informed food choices.

3.3.3 Other Countries

3.3.3.1 Pakistan

The Pakistan Standards and Quality Control Authority (PSQCA) is responsible for developing and enforcing standards for food and dairy products in Pakistan. The Punjab Food Authority (PFA), Sindh Food Authority (SFA), and other provincial food authorities oversee food safety and quality within their respective provinces. The Pakistan Dairy Development Company (PDDC) is involved in promoting dairy development and quality improvement initiatives.

3.3.3.2 Bangladesh

The Bangladesh Standards and Testing Institution (BSTI) is responsible for setting and enforcing standards for food and dairy products in Bangladesh. The Directorate General of Food (DG Food) under the Ministry of Food is tasked with ensuring food safety and quality, including dairy products. The Bangladesh Milk Producers' Co-operative Union Ltd. (Milk Vita) is a key organization involved in regulating and promoting the dairy sector in Bangladesh.

3.3.3.3 Sri Lanka

The Sri Lanka Standards Institution (SLSI) develops and maintains standards for food and dairy products in Sri Lanka. The Ministry of Health, through its Food Control Administration Unit, is responsible for ensuring food safety and quality, including dairy products. The National Milk Board (NMB) oversees the dairy industry's development and regulates milk production, processing, and marketing.

3.3.3.4 Nepal

The Department of Food Technology and Quality Control (DFTQC) under the Ministry of Agriculture and Livestock Development is responsible for regulating food safety and quality standards in Nepal. The Dairy Development Corporation (DDC) is a government-owned corporation involved in regulating and promoting the dairy industry in Nepal (Table 2.1).

Table 2.1 Regulatory standards for food and dairy safety in India, Japan, Nepal, Bangladesh, and Sri Lanka

Country	Regulatory Authority	Key Regulations	Standards
India	Food Safety and Standards Authority of India (FSSAI)	Food Safety and Standards Act, 2006—Food Safety and Standards (Food Products Standards and Food Additives) Regulations, 2011—Food Safety and Standards (Licensing and Registration of Food Businesses) Regulations, 2011 Food Safety and Standards (Packaging and Labelling) Regulations, 2011—Food Safety and Standards (Contaminants, Toxins, and Residues) Regulations, 2011	Milk and Milk Products (IS:1479:1991) Dairy Milk Powder (IS:1165:1992) Ice Cream (IS:1167:1985) Butter (IS:13690:1992) Ghee (IS:13690:1992) Cheese (IS:2785:1992)
Japan	Ministry of Health, Labour and Welfare (MHLW)	Food Sanitation Act—Standards for Milk and Dairy Products	Standards for milk and milk products (Notification No. 370 of the Ministry of Health, Labour and Welfare, 1951)—Standards for butter and cheese (Notification No. 264 of the Ministry of Health, Labour and Welfare, 1959)
Nepal	Department of Food Technology and Quality Control (DFTQC)	Nepal Standard (Food) Regulations, 1997 Nepal Standard (Packaged) Milk Specification, 1995	Dairy Products—Specification (Nepal Standard No. 2473, Part 4: 2056) Pasteurized milk—Specification (Nepal Standard No. 3141, Part 1: 2053) Flavored milk—Specification (Nepal Standard No. 3141, Part 2: 2053)
Bangladesh	Bangladesh Standards and Testing Institution (BSTI)	Bangladesh Standards (Food) Order, 1972; Bangladesh Standard Specification for Pasteurized Milk, Powdered Milk, and Dairy Permeate	Pasteurized milk—Specification (BDS 1112:2002) Whole dried milk—Specification (BDS 179:2000) Skimmed milk powder—Specification (BDS 180:2000)
Sri Lanka	Sri Lanka Standards Institution (SLSI)	Sri Lanka Standards (Food) Regulations, 1991; Sri Lanka Standard Specification for Pasteurized Milk	Pasteurized milk—Specification (SLS 731:2012) Milk powder—Specification (SLS 364:2001) Ice cream—Specification (SLS 33:1984)

4 Challenges for Establishing the Safety Concerns

4.1 Raw Material Quality

Raw materials can harbour various microorganisms, including bacteria, molds, and yeasts, which can contaminate food products during processing. Pathogenic microorganisms such as *Salmonella*, *Escherichia coli*, and *Listeria monocytogenes* pose significant risks to food safety if present in raw materials. Controlling microbial contamination requires stringent hygiene practices during production, proper storage conditions, and effective sanitation procedures for equipment and facilities. The emerging pathogens and contaminants in the food and dairy industries lead to significant challenges to food safety and public health. The evolving technology in the food and dairy industries explains the entry of novel viruses into the food chain and their effect on food safety. Enhancing the culture-independent and molecular biology-based detection techniques is crucial. The primary variables influencing the introduction of infections and pollutants in the food and dairy industries are farming techniques, animal husbandry, horticulture, transportation for additional processing, advancements in food technology, distribution patterns, eating habits, etc. The contamination with bacterial pathogens can lead to a risk to public health, that results in sporadic illness or outbreaks of disease. Continuous monitoring of processes, research, and implementation of preventive measures are crucial to address these concerns (Uyttendaele & Boec, 2016). The presence (or emergence) of novel or unexpected pathogens in foods is likely one of the most significant developments that will affect food safety during the next fifty years (Tauxe et al., 2010). Primarily, emerging microorganisms consist of:

- A. **Yersinia** is a bacillus-to-coccobacillus, gram-negative bacterium that can be found in a variety of dietary and environmental sources. It is thought that one of the most prevalent milk-borne infections that causes yersiniosis is *Yersinia enterocolitica*. It is possible for *Yersinia* to proliferate at temperatures very near to freezing. Long storage periods for food held at refrigerator temperatures are made possible by vacuum packaging techniques, which also provided sustenance for the bacteria. A foodborne illness called human yersiniosis, which is brought on by *Yersinia enterocolitica*, is commonly found in pork products. Therefore, the industrialization of pig slaughter and modifications in livestock farming are crucial to removing this agent from pig herds, which is a necessary step in producing pork free of human pathogens (Nesbakken, 1992).
- B. **Campylobacter** is a gram-negative, thermophilic bacteria that is one of the four main causes of diarrheal illnesses in the world. Poultry is the source of the emergence of *Campylobacter* infections in humans. The poultry's body temperature of 41 °C facilitates the growth of *Campylobacter* in its digestive system. The major causes of the rise in *Campylobacter* counts on the final product are the large-scale production of poultry in enclosed buildings, which allows the bacteria to proliferate during the capturing and transportation stages to the

slaughterhouses, as well as the methods of slaughter that result in severe fecal contamination (Oliver, 2000).

- C. *Arcobacter butzleri*, One of the three species of *Arcobacter butzleri* that have been recovered from humans and animals is found in drinking water reservoirs, water treatment facilities, rivers, canal water in large cities, and contaminated water wells. It may be more prevalent in developing nations with insufficient water supplies and is contracted by ingesting contaminated water and undercooked poultry (Wesley, 2001).
- D. *Escherichia coli* O157:H7, A toxin resembling Shiga is produced by the *Escherichia coli* O157:H7 serotype of the bacterium species. Eating uncooked or contaminated food, like raw milk or undercooked ground beef, can cause illness, the most prevalent of which is foodborne illness (Simonet, 1999).

Raw materials may contain chemical contaminants such as pesticides, heavy metals, mycotoxins, and veterinary drug residues, which can pose health risks if present in food products. Chemical contaminants can enter the food chain through various sources, including agricultural practices, environmental pollution, and processing equipment. Establishing chemical safety involves monitoring and controlling the use of chemicals in agriculture, implementing good agricultural practices (GAP), and conducting regular testing and analysis of raw materials for chemical residues. Emerging contaminants are man-made or naturally occurring substances, microbes, or both that are not regularly observed in the environment and have the potential to do harm to human well-being, the natural world, or combined. Microplastics and nanoplastics (M/NPs) are also emerging contaminants in food that can enter the human body through inhalation, ingestion, and skin contact (Skovgaard, 2007). Ingestion of fertilisers and pesticides by people can lead to adverse health effects. Fruits and vegetables containing pesticide residues, as well as some of their derivatives, can have negative effects. For example, metabolites from organo-chlorine pesticides have been detected in fatty foods. Toxic heavy metals are released when insecticides and fertilisers are used (Kobayashi et al., 2011). Animal farming uses antibiotics, such as veterinary medications, whose residues can be dangerous to humans if consumed in excess. But they may also be found as residues in food products due to inadequate quality control procedures. Due to lack of proper refrigeration, antimicrobials are also sometimes added to dairy products as a preservative because of lack of refrigeration (Donkor et al., 2011). In order to decrease the possibility of food contamination, cleaning and disinfecting surfaces that come into touch with food during food processing is acceptable. As such, these methods must be approved by law. However, many chemicals, such glass cleaners and some metal cleaners, cannot be used in the food and dairy industries because they leave harmful residues behind. Using more sanitizer than is permitted could leave some residue concentration on treated materials, surfaces, or food, even in

lightly processed fruits and vegetables. For this reason, it's crucial to measure the amount of residual chemicals avoided in the food and ensure that they have been eliminated (Helmschrott and Wildbrett 1985).

Raw materials may contain physical contaminants which can pose significant risks to food safety and consumer health if not properly managed. Foreign objects such as glass, metal, plastic, wood, stones, or insects can accidentally contaminate raw materials during harvesting, transportation, processing, or packaging. These objects may pose choking hazards, cause injuries, or lead to contamination of food products if not detected and removed. Recent challenges posed by physical hazards in raw materials for food and dairy safety have emphasized the importance of stringent quality control measures and risk management strategies. Globalization has led to increasingly complex food supply chains, with raw materials sourced from diverse geographical regions. Managing physical hazards becomes more challenging as raw materials pass through multiple stages of production, transportation, and distribution, increasing the risk of contamination. New types of physical hazards, such as plastic fragments from packaging materials, microplastics, or allergen cross-contact, are emerging as potential threats to food and dairy safety. Addressing these emerging hazards requires ongoing research, monitoring, and adaptation of control measures. The globalization of food trade has led to an increase in imported raw materials and ingredients, which may come from countries with different regulatory standards and quality control practices. Ensuring the safety of imported raw materials requires effective collaboration between importing and exporting countries and robust inspection and testing procedures. Food detection techniques need to monitor and assess all potential risks from each stage of the food manufacturing process to guarantee food safety at each and every stage of the food supply chain. Therefore, one of the most important steps in guaranteeing food safety and protecting consumer health is the early identification and quantification of trace-level pollutants in food. For the investigation of food safety, several new techniques have been developed recently, including biomolecule-based sensing techniques and traditional techniques. Unfortunately, most of these techniques require skilled professionals, are expensive, time-consuming, and dependent on laboratories. The development of quick, easy, accurate, affordable, and portable food sensing methods is crucial to solving these issues (Hitabatuma et al., 2022).

4.2 *Processing Parameters*

When high cooking temperatures are combined with outside variables, harmful chemicals may occur. This could negatively impact the safety and quality of the meal. Food processing methods include heating, baking, roasting, grilling, canning, hydrolysis, and frying at temperatures higher than those used in cooking. These methods can produce a wide range of toxic compounds in food, including acrylamide, nitrosamines, furanes, PAHs, and others.

4.3 Packaging and Storage Conditions, Supply and Distribution Systems

The need for safe and high-quality food among consumers, free trade policies, and globalisation have put pressure on various partners in the agri-food supply chain. Influence, contributions, socioeconomic factors, and environmental factors are all essential to the creation of an international supply chain flow that is successful. A range of approaches and theoretical frameworks have been developed to enhance the profitability and efficacy of the agri-food supply chain. Furthermore, a number of gaps and new issues in the supply chain continue to impede productive and sustainable food production (Bhat & Joudu, 2019).

When managing risks associated with the global food trade, it is important to take into account regional differences in the prevalence of various food-borne viruses. It is critical to understand that acceptable risk thresholds for food-borne risks will vary based on the area microbiological conditions in order to safeguard human health and decrease the incidence of food-borne diseases. The relevant international organizations, including the Codex Alimentarius and the World Trade Organisation, should recognise this idea. It should also be taken into consideration when developing pertinent international documents, such as risk management processes generally and sampling plans and criteria.

The food business may be encouraged to provide food items with a documented low frequency of infections if regional standards are accepted. In the end, this will lower the prevalence of food-borne illnesses, which will benefit consumers in every nation (Kruse, 1999).

5 Opportunities for Establishing Safety

The objective of food safety is to prevent dangerous microorganisms and chemicals from entering, growing, or surviving in the food supply chain, both domestically as well as internationally. Food safety is being faced with problems from the desire to minimise food waste, the global reach of food supply chains, and the cost-effective utilisation of natural resources like clean water. This will use the scarce water and nutrient resources to generate more food. The diagnosis of the necessary conditions, the application of good manufacturing practices, the establishment of sanitation standard operating procedures (SSOPs), the training of food handlers, and the hazard analysis and critical control point (HACCP) were the phases involved in the construction of a food safety system. The steps outlined in a flow chart for ongoing worker adherence to the system and training are the primary areas of difficulty faced during the deployment of the food safety system. In spite of this, the adoption of the food safety system resulted in notable drops in the populations of indicator microbes,

demonstrating that even while difficult, it is possible to be carried out by small-scale food industries (Cusato et al., 2013). Communities today place a high value on sustainable food production, but there are significant differences in infrastructure, organizational capacity, and teaching capabilities between nations, and food protection (including food quality, food safety, and preservation) must be addressed internationally. The most common cause of foodborne illness in low- and middle-income nations is recognized to be biological risks. Additionally, they discovered that the most frequently mentioned concerns regarding food safety were bacterial pathogens, which were followed by pesticide residues, a healthy diet, and a few contextual factors that were thought to have a major influence on food safety and included health, food safety, and agricultural policy, as well as appropriate legislation and government enforcement.

5.1 Dairy Sectors

It is preferable for dairy product monitoring to concentrate on the most significant risks to food safety along the dairy supply chain. To do this, trends in the dairy supply chain that could have an impact on the existence of microbiological, chemical, and physical risks were evaluated. Dairy products are more likely to include microbiological dangers than chemical or physical ones. The most significant microbiological risks in dairy products have been determined to be *Salmonella*, human pathogenic *Escherichia coli*, *Staphylococcus aureus*, and *Listeria monocytogenes* (Kaavya et al., 2024). The most common associations with soft and semisoft cheeses are *L. monocytogenes* and *S. aureus enterotoxins*, while the most common associations with raw milk are human pathogenic *Salmonella spp.*, *Cronobacter spp.*, *E. coli*, and *Campylobacter spp.* are the microbiological dangers in powdered infant formula that have people most concerned. Aflatoxin M1, dioxins, dioxin-like compounds, and veterinary medication residues are the most significant chemical dangers found in dairy products. Chemical risks mostly arise on dairy farms and can build up after additional processing. Particles of plastic, glass, and metal that are introduced during processing are the most significant physical risks. Climate change and farm-level modifications that enhance animal welfare and environmental sustainability are other developments impacting food safety.

When properly pasteurized and processed, dairy products have a good track record for food safety. Nevertheless, unpasteurized milk can include adulterants like antibiotic residues and act as a vector for the spread of zoonotic diseases when consumed, as is prevalent in developing nations with low control and oversight of the dairy industry. By taking into account the entire dairy production system, using antimicrobial medications with caution, and implementing effective farm management techniques like Dairy Dynamic Management, a One Health approach to dairy production medicine and management tackles these issues. These management techniques provide as further evidence that milk producers in the United States

supply safe, nutrient-dense milk with positive health impacts, and that similar practices are required in developing countries to improve nutrition, health, and overall wellbeing (Garcia et al., 2019).

Since hazardous germs cannot survive or thrive in dry foods because of their low moisture content and water activity, dry foods—like powdered milk—are frequently regarded as safe from microbial contamination by means of food safety. Nevertheless, pathogenic bacteria may disguise themselves as dried food items if they are contaminated. Foodborne infections caused by a variety of bacteria, such as *Salmonella* spp., *Escherichia coli*, enteropathogenic *Campylobacter jejuni*, *Yersinia enterocolitica*, *Cronobacter* (*Enterobacter sakazakii*), and *Staphylococcus aureus*, may appear in milk and dairy products. Upon three months of storage, the enteric *Salmonella* in skim milk powder was still alive, with a water activity (a_w) at a minimum 0.33. *Escherichia coli* O157:H7 viable cells are said to be able to endure a year at 5 °C in new born formula powder. The combined effects of temperature and storage duration resulted in a considerable reduction in the endurance of *Escherichia coli* in powder milk. According to guidelines from the U.S. Dairy Export Council, milk powder ought to be kept in a cool, dry location with a maximum temperature of 27 °C and a maximum relative humidity of 65%. Products made from milk powder must be kept in containers that are resistant to light, air, and moisture (Paswan & Park, 2020).

Although small-scale frozen dessert equipment may not fulfil published comprehensive design and construction sanitation requirements, or may fail inspection when compared to National Sanitation Foundation or 3-A sanitary standards, frozen dairy desserts have good safety performance. Problems with sanitary equipment design can lower cleaning and sanitation effectiveness, which raises the risk of harmful germs contaminating a process after it has been completed. The frozen dessert sector is extremely concerned about outbreaks of *Listeria monocytogenes*. When infected ice cream was placed on a stainless steel surface, *L. monocytogenes* was able to survive for up to six weeks at room temperature and nine weeks at 48 °C. Additionally, when applied at the concentration and contact time (1 minute) suggested by the manufacturer, chlorine- and acid-based surface sanitizers did not negatively impact *L. monocytogenes*; nevertheless, 5 to 20 minutes of contact time was necessary to significantly reduce Colony forming unit (CFU) (Inuwa et al., 2017).

5.2 Food Sectors

Fruit and vegetable-related foodborne illness outbreaks and border rejections of fresh produce because of non-compliance tests are becoming more common. These events cause food waste and financial loss as well as erode public faith in the safety of fresh produce. Fresh produce safety identifies risk factors for contamination with enteric bacterial pathogens by combining local situational observations with crop sampling, testing, and analysis of the production environment (soil, water, and

contact surfaces). The presence of pathogenic Shiga-toxin-producing *E. coli* (STEC), *Campylobacter* spp., *Salmonella* spp., and generic *E. coli* on strawberries as well as in the environment where strawberries are grown. The choice of water sources and the application of water treatment techniques could contribute to a higher standard of fresh produce safety. To ensure both the quality of the leafy greens and the sustainability of the environment, appropriate irrigation management techniques are required (Uyttendaele et al., 2016).

The availability of aquatic food for human consumption is determined by the output of fisheries and aquaculture, imports, exports, and equitable distribution. Food originating from aquatic habitats has a significant role in human health and nutrition. Maintaining the long-term production and supply of such food, from both aquaculture and wild-capture fisheries, is a significant and ongoing concern for civilization. Aquatic food security is achieved when there is a sufficient supply of food to meet demand and preferences, when it is safe to provide nutritional benefits with minimal health risks, when it is sustainable to feed present and future generations, when it is shock-proof to provide resilience to shocks in production systems and supply chains, and when it is sound to adhere to legal and ethical standards for the welfare of people, animals, and the environment. The social, economic, and environmental sustainability of production systems and supply chains; the resilience of systems to social, economic, and environmental shocks; the welfare of fish, people, and the environment; and the authenticity of food are the main areas of focus. The aquaculture, fisheries, and trade sectors provide a sufficient supply. Consumers face minimal health hazards from a safe food source. When levels of contamination from chemicals, radionuclides, or human pathogens are kept within scientifically accepted bounds and aquatic products are harvested, handled, processed, stored, and prepared in a way that inhibits the growth or contamination of microorganisms, then the food source is deemed safe. Pathogens and biotoxins are the most common biological dangers affecting aquatic food consumers, and consuming more than the recommended amount can cause illness. Concern should also be expressed about the presence of human-pathogenic viruses and bacteria in both farmed and wild filter feeders. Eating bivalve molluscs poses a direct risk to human health because they are commonly consumed uncooked and can concentrate protists, bacteria, and viruses from their environment. Eating fisheries products that naturally contain marine toxins can cause serious illness in humans. Toxins produced by naturally occurring phytoplankton build up in shellfish while feeding, especially in the case of filter-feeding bivalve molluscs. Water samples are analysed for toxicity quantification in molluscs and microscopic identification of phytoplankton taxa that produce toxins in order to help reduce risk. When the allowed thresholds for toxins in shellfish tissues are exceeded, shellfish harvesting sites are closed. Fish and shellfish can acquire environmental contaminants, including pesticides, heavy metals, and persistent organic pollutants, which can be harmful to the public's health. Maximum allowable residual levels for authorised and other chemicals have been set by the EU, and samples of fish, both domestic and imported, are checked (Jennings et al., 2016).

The application of technological advances and improvement tactics in production chains to boost the sustainability, productivity, and quality of wheat flours, pasta, bread, and bakery items was examined by Cappelli and Cini (2021). The poor dough rheological properties, improved nutritional content, and lower bread volume of ancient wheat products, such as whole wheat flours, doughs, and bread, are caused by the negative effects of bran and middlings. They also introduce significant rheological problems in dough, particularly with regard to the formation of the gluten network. To enhance the wheat cultivation stage, innovative and sustainable methods of innovation and development are needed. Examples of such improvement strategies and technical innovations include the use of wheat straw vinegar instead of chemical fungicides to prevent *Fusarium* head blight, which is caused by the fungal pathogen *Fusarium graminearum*; the impact of seeding density and nitrogen and sulphur fertilisation on wheat kernel composition, flour quality, dough rheology, and bread characteristics; and the finding that the protein composition of the tested ancient wheat cultivars was little affected by the nitrogen fertilisation levels. To produce finished goods with the right qualities, the wheat milling process must be carefully managed. Wheat conditioning and milling can also lessen the environmental effects of energy and water consumption while improving the quality of flour, semolina, dough, pasta, and bread. The kneading phase, which has the most influence on flour quality, dough rheology, and bread characteristics, is crucial to achieving appropriate dough rheology and bread characteristics in addition to the milling process. The most sustainable way to control dough quality and characteristics is to add carbonic snow and organic acids, manage water addition correctly, and develop autonomous and adaptive kneading equipment that can track kneading process in real time. Another strategy for improvement that can improve bread characteristics, dough rheology, and environmental protection is the use of alternative protein sources, such as protein from animal sources, like egg albumen, dairy products, and soya, in the bread-making process. However, there is no discernible lessening of environmental stresses in these protein sources. The most influential stages in the production chains of pasta, bread, and bakery goods can be found using Life-Cycle Assessment (LCA), which helps create environmentally friendly innovations and enhance production chain strategies.

6 Advanced Techniques and Tools for Ensuring Safety Concerns for Detection and Quantifications of Various Contaminants

The world's most urgent problem today is food safety because of the world's growing urbanization and population growth. Due to the overabundance of population growth, there is a great demand for food production and commercialization. This has raised awareness of the need for food safety and quality control to match

consumer expectations and lessen the serious issue of foodborne illness. Food detection techniques need to monitor and assess all potential risks from each stage of the food manufacturing process to guarantee food safety at every stage of the food supply chain. Therefore, one of the most important steps in guaranteeing food safety and protecting consumer health is the early identification and determination of trace-level pollutants in food. For the investigation of food safety, several new techniques have been developed recently, including biomolecule-based sensing techniques and traditional techniques. Unfortunately, most of these techniques require skilled professionals, are expensive, time-consuming, and dependent on laboratories. The development of quick, easy, accurate, affordable, and portable food sensing methods is crucial to solving these issues (Hitabatuma et al., [2022](#)).

6.1 Advance Techniques for Detection in Respect of Following

Several technologies have recently been evolved for quick detection of spoilage microorganisms and pathogens in dairy products during processing, storage, and distribution. These recent techniques provide a speedier, more steady, and comprehensive insight of food products' microbial health. The innovative approaches are cost effective than standard microbial detection methods and deliver immediate analytical results for perishable goods, sometimes in the form of in-package sensors. As a result, these items may find new markets and have lower overhead expenses. Other apps have offered immediate data on milk quality to help enhance quality practices and processing efficiency throughout the supply chain.

6.1.1 Micro-Organism (Spoilage and Pathogens) and Toxins

Conventional approaches and different sensor-based methods are the two groups into which the detection methods can be divided. The majority of conventional methods for identifying poisons and illnesses are laboratory-based and usually require a considerable amount of time. Numerous novel techniques, including biosensors, have been created. Every method has benefits and drawbacks. The chosen technique should be accurate, dependable, and rapid enough to produce data that can be trusted while also being selective to a specific infection or toxin. Toxins and pathogen detection methods might differ in terms of size, specificity, and cost. The immunology-based method, the count method of culturing and colony, and the polymerase chain reaction method (PCR) are some of the different standard methods for pathogen detection. The traditional techniques for identifying endotoxins are the limulus amoebocyte lysate and the rabbit pyrogen test. The FDA has approved four methods for the identification of endotoxins: chromogenic assay, colorimetric (lower protein), gel-clot, and turbidity metric (spectrophotometric).

Novel Techniques include Different biosensor-based methods can be used for the detection of pathogens. Different types of biosensors include Optical, Electrochemical, Amperometric, Impedimetric, Potentiometric and biosensors grounded on mass sensitivity i.e. Quartz Crystal Microbalance (QCM) and Surface Acoustic Wave (SAW). Smart sensors protect food quality against contamination with pesticides, fertilizers, dioxin, modified organisms, anti-nutrients, allergies, medications, and other substances by detecting, analyzing, and quantifying at the molecular level contents of various biological origins (Alahi & Mukhopadhyay, 2017).

Ultraviolet radiation is a promising food processing technology that eliminates pathogenic and spoilage microorganisms while maintaining nutritional and sensory quality. It offers numerous advantages over traditional methods. Furthermore, it is non-toxic and generates no waste. While UV radiation can render a broad range of bacteria inactive, there are a number of issues that need to be taken into consideration, especially when it comes to its use in food (Delorme et al., 2020).

When biological receptors and a wide range of nano-sensing materials are combined to create an integrated system, bioanalytical devices known as nano-biosensors are created. Biosensors of various types have been developed to detect food-borne infections and substances that lead to food deterioration (Singh et al., 2023; Tripathi et al., 2023).

6.1.2 Chemical Contaminants like Antibiotics, Pesticides, Melamine, Heavy Metals, Etc

A class of porous materials known as metal-organic frameworks (MOFs) exhibits great potential in a wide range of applications due to its high porosity, abundant functional groups, and tunable chemical and physical properties. Because of its great porosity, structural diversity, and flexibility, MOFs have attracted a lot of attention. Thus, MOF-based sensing techniques provide a state-of-the-art approach to the rapid and precise identification of heavy metals, poisons, illegal food additives, pathogenic microbes, veterinary drugs, persistent organic pollutants (POPs), and pesticide residues. Because MOF-based sensing techniques are portable, affordable, dependable, sensitive, and stable, they could be helpful instruments for evaluating food safety (Hitabatuma et al., 2022). A new avenue for the quick and accurate identification of heavy metals, allergies, toxins, pesticide residue, additives, and other chemical and physical pollutants is opened up by microfluidics and microfluidic analytical instruments. Microfluidic technology is a great option for field application, especially in places with limited resources because of its portability, miniaturisation, and dramatically lower sample/reagent volume. The science of creating microfluidics devices (also known as “labs-on-a-chip”) for a variety of uses and observing the behaviour of minuscule volumes of fluid within micrometer-sized channels is known as microfluidics (Weng & Neethirajan, 2017).

6.1.3 Adulterants

A variety of food pollutants are introduced into the food chain as a result of the globalisation of food and its intricate networking system. This can occur naturally, purposefully, or accidentally. Food safety is currently a major worldwide problem as a result of this circumstance, which has highlighted the necessity for efficient systems that can handle the fastest possible detection of food contamination. Because of its exceptional sensitivity, speed, and ability to read fingerprints, Surface-enhanced Raman spectroscopy (SERS) has been considered as one of the main options in this instance. These attributes contribute to its ability to identify molecules at a single level. According to Tsagkaris et al. (2021), the combination of liquid chromatography-tandem mass spectrometry (LC-MS/MS) and gas chromatography-tandem mass spectrometry (GC-MS/MS) has demonstrated the potential to identify molecules as low as the mg kg⁻¹ level, which is comparable to 1 ppb.

7 Application of Internet of Things (IoT), Artificial Intelligences (AI), GPS Monitoring, Bar Coding, Etc Ensuring Food and Dairy products Safety at Different Stages like Farming, Processing, Packaging, Transporting, Retailing

Kodan et al. (2020) state that farmers can reap several benefits from the application of Internet of Things technology in agriculture, such as enhanced productivity, water conservation, instantaneous data and production insight, decreased operating expenses, superior production quality, accurate assessment of farms and fields, remote monitoring, and equipment monitoring. The extended applications of IoT in agriculture include precision farming, drone agriculture, smart greenhouses, and livestock monitoring. Data mining technology is incorporated into the IoT -based food quality and safety monitoring system to provide early warnings of food safety along the farm-to-fork chain. In case of failure to do so, these devices can automatically notify the food supplier, preventing losses and spoiling and guaranteeing that high-quality products are sold. IoT technologies show great promise for managing and supplying traceability, visibility, and controllability issues and the supply chains that are safer, more effective, and sustainable are anticipated in the near future. Three levels make up the platform that has been established based on IoT technology: the application layer, the communication layer, and the sensory layer. DNA barcoding, RFID (Radio Frequency Identification), Real-Time Tracking and Tracing Systems (RT3Ss), GS1 bar code technology etc., are some of the IoT technologies used for tracking and tracing the concerned product in the supply chain. Industry 4.0

emphasis on the use of networked information-based technologies and increasingly potent, affordable computing in manufacturing enterprises and is widely believed that factories and plants with Internet connections are more productive, efficient, and intelligent than those without. With block chain technology, users can view every transaction in real time and simultaneously and have the benefits in food supply chain such as transparency, information accuracy food safety, and payment facility. IoT can be very helpful for sophisticated and more accurate shelf-life prediction. A variety of models can be used, and these models involve mathematical and statistical correlations between three sets of variables such as intrinsic factors, extrinsic factors, and implicit factors. A user-friendly information relaying system can greatly enhance the importance of a food label by increasing transparency and fostering consumer trust. The IoT system based on nanomaterials, biosensors etc., integrated with a signal transducing element can be used as an analytical tool in packaging materials. This sensor generates a barcode that is easily machine-readable, allowing for traceability, correlation of events, and retrieval of product history, including use, location, shipment, and delivery.

Radio frequency identification, or RFID, is a new technology that could have a big impact on the agri-food industry. Automated toll collection, library administration, preventing theft or counterfeit goods, tracking animals, and access control systems are a few of the current applications. The application domain is expanding to include real-time monitoring, quality control, food safety, traceability systems, intelligent transportation, and online information systems for consumers thanks to advancements in sensor technology, communication networks, and their integration with RFID technology. Due to the special characteristics of RFID systems, there are several potential advantages, such as higher process speed and efficiency, improved information accuracy, lower labour costs, and fewer inventory losses (Kumari et al., 2015).

Large volumes of data are produced by the sensors used in the food production chain. These data are easily accessible in real time, but they need to be accessed in a safe environment. Blockchain technology may be used to achieve this. However, blockchain technology cannot be manipulated, industries are vying for its adoption. In conclusion, it's a peer-to-peer network that stores data instead of a central place, making it a distributed and secure ledger that can be read and written from any authorised location. Blockchain offers several advantages for food logistics, such as increased shipping effectiveness, transparency, tracking cargo or items, reduced worries about lost or stolen goods, and quicker invoicing and payment processing. Most logistics-related problems, including those with procurement, transportation management, track & trace, customs cooperation, and trade financing, can be made easier with its assistance. Food product import and export require an enormous amount of documentation (Jagtap et al., 2021).

According to da Costa et al. (2023), food waste poses a serious threat to the environment, the economy, and food security. Because fruits and vegetables have short shelf lives and are highly perishable, monitoring them with a combination of temperature and humidity sensors is the most common research goal. However, there

are many other applications and technologies being investigated in the field to reduce food waste. While the monitored parameters, communication protocols, data storage, and application layers are evaluated in sensor technologies, the product type, supply chain stage, and geography are examined in supply chain characteristics. Food Loss and Waste (FLW) can take place at all points in the supply chain, from farm to consumer level, via producers, distributors and retailers and the rate of loss varies according to the product, as it is exceptionally high in fresh produce. A variety of technologies are used to gather data about food products in order to analyse their quality. For example, external devices are attached to the outside of the package, while internal devices are placed inside the package, either on the lid or in the headspace of the package. Adoption of new IoT-based real-time monitoring technologies, which have applications in precision, traceability, visibility, and controllability during the manufacturing, storage, and transport phases, is a promising new development in food supply chains. Fruits and vegetables waste more than any other food category due to their high perishability and short shelf lives. Environmental factors, such as temperature and relative humidity, both affect and contribute to the deterioration of food goods. In case of seafood and meat, the spoilage occurs mainly due the primary mechanisms such as microbial growth, lipid oxidation and enzymatic reactions, Conversely, a pH that is almost neutral, strong water activity, and a nutrient-rich environment are favourable for the growth of many bacterial species. In the common characteristics of the food supply chain such as food type, supply chain stage, and country, the real-time monitoring technologies are applied. Sensing Technologies using software applications, sensing parameters like ripeness, sound, tissue moisture, color, RH, etc., real-time data transferring technologies such as Wi-Fi, RFID, etc. for the data communication and data storage layer for data storage are used in the real-time sensors in food supply chains.

8 Future Opportunities and Conclusion

Without a question, one of the most important issues facing the world today is food safety, for which people are always struggling. To satisfy consumer and regulatory needs, portable, quick, affordable, and highly sensitive analytical instruments are needed for food safety and quality control. Food pollutants, such as pesticides, veterinary medications, heavy metals, unlawful additives, and food pathogens/toxins, are detected using a variety of biosensors. Food science and nanotechnology will become more closely connected as a result of the advancement and improvement of food safety detecting technology applications. The food business presents a plethora of potential for the development of a safety culture analysis tool. It is anticipated that the system will be implemented gradually and cautiously, with extensive research, optimization, and testing of its overall viability and effects coming next. Thanks to the application of nanotechnology, remarkable advancements have been accomplished in the disciplines of food science and research. Nanotechnology can

be used to identify pollutants, diseases, and pesticides, and tracking, tracing, and monitoring can help maintain food quality. Since the development of a safe and effective food product delivery system requires advanced and cost-effective processing, it is a major concern.

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Chapter 3

Quality Assurance and Control in Food and Dairy Products



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1 Introduction

Food is an essential component, and the food sector contributes significantly to the global economy and being an indispensable component of living, food safety is a fundamental issue for all food manufacturers and stakeholders. Consumers' awareness of nutrition and health has also prioritized their safe food options (Tomašević et al., 2013). Modern quality management systems (quality assurance and control) and Hazard Analysis and Critical Control Points (HACCP) have a substantial impact on human health in the food sector. HACCP is a Food Safety Management System (FSMS) that has been recognized by the international food safety community as a global guideline for addressing food issues (Fig. 3.1). Both systems identify and manage potential hazards during the production process and ensure food safety for consumption (Radu et al., 2023). In the last two decades, a plethora of third-party food safety certification processes have emerged, which include International Standards Organization for (ISO) 9001:2015, ISO 22000:2018, Food Safety System Certification (FSSC 22000), HACCP, International Food Standard (IFS), Safe Quality Food (SQF) and industry-based FSMSs, all of which are all public based (Lee et al., 2021). Food safety decisively affects human health and well-being. Despite, the fact that access to safe, nutritious, and healthful food is a basic human right, many communities are unable to exercise this right. As a result, people will be adversely affected by food-borne diseases, containing harmful bacteria, viruses, parasites, and physical or chemical contaminants, causing acute or chronic ailments or disorders from diarrhea to cancer, deteriorating public health and development.

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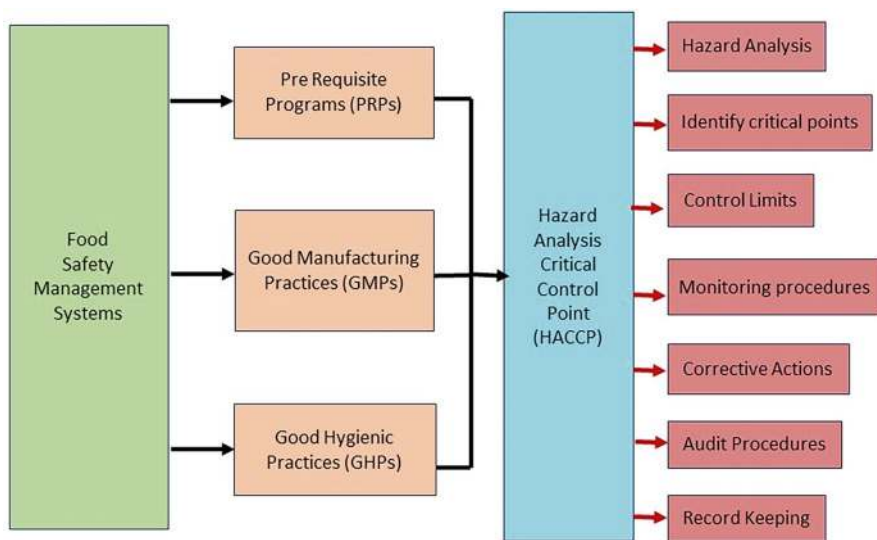


Fig. 3.1 Food Safety and Management Systems in Food Quality Control and Safety

The 75th World Health Assembly of the WHO Global Strategy for Food Safety 2022–2030, held in Geneva, Switzerland May 2022, aimed to ensure that everyone, around the world, consumes healthy and safe food, therefore reducing the onus of foodborne diseases (FBD). The worldwide impact of FBD caused by the 31 epidemic in 2010 was 33 million, with children under the age of five suffering 40% of the burden (Havelaar et al., 2015). Considering the obvious significance of FBDs to human health, the exact level of food contamination and the impact on society are still unknown. Previous research on the worldwide burden of all diseases did not consider contaminants in food as risk factors (Lim et al., 2012).

Governments and regulatory agencies all around the world have enacted laws and regulations that food developers need to comply with regulatory guidelines of every nation to control the standards of food producers, like the Food Safety and Standards Authority of India (FSSAI), functions to establish food product standards for the manufacturers, and oversees their, processing, storage, packaging, and distribution to ensure compliance through audits and inspections. The United States federal agency, Food and Drug Administration (FDA), monitors products such as pharmaceuticals, medical devices, biological products, tobacco products, nutritional supplements, food additives and cosmetics, and nutritional supplements and approves after inspection and check. Other countries' regulatory and food standards include the China Food and Drug Administration, and the European Food Safety Authority (Varghese et al., 2022). However, several food scandals in the previous several decades have severely eroded public trust in the food business, including gutter oils and milk adulterated with melamine (Yang et al., 2009; Ng et al., 2015). To prevent similar food scandals the international standard for food safety and quality were strengthened and harmonized by the Food Agriculture Organization (FAO)

by creating tools and manuals for various food control administrative and technical issues. The Codex Alimentarius Commission adopted new or updated standards during its session in Geneva in July 2010. The requirements for additives, ingredients, and pesticide residue constraints have been amended to promote the quality and safety of food, ensure fair trade practices, and protect consumer health. The new regulations limited the amount of melamine that can be present in foods, infant formula, and animal feed without causing health problems (Ali Mekouar, 2010). The food industries must vigilantly monitor the protection and integrity of food and consumer rights.

Food contamination can be intentional or unintentional and can prevail from various sources, including bacterial contamination, phytotoxins, pesticides, drug misuse, chemical addition during processing, and evolving chemical hazards. To date, several physical, chemical, physicochemical, and biochemical techniques like chromatography, capillary electrophoresis, and spectroscopy, have been successfully employed to detect food fraud. Nevertheless, ongoing research is being conducted to understand contamination sources and better prevention methods. Significant efforts have been made to establish more advanced and efficient novel analytical strategies for food quality assurance and control. The advancement and expansion in modern omics technologies and associated techniques have outperform over other existing standard methodologies due to their higher sensitivity, quantitative accuracy, preciseness, and multiplexing characteristics, to detect and identify contaminants and pollutants, even in trace amounts. A promising tactic for overcoming the difficulties in upholding quality control and avoiding global food fraud. Proteomics, genomics, and transcriptomics are the trending advanced cutting-edge tools that are rapidly transforming our strategies pertaining to the prevention of diseases, detection, and food toxins production by pathogens. Genome sequencing of microbes, for example, has progressed from an investigation tool into a method that could be explored to characterize the food-borne pathogenic strains in routine monitoring systems (Bergholz et al., 2014). Another advanced technique combating the challenges is the introduction of the microneedle technique with analyzing tools for food assurance. The technique uses rapid sample methods and cost-effective technology to speed up the analysis process, ensuring food safety and efficiency. Microneedles (MNs) provide a revolutionary technique for food sampling and analysis due to their precision engineering and small size (Faraji Rad, 2023). MNs are normally made with specialist procedures. Common techniques include photolithography (Roh et al., 2022), laser processing (Tu & Chung, 2016), 3D printing (Krieger et al., 2019), two-photon polymerization (Faraji Rad et al., 2021), and various other approaches (Nagarkar et al., 2020). MNs can be made from many materials, including metals like titanium (Dong et al., 2023) and biocompatible polymers like silk (Wang et al., 2023), according to their suitability for specific uses in the field. Biosensor technology is also gaining popularity among scientists in the food sector. Advancements in nanotechnology, application of biometrics, and materials are driving growth in the market. This new analytical technology offers numerous advantages for food analysis and is portable, making it easy to detect specific substances on-site. The food is also affected by pollution which may lead to

microbiological, chemical, and physical contamination. It can occur in several phases, including collection and cleaning, processing, and storage.

Food contamination can cause serious illnesses, particularly food-borne infections. Food contamination by physical methods can occur during any stage of manufacturing, including the introduction of foreign materials such as plastics, glass, hair, insects, and metal components. This can pose health risks to customers and may be caused by negligence on the part of food manufacturers or equipment. Chemical contamination is commonly associated with agrochemicals due to the widespread use of pesticides and fertilizers, which can constitute a considerable public health risk when consumed by humans. Pesticide residues have been found in fruits and vegetables, according to recent reports. Nerín et al. (2016), suggested that pesticide-contaminated food may cause health concerns to people due to the presence of harmful compounds including lead, mercury, and arsenic in soil and water. Microbiological contamination includes bacteria, fungi, and other infectious materials that occur unintentionally or accidentally. *Salmonella* and *Escherichia coli* are the causative agents contaminating the products during preparation and processing, or by consumers themselves. Improper food handling, such as storing it at high temperatures, can result in degradation and toxin generation. This chapter discusses the role of food quality and control agencies, their safety guidelines and regulations preventing food contamination, and the use of advanced physicochemical, biochemical, and biotechnological technologies, which include transcriptomics, proteomics, metabolomics, and various other methods for food and dairy product quality control and improvement.

2 Global Frauds and Food Supply Chain Management

Food adulteration and fraud involve several fundamental types of fraudulent economic activities. Commercial fraud involves the loss of product quality and is characterized by non-compliance with food laws, purposeful consumer deception, and financial gain. Other malpractices, such as incorrect storage temperature or missing expiration dates on food labels, can also be considered fraudulent. Adding less expensive other than food substances into highly valued products, such as adulterating cow milk powder with plant-based oils or animal fats, utilizing processed olive oil to substitute extra virgin olive oil, and mislabelling ordinary foods causes consumer deception. The Rapid Alert System for Food and Feed (RASFF) also defines fraud as counterfeiting, mislabelling, incorrect expiration dates, missing or abandoned health certifications, unlawful importation, or fraudulent behavior. The Economically Motivated Adulteration (EMA) system covers misbranding, counterfeiting, transshipment, and artificial improvements, whereas the USP database only analyzes furthermore addition, replacement, and eradication. The EU Food Fraud Network (EU-FFN) is a forum where Member States and European countries can exchange information as well as collaborate against agri-food chain legislation infractions. The most prevalent breaches reported in the EU-FFN's Annual Reports

from 2015 to 2019. The report shows that mislabelling fraud scaled from 33.3 per cent in 2015 to 47% in 2019, whereas other types of fraud decreased from 22.2 to 15% for documentation and 33.3 to 20% for replacements (Visciano & Schirone, 2021). Food fraud and adulterations (FFA) can originate from either the food supply chain or distributional integrity i.e., misrepresentation of product origin. In 2002, Australian officials arrested a big shipment of honey branded as coming from Singapore, even though Singapore was not producing honey at the time. The inquiry revealed that the honey was unlawfully transferred to Singapore through China and then subsequently transported to Australia to circumvent the restriction of Chinese nectar, demonstrating distributional integrity (Leeder, 2011).

The increase of FFA cases has prompted government agencies to develop strict surveillance and approval procedures, extending the process of international managing the supply chain. Many international transactions now require import, export, and inspection certificates for food safety. This has resulted in investment in pricey technology for product inspection and traceability. Governments have implemented rules and policies to promote security throughout the chain of food supply (Owolabi & Olayinka, 2021). Another highly advanced sophisticated method for determining food legitimacy is the use of nuclear science technologies for trace element analysis, as well as volatile organic compound profiling. Food products can be linked to the environment or place where they were produced utilizing persistent isotope testing in conjunction with trace metal assessment analysis; additionally, these techniques may identify the agricultural methods employed during the production process. However, this technique may prove quite accurate but is also expensive and requires a substantial amount of expertise to effectively use. The findings, like those of smaller portable devices, are just as good as the comparative data found in reference databases. Nuclear Magnetic Resonance (NMR) spectroscopy is another potent approach that provides an ideal application to detect food fraud since it can quickly analyze mixtures at the molecular scale without any requirement for separation or filtration phases. The ability to test an extensive variety of compounds simultaneously enables both targeted determination and measurement of several compounds in a couple of minutes. The analysis produces a chemical pattern of chemicals which may be conveniently compared with multiple reference spectrums associated with real foods implementing automated procedures. The efficacy of the commencement of these strategies primarily depends upon the accessibility of suitably offered databases.

2.1 Food Frauds: International Case Studies

Food fraud is a never-ending competition among food scammers who devise creative techniques for deceiving clients, bureaucrats as well as attentive food consumers. Fraudsters have a catastrophic advantage in this competition since they are free to devise whatever means to increase their profits, regardless of the well-being of consumers. Several food scandals have been reported including

melamine-adulterated milk in China, which has been of high concern. Several firms, including big dairy industries in China, were charged in this scandal, particularly the Sanlu infant formula milk products, which had caused 42, 94,000 babies unwell, resulting in roughly 51,900 hospitalizations and six infant fatalities (Yang et al., 2009). The problem of oil adulteration in China was identified with gutter oil, which was estimated to account for one-tenth of all cooking oils in China. Gutter oils were uncovered in Taiwan, and the resulting oils and products were shipped to Hong Kong, Singapore, and other places (Ng et al., 2015).

Contamination of beef using meat from horses caused the adulteration crisis in Europe and raised concerns about the use of horse meat as an emerging adulterant in the meat sector. The discovery of horse DNA in frozen beef burgers brought attention to this problem of meat adulteration. Horsemeat is used instead of beef due to cheaper production costs (Boyacı et al., 2014), which has impacted public trust in the industry. In 2007, a replacement of monkfish with pufferfish caused two cases of tetrodotoxin poisoning (Cohen et al., 2009). Armani et al. (2015) detected a similar deadly fraud in a couple of samples mislabeled as squid for pufferfish. When an allergy is not stated on the label, such schemes can have awful consequences for victims, including sickness or even death. Various mislabelling cases have been reported, and examinations in Asia utilizing DNA bar codes have shown incidents of mislabeling of fish. An investigative fish examination conducted in Malaysia in 2016 discovered that 16% of raw, freshly processed, preserved fish were mislabeled (Chin et al., 2016). The barcoding of DNA investigations across China found extensive mislabeling of seafood in the market (Xiong et al., 2019). The chairman of a food processing company was found guilty of mislabeling high-quality olive oil while blending it with low-grade palm oil and other low-cost oils. The blend included both harmful artificial colorants and lower-quality oils (Logan et al., 2016). Milk fraud often entails dilution with non-milk fats and oils, such as artificial enhancement, soybean, or animal fats, chlorine, formaldehyde, urea, hydrogen peroxide, sucrose, cane sugar, and detergents (Montgomery et al., 2020). Globally, Pakistan ranks as the fifth-largest milk manufacturer, and its adulteration with urea, water, and other chemicals is a common practice that authorities often confiscate. Authorities in Bangladesh were compelled to turn down an artificial fruit juice production facility for using harmful chemicals to manufacture beverages that did not include any fruit. In Australia, approximately 20% of honey contains corn or sugar syrup. The number of incidences in counterfeit products increased by 50% for Asian imported goods. Food Safety Modernization Act requires the Food and Drug Administration (FDA) to conduct vulnerability analysis to safeguard food from deliberate adulteration and to avoid behaviors that endanger public health (Ulberth, 2020). Regulatory initiatives alone are insufficient to address this issue; new technologies have the potential to bridge the gap. Using several detection systems with varying sensory capacities in different combinations makes it more difficult for food fraudsters to identify vulnerabilities in any specific technology. To address the issue of milk adulteration, relevant countries should establish public-private partnerships to increase knowledge, information accessibility, awareness, and risk communication capability (Jairath & Purohit, 2013; World Health Organization, 2018).

Consumer organizations can help to raise awareness of the prevention techniques and health dangers associated with contaminated food through the popular press media (Roy et al., 2017). Everybody involved in the supply chain of food, agriculturists, food manufacturers, merchants, retailers, and consumers, should receive education and training to promote food safety. Effective risk management and food awareness promote safe agri-business growth within both domestic and foreign markets. Long-term prevention requires addressing and resolving inherent economic concerns at national and international levels.

2.2 *National Case Studies*

The Indian food business has a lot of potential, but it is heavily influenced by the threat of counterfeiting due to less severe food safety standards and regulations. Food fraud in any form poses a risk to food safety. The diversity of food rules in India (controlled by nine distinct ministries) is a severe drawback for producers, retailers, and consumers. The Food Safety and Standards Act of 2006 is currently the primary major law developed to integrate India's food security laws from regulation to self-compliance for food products processing and manufacturing industry for systematic and scientific re-orient of the food. It also served as a foundation for the emergence of the Food Safety and Standards Authorities of India (FSSAI). The scarcity of accredited laboratories and technical manpower remains a major challenge. Recently, the new Consumer Protection Bill prescribed the degree of strict punishment for life-threatening contaminated food. There are several frauds reported in India. Counterfeiting is a global problem to be addressed. According to the Authentication Solution Providers' Association and State of Counterfeiting in India 2020 report, aggregate counterfeit incidences have increased by 24% in India, between 2018 and 2019, particularly in three investigated sectors including food and beverages. There were around 249 incidents recorded in 2019 throughout the three fast-moving consumer goods (FMCG) sectors, 129 including the dairy industry. In a study, investigations have revealed a diabolical honey adulteration that avoids purity inspections, with serious health repercussions during the COVID-19 pandemic. According to studies conducted by the Centre for Science and Environment (CSE) with lab tests in Germany and India, 77% of honey samples promoted by famous Indian companies were contaminated with sugar syrup. Only three out of 13 honey brands pass the widely known Nuclear Magnetic Resonance Spectroscopy (NMR) test. Since, India is the world's largest milk producer, accounting for twenty-four percent of global milk production, adulteration of milk and artificially synthesizing milk in India have received widespread media coverage, with persuasive proof from the authorities, and research journals (Handford et al., 2016; Moore et al., 2012). Research on India's status in milk adulteration reported that about 68% of milk tested in India was contrary to FSSAI (Roy et al., 2017). Another study revealed that 50 milk samples collected from Hyderabad, India were found

contaminated with urea (60%) and formalin (32%) reported by Singuluri and Sukumaran (2014). An analysis of milk samples collected from 365 homes in urban and rural areas, of Uttar Pradesh, India detected urea adulteration of 40% and 8% respectively. The most prevalent signs recorded among children who consumed contaminated products were nausea, vomiting, and vision issues. Up to fifty-two percent of urban adolescents experienced diarrhea and vision issues, which could have been caused by the elevated levels of urea and surfactants in the contaminated milk they had ingested. (Bhatt et al., 2008).

3 Quality Control and Identification of Adulterants in Dairy Industries

Adulteration in dairy products has major health repercussions, to counteract this malpractice, adulterants can be recognized using DNA-based approaches. Milk and whey proteins contain a large amount of background DNA. Both of these products contain source DNA (cow), as well DNA from microbes, natural vegetation, and dairy products, as well as in the case of whey proteins from cheddar-making processes. The genetic material in such products is preserved during the process, including pasteurization. Using 16S Metagenomics technology, which allows researchers to analyze microbiomes, the microbial DNA contained in protein samples can be identified and correlated to a controlled library, resulting in a microbiota presence in these unprocessed products. This profile can be assessed for both alpha and beta diversity, for the presence of the amount and types of bacteria. The microbiota profiles of milk and whey proteins are notably different (Thompson et al., 2021). Herbalife Nutrition experts demonstrated that the microbiome characterization of processed cow proteins can be used to identify source materials. Using 16S Metagenomics, the alpha and beta diversity of each protein powder's microbiome profile may be combined with primary coordinate analysis to construct differential groups, resulting in a novel raw material identification method. This indicates how microbiome strategy in assuring product authenticity can be a valuable forensic tool for quality control.

People's trust in milk and dairy products is low due to a few instances of industries engaging in adulteration. Milk production linkages are auditable and specifically controlled to prevent milk contamination. Contaminating agents are recorded and monitored at the milk foyer, in the cooled milk reservoir, using precise accurate sample procedures required in the monitoring analytical processes for milk quality in the Dairy Industry Management Assurance of Food Safety (Velázquez-Ordoñez et al., 2019). The specificity of methods for identifying milk proteins is currently being debated, and the USP (U.S. Pharmacopeia) and Food Chemical Codex (FCC) recommended identification method of whey protein is based on a combined examination of lactose, protein, ash, loss on drying content, and protein (Thompson et al., 2021). After China's melamine scandal in infant milk formula, the government has

imposed stringent regulations and policies in the milk and dairy industry. Since India is the largest milk producer in Asia, to combat the perception of contaminated milk in India, FSSAI conducted the 'National Milk Safety and Quality Survey 2018'. A large volume of milk samples was collected and evaluated on-site for quality and safety standards. Confirmatory analysis was performed on samples found to contain pollutants or adulterants utilizing advanced technology and established methods. Proficient analysts conduct testing techniques at NABL-accredited laboratories recognized by FSSAI. The findings from the survey refute the perception of widespread milk adulteration in the country ([Report_Milk_Survey_NMQS_Final_18_10_2019.pdf \(fssai.gov.in\)](#)).

Dairy processing also includes the cheese-making method as a post-processing activity. Cheese is the most expensive dairy product when compared to other dairy products and milk. The production process is more susceptible to global fraud. The Web of Science, Science Direct, PubMed, and Scopus databases were analyzed to determine the most effective way to detect fraud in all types of cheese. Because of its numerous applications, mozzarella cheese had the highest rate of adulteration of any cheese. Chemical and biosensors have been recently used to detect and monitor bacterial growth and milk deterioration indicator markers, which evaluate dissolved oxygen, CO₂ production, pH, and conductivity. The sensors have various advantages, like high sensitivity, quick analysis, minimum sample requirement, and real-time monitoring of milk deterioration. Electronic nose and tongue methods for detecting mobile and inert components associated with microbial growth and milk spoiling (Poghossian et al., 2019).

Various technologies were employed to evaluate cheese fraud, namely, polymerase chain reaction (PCR), spectrometry, electrophoresis, ELISA, sensory analysis, near-infrared, and nuclear magnetic resonance (NMR). PCR and spectrometry have been the most often utilized fraud detection tools. Furthermore, sensory evaluation was the least commonly used technique (Abedini et al., 2023). Fraud in the food business is predicted to cost more than \$50 billion annually (Soon & Abdul Wahab, 2022). Research suggests that replacing ingredients and reducing fat in cheeses is a significant contributor to food fraud. A salt content study revealed 30 falsified dairy items, including 29 instances of cheese. Montgomery et al. (2020) found that 10 out of 15 dairy products had lower fat content than advertised. In a separate study, Owolabi and Olayinka (2021) found that dairy goods had the highest fraud prevalence across all food goods (Owolabi & Olayinka, 2021).

4 Technological Advancements and Emerging Tools in Quality assurance of the Food Sector

Numerous cases of food fraud have raised concerns among customers about food safety and quality. As a result, combating fraudulent practices and food adulteration poses a tremendous problem for the food industry, but it is vital both monetarily and

in terms of safety. Legislation and governance strive to mitigate possibilities, industry-wide challenges, and vulnerable products. The biochemical intricacies of food products, and new analytical methods such as proteomics, and genomics must be used over conventional methods to properly characterize the molecular features of food ingredients and monitor any quality deviations. Conventional methods of food validation, such as physicochemical and biochemical analysis or aesthetic characteristics, are currently being explored. The emerging technologies used in this area for mitigating food fraud and scandals are ultrasonics, pulsed electric field, and microneedle analysis. On the other hand, the employment of molecular-based tools, such as omics-related methodologies, is assisting in the resolution of food fraud issues due to the arduous, time-consuming, and ineffective nature of traditional methods. Such *in silico* technologies could be utilized to create molecular templates for investigating the biochemical and chemo-molecular properties of food components, hence validating the quality of food for high throughput screening. The amalgamation of molecular analysis with modern techniques such as electrophoresis, chromatography, and spectroscopy, as well as genome characterization, will provide a firm strategy for investigating the quality dynamics of food ingredients.

4.1 Omics Studies on Food Quality and Safety: An Insight

4.1.1 Foodomics and Its Application in Quality Control of Food

The current technology for managing industrial processes and identifying bacterial pollutants in food is limited (Prakash et al., 2020). As a result, analytical approaches are increasingly shifting toward inventive and multidisciplinary approaches, abandoning those that were previously deemed to be standard. The application of ‘omic’ technologies for food analysis yields superior analytical quality results and can be tailored to the researcher’s desired methodology for the study (Fig. 3.2). Thus, cutting-edge techniques such as genomic, transcriptomic, proteomic, and metabolomics may be demonstrated to be useful technologies for assessing and deciphering food products, as well as data production and analysis of the differential expression of transcripts, genes, metabolites, and proteins (Zheng & Chen, 2014).

The utilization of these technologies in food science is known as ‘foodomics’ and is pursuing challenges linked to food quality control, gradually replacing the non-enhancing currently established methods (Ferranti, 2018). Several recent research investigations have focused on the application of foodomics for the study of food components to continuously enhance the food given to consumers.

(a) Detection of microbiological contaminants and their toxins

Commonly known microorganisms that severely deteriorate the health of different age groups of people are *Clostridium perfringes*, *Salmonella sp.*, *Brucella sp.*, *Campylobacter jejuni*, *Listeria monocytogenes*, *Escherichia coli*, *Mycobacterium bovis*, *Mycobacterium tuberculosis*, *Enterocolitica*, *Staphylococcus aureus*, and

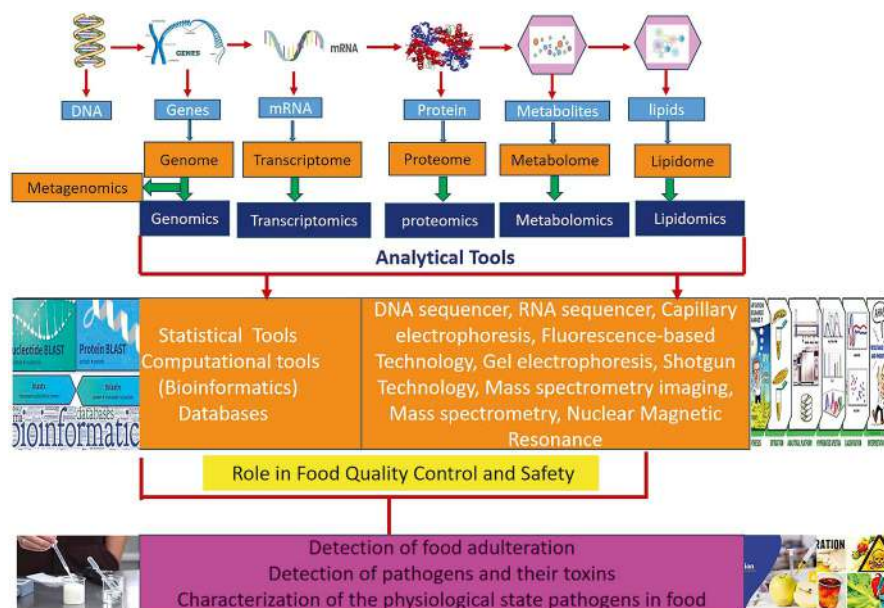


Fig. 3.2 Technological advancements and analytical tools in quality assurance and quality control of food safety system

Norovirus (Pal et al., 2016; Kaavya et al., 2024). Transcriptomics could be extremely effective in predicting the active role of pathogenic bacteria in dairy products. The behavior and evaluative influence of cheese matrix on the expression of *Staphylococcus aureus* virulence genes alone or in combination with *Lactococcus lactis*, a prominent contaminant in the dairy ecosystem, was investigated (Cretenet et al., 2011). It is achievable for microbial action under varied external settings through the RNA molecules analysis since the food matrix has a critical influence on the expression of genes in activities like as growth, survival, or the amount of pathogenicity toward the host (Chen et al., 2021). The systems and substances in food matrices unavoidably affect individual genes and pathways in microbes through integrated systemic metabolic responses, as proven in both phenotypes and transcriptome investigations. These discoveries, along with transcriptome research, could blaze avenues for the creation of new preventative strategies for the most frequent foodborne infections. Current research proposes that examining the proteome of microorganisms can be a useful method for swiftly detecting illnesses in food samples. The approach matrix-assisted laser desorption/ionization and analysis of ions generated through time-of-flight (MALDI-TOF) appears to yield reasonable findings for researchers' expectations. This approach aims to obtain a protein fingerprint characterizing each microbe at a specific physiological stage. This particular protein profile could be exploited for the unambiguous detection of infections in food matrices (Piras et al., 2016).

(b) *Combating food fraud and authentic assurance*

Accurate and reputable testing methods are required to monitor and manage food authenticity, as well as to ensure precise and accurate marking of foodstuffs, ensuring that the components contained in a food product are of the type and quality indicated by the supplier. A lack mismatching between the packed product and the one shown on the packaging is assumed to be fraud against consumers and could potentially be a crime. As a result, the food business must be attentive to defend food safety and consumer rights. Several techniques, including as chromatography, capillary electrophoresis, and spectral analysis, have been effectively employed to detect food fraud. However, in recent omics technologies and techniques have surpassed more conventional procedures in terms of sensitivity, accuracy, and multiplexing technique (Ortea, 2021). One of the most typical fraudulent tactics in the dairy industry includes the replacement of a specified type of milk for a more profitable one (Böhme et al., 2019). Milk adulteration has an impact on the items derived from it as well. The proteome, as well as metabolome in dairy cow cells, have been investigated to identify contamination. Metabolomics also gives unique markers for individual products to validate their identity. A factor such as the breed will result in a distinct metabolomic profile in the milk, which can be extended to goods made from it. Extrinsic factors, such as diet, environment, processing, or retention, will all have the same effect (Zhu et al., 2021). Correctly defined molecules as biomarkers may provide a perfect platform for detecting alteration in dairy products and milk. A research investigation was conducted for the development of chemical fingerprint to distinguish between the cheeses. An untargeted metabolomic technique combining chromatography with MALDI-TOF enabled the selection of the biomarkers that best defined the cheeses, with as well as without a quality seal (Rocchetti et al., 2018).

4.1.2 Proteomics

Proteins are trustworthy indicators to accurately predict food quality, origin, and composition identifying marker proteins or peptides during processing can help to manage regulatory compliance and product quality. Proteomics involves analyzing proteins in a biological system at a certain moment and under defined conditions (Boersema et al., 2015). It has provided vital insights into the content, allowing for the development of novel food items, safety assessments, and quality control measures. This helps to identify proteins, and understand protein-protein interactions, post-translational modifications (PTM), and protein localization. Food proteomics is a methodological investigation of a food's proteins, focusing on their bioactive and functional qualities. It has emerged as the advancement of food science research. Various proteomics techniques like gel-based electrophoresis, mass spectrometry (MS), and protein profiling and fingerprinting are employed in the food industry. There are three approaches for proteomics study, qualitative, quantitative, and functional. Qualitative proteomics identifies and characterizes proteins in food products, which can include all or a selected subset of proteins of interest. Quantitative

proteomics utilizes both relative and absolute quantification to accurately measure protein amounts across samples. Typical uses include studying changes in the food proteome due to raw material variations, technological processing, and storage conditions. Kierner and Cesareni (2007) define functional proteomics as the study of protein-protein and protein-molecular interactions and their implications. Serim et al. (2012) used activity-based probes to profile enzyme levels and test potential inhibitors. The research also demonstrated the protein expression of low-abundance proteins in human milk's whey fraction, as well as their rapid changes over a year (Liao et al., 2011), the proteome analysis of goat milk was conducted and identified the different characteristics in goat milk as compared to human and cow milk (Zhang et al., 2013). In recent years, the use of proteomic techniques has significantly boosted our ability to understand the heterogeneity in proteins resulting from complex and diverse patterns of post-translational modifications (PTMs). Processing, storage, animal care, and heat treatment all have an impact on milk and dairy product quality through post-translational modifications (PTM), such as phosphorylation (Bijl et al., 2020). Milk protein functioning is influenced by various PTMs, including protease susceptibility, calcium-binding affinity, micelle stability, state, and chemical solubility. Characterizing PTMs in milk proteins provides insights into their nutritional and technical features. Caseins are widely utilized in proteomics to explore phosphorylation sites and are regarded as model phosphoproteins (Le et al., 2017).

Bottom-up" protein analysis is the process of characterizing proteins by analyzing the peptides produced from the protein during proteolysis. It is performed on a combination of many different kinds of proteins, known as shotgun proteomics, which is similar to shotgun genomic sequencing. The experiment involves fractionating the protein mixture before subjecting it to LC-MS/MS analysis (Zhang et al., 2013).

(a) *Gel-based and gel-free approaches for quantification of proteins*

Proteomics relies heavily on two-dimensional gel electrophoresis (2-DE), however, questions about its effectiveness have hampered its use as a primary methodology. As mass spectrometry (MS) advances, shotgun procedures are gaining popularity as a novel tool for gel-free quantitative analysis. Combined with MS, the shotgun proteomic workflow enables sensitive and high-throughput protein profiling, resulting in accurate quantification (Abdallah et al., 2012).

(b) *Mass spectrometry (MS)*

Mass spectrometry has emerged as a highly advanced method used for protein identification, quantification and characterization, and analysis of complex protein samples in the past decade, devoted to advancements in protein sequence databases, and user-friendly and easily accessible equipment. A new toolset of label-based and label-free quantitative proteomic approaches is now accessible (Aebersold & Mann, 2003; Cairns, 2011). MALDI and liquid chromatography with tandem mass spectrometry (LC-MS/MS) allow for the analysis of intricate protein combinations in

food samples. Mass spectrometry-based approaches reveal information on protein sequences, alterations, and interactions between proteins.

(c) *Protein profiling and fingerprinting*

Two-dimensional difference gel electrophoresis (2D-DIGE) and shotgun proteomics, which are utilized for protein analysis between different food samples or treatments, focus on comparing protein expression patterns. Peptide mass fingerprinting (PMF) and selected response monitoring (SRM) techniques are used, whereas protein fingerprinting determines the quantities of particular proteins of interest. It is a large-scale protein identification method that involves endoprotease for digesting unknown proteins to extract their constituent into tiny peptides. MS analysis is used to accurately determine the mass of peptides. This is a top list of the undetected protein's peptides. The peak sequence is compared to the hypothetical peptide peak sequence derived from the computational digestion of repository proteins, while the software determines the most suitable match. This approach offers the advantage for not relying on the sequencing of proteins for protein identification (Cottrell, 1994). This method bears the limitation of the database requirement of the protein already described on another organism.

(d) *Bioinformatics analysis*

Bioinformatics tools serve as essential for data analysis and understanding in proteomics. They make it easier to identify proteins, search databases, and predict protein functions, and pathways. Bioinformatics mechanisms foster the incorporation of proteomics data with other omics data, thereby understanding the complete characteristics of the food products. Bioinformatics treatment of MS data has enhanced proteomics techniques, enabling high-throughput protein and peptide identification and quantification. Food quality and safety studies primarily use two consecutive techniques for proteomics: discovery and focused proteomics. Food proteomics aims to identify potential biomarkers by identifying a specific proteome using a bottom-up approach. This involves protease such as trypsin for digesting proteins of interest into peptides, and analyzing the resulting peptides using MS. Targeted food proteomics approaches identify peptide biomarkers in biological samples or food goods with high precision, compassion, and consistency (Carrera, 2021). Hence, proteomics is a valuable tool for nutritional food science studies, bringing together research organizations, food agencies and enterprises, and government regulatory bodies to gain insight into food composition, quality, and safety.

4.1.3 Genomics and Metagenomics

Using genetics and sequencing to detect foodborne pathogens is transforming food safety diagnostics. Next-generation sequencing is used to ascertain taxonomy, describe new species, and construct genomes. They also predict microbial functions, assess risk, identify transmission dynamics, and monitor foodborne pathogens. Sequencing-based diagnostics especially whole genome sequencing (WGS)

are increasingly being used by governmental, and industrial enterprises addressing public health to replace time-consuming laborious conventional procedures, highlighting their importance. The developing computational approaches detect and characterize foodborne pathogens, and improve molecular diagnostic resolution as well. Molecular approaches that sequence microbial genes or genomes have revolutionized food microbiology research (Stasiewicz et al., 2015). Molecular technologies detect certain microbial gene sequences to identify species, groups, and functional features like pathogenesis or resistance to certain antibiotics. Most nucleic acid amplification tests (NAATs) and sequencing-based procedures use polymerase-chain reaction methods to identify, characterize, and molecularly type microbial isolates from food (Banerjee et al., 2022.). Next-generation sequencing (NGS) and WG) have revolutionized the identification of cultures in clinical, environmental, and food samples over the past decade. Sequencing-based approaches, including single nucleotide polymorphism (SNP), whole genome (wg), core genome (cg), and multilocus sequence typing (cgMLST and wgMLST), have become the backbone of molecular epidemiology research (Banerjee et al., 2017).

Next-generation sequencing enables culture-independent diagnostic assays (CIDA) for pathogens found in food. The use of CIDAs in clinical laboratories and hospitals to detect gastrointestinal and food-borne pathogens demonstrates the growing acceptability of molecular tests in infectious disease diagnoses during the past decade. CIDA does not involve isolating pure pathogen cultures. During the lack of pure culture isolates, CIDAs limit downstream analyses such as antimicrobial drug resistance, isolate-dependent cellular and molecular typing, and WGS. This greatly impedes epidemiological investigations into foodborne infections, including integrating genomic data from an outbreak-causing pathogenic strain into a detection system. (Marder et al., 2017). Metagenomics-based techniques can detect pathogens in food more quickly due to shorter culture enrichment times. Culture enrichment is essential in food microbiological diagnostics due to the low abundance of target pathogens and the potential presence of damaged cells. Enrichment is necessary to get microbial materials that exceed the detection limit. Although CIDT has made significant progress in identifying foodborne pathogens, it is important to significantly reduce detection time for faster source tracing and actionable interventions. Real-time sequencing using nanopore technology shows great promise in this tool (Leggett et al., 2020).

Metagenomic methods, such as metabarcoding, shotgun, and long-read metagenomics, identifies the entire microbial populations in food, their ingredient, or environmental sample, making them a disruptive force in food safety diagnostics. There has been a significant growth in the use of high-throughput sequencing to examine the food microbiome over the past decade. The search for 'food microbiome' and 'food microbiota in the Web of Science database recognized 25,448 publications from 2010 to July 20, 2021. Among this database, 3741 publications contained the term 'safety' and 788 contained the term 'spoilage' (Billington et al., 2022). The remaining uses may potentially be related to food safety. Food composition testing can detect harmful contaminants like allergens or toxins, while microbial consortium assessment can detect potential pathogens (Brown et al., 2019; Mora et al.,

2019). The food quality control is based on the sequencing technologies classified into two categories: parallel short-read sequencing generates reads that range from 600 base pairs (bp) and long-read sequencing of a single molecule which produces reads greater than 1000 bp. A key method for characterizing the bacterial community is the quantification of the microbial community's taxonomic diversity, which determines the type and wealth of microorganisms present. Taxonomic diversity can be used to characterize and compare communities, with more shared taxa indicating more similarity. Metagenomics often measures biodiversity in taxa by evaluating valuable marker genes, classifying sequences into defined taxonomic groups, or assembling them into different genomes. These approaches may not be distinct and could be overlapping (Sharpton, 2014).

4.1.4 Lipidomics

Lipids, a major macronutrient among protein, fat, and carbohydrate), known as fat in food science have multiple roles in food as well as in human physiological processes. Adulteration alters the lipid profiles of food, which can be detected using lipid profiling methods. Food lipids, such as those found in oils, milk, and meat, can be authenticated by using chemometric methods. Lipidomics is an emerging subdiscipline of metabolomics that analyses lipids in biological systems, and their functions in pathways and networks (Han et al., 2012). This branch studies the biological activities of lipid molecular species and their impact on protein expression in lipid metabolism and gene regulation. The recent burgeoning engrossment in lipid research elucidates their critical biological importance (Yetukuri et al., 2008). Researchers are developing advanced instrument-based techniques with high sensitivity with MS for lipid characterization, showing promise in lipidomics analysis, having diverse lipid species and similarities in structure across classes and subclasses.

4.1.4.1 Application of Lipidomics in Food Quality Assurance

Lipidomics has been applied in food science research for quality assurance, particularly authentication of plant, animal, and edible fungi-derived foods. Lipid profiling technologies, when combined with chemometrics, can detect counterfeit foods and distinguish between distinct species, geographical origins, and food preparation methods based on minor lipid content variations. Lipidomics investigations provide extensive information on lipid structures and levels, allowing scientists to understand underlying mechanisms in physiological and pathological processes. Global lipidomics approaches an attempt to examine several lipids using a single technique, including unnoticed lipids. The approach is usually nonmeasurable. The instrument response to a given lipid in MS analysis varies depending on the biological matrix composition. To achieve absolute quantification using MS, an

isotope-labeled lipid standard must be used for each measured lipid, which is not currently feasible. Advancements in analytic methodologies and apparatus have made it possible to quantify more significant lipidsh (Hyötyläinen & Orešič, 2015).

Milk and its derivatives, including cheese, butter, and yogurt, are a valuable source of protein, fat, and other nutrients. Milk and dairy products have considerable nutritional value but are often adulterated. Lipid adulteration in milk and other dairy goods involves adding vegetable-derived oils (e.g. soybean oil, peanut, and palm oil), animal fats, or other fat-containing foods to increase fat content (Liu et al., 2018). Since due to the predominant similarity in lipid composition it is a difficult task to detect adulteration in food and dairy products based on lipid profiling. De Oliveira Mendes et al. (2016) developed a novel technique for detecting milk adulteration by GC-FID and capillary zone electrophoresis with UV detection. The fatty acid (FA) profiles of milk and whey from GC-FID were used for orthogonal partial least square -Discriminate analysis (OPLS-DA). Six FAs (myristic, palmitic, stearic, vaccenic acid, cis-vaccenic acid, and linoleic acid) were identified as suitable markers for differentiating the two groups. Capillary zone electrophoresis was used to quickly quantify six fatty acids in contaminated milk samples, with whey content ranging from 4% to 20%. Another emerging proficient method, MALDI-QTOF-MS has been used to identify adulteration of milk protein powder with vegetable oils or fats. The mixing of unnatural fat in milk, such as hydrogenated plant-based oil enhanced the abundance of ion clusters at m/z 881 and 907 in MALDI-QTOF spectra (Garcia et al., 2012).

The research provides nutritionists with detailed information on lipid distribution in milk and identifies biomarkers for detecting fraud. In Chinese marketplaces, high-value milk (e.g. goat) is adulterated with low-value replacements (soy and bovine), necessitating the use of quick and reliable authentication procedures (Ali et al., 2017; Li et al., 2017b). Such methodologies outperformed classic markers screening methods, providing precise information on lipid composition in milk samples. A few other robust technologies for lipid analysis, based on mass spectrometry are direct infusion, chromatographic separation, desorption and ambient ionization, and mass spectrometry imaging. Nuclear magnetic resonance (NMR) spectroscopy (^1H , ^2H , and ^{31}P) is a promising method for metabolomics due to its non-invasive nature and quick turnaround time (Takis et al., 2019). However, it is not widely employed in lipidomics. NMR-based lipid analysis is less sensitive than MS-based methods. It confirms lipid fraction structures by assigning resonances to specific moieties based on chemical shifts (Li et al., 2017b).

4.2 Physicochemical Tools for Quality control and Assurance

In addition to omics research, several other physicochemical analytical approaches have implications for food safety and quality management (Fig. 3.3).

4.2.1 Pulsed Electric Field

Pulsed electric field (PEF) offers another promising new technology for milk and related product quality management. It stands out as a prospective environment-friendly nonthermal technology in the food and milk sector for mitigating the detrimental effects of conventional heat processing without altering the nourishing, functional, and sensual properties of food products. In terms of effectiveness PEF treatment inactivates the pathogenic microorganisms responsible for the spoilage of milk and its products while retaining the authenticity of process parameters, food qualities properties, and microorganism profiles and assuring the quality of milk and dairy products (Cavalcanti et al., 2023). Nonthermal technology principally works on the indirect heat mechanism in food processing. These new approaches within the food sector promote sustainability by minimizing processing associated costs, energy usage, and waste products, while also improving resource effectiveness. These procedures can maintain a food's nutritional, sensory, and functional qualities more effectively than standard heat-based treatments. Other nonthermal technologies, such as ultrasound (US), high-pressure processing (HPP), cold plasma (CP), and pulsed light (PL), have been increasingly adopted by the food industry as alternative methods for food processing. PEF treatment is a promising and adaptable method for treating liquid, semi-solid, and solid foods for various reasons (Syed et al., 2017).

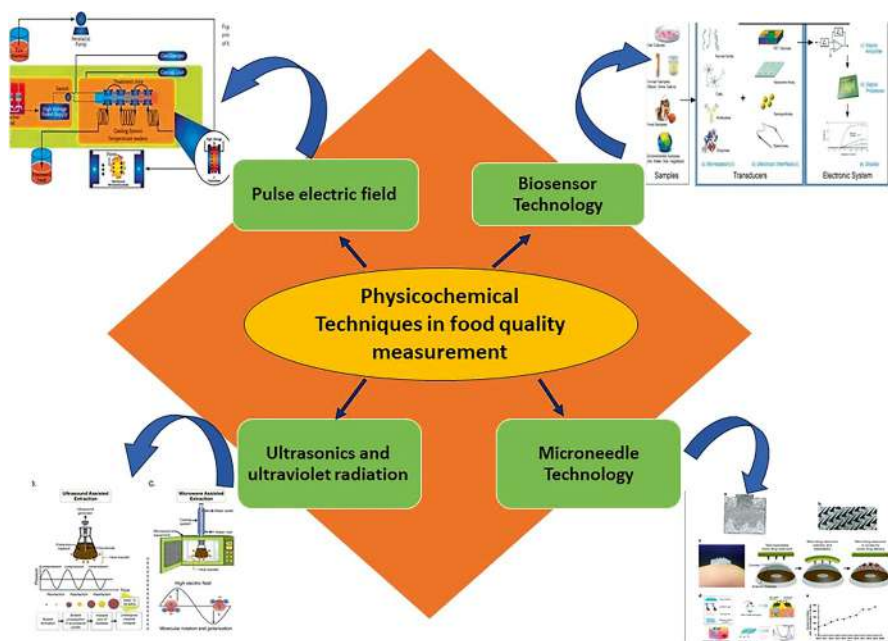


Fig. 3.3 Advanced physicochemical methods for identification of food-borne pathogens and adulterants

4.2.2 Ultrasonics

In medicine, ultrasound is used for scanning and imaging. Low-power intensity and high-frequency acoustic pulses are sent from a transducer. Ultrasound detection is often performed at low intensity and high frequency. In the food sector, it offers a quick, accurate, cost-effective, and non-destructive way to analyze and monitor food qualities during processing (Feng & Yang, 2011). This technique also has a possible application as an online sensor for measuring food qualities during preparation. Real-time ultrasonic measurements allow for the optimization of product quality by adjusting composition and process parameters. Low-intensity ultrasonic waves of 50 or 100 kHz have been used to evaluate the healthfulness and quality of numerous fruits and vegetables, including apples (Kim et al., 2009), carrots, tomatoes, melons, avocados, and mangoes, based on ripeness, texture, and firmness. The process used ultrasonic parameters like velocity and attenuation which were compared to the physical features of the product. Ultrasound streaming in a liquid can identify microorganisms that alter their physicochemical characteristics, such as viscosity and elasticity, due to microbial activity (Elvira et al., 2006). Some food materials require enzymatic inactivation to maintain their quality and stability. Acoustic cavitation causes chemical and physical damage to cell walls, leading to the inactivation of microorganisms. Ultrasound can kill bacteria in liquid foods by both cavitation and intracellular cavitation, disrupting structural and functional components until cell lysis occurs. Ultrasound technology can be useful for quality assurance and food safety.

4.2.3 Ultraviolet Radiation

Thermal processing serves as a primary disinfecting procedure used in the dairy sector to maintain and ensure the security of goods and prolonged shelf life. UV-C radiation is a non-chemical, non-thermal intervention method that employs physical force and is secure, friendly, and non-toxic. Nonthermal technologies have been extensively researched in response to increasing demand from customers for natural and healthier products. Shortwave ultraviolet light (UV-C) irradiation has several benefits, including inexpensive maintenance and installation costs, minimum energy consumption, and food preservation without the negative consequences of heat treatment (Delorme et al., 2020). UV-C radiation can effectively kill microorganisms that are pathogenic and spoil in milk and other dairy products by causing damage to DNA, the activity of enzymes, and cytoplasmic membrane integrity. Jermann et al. (2015) found that revolutionary food processing methods like UV resulted in improved quality of 94%, 92% safety, and 91% longer shelf life. Few studies have looked at the impact of ultraviolet (UV) radiation on the microbiological safety and inherent quality characteristics in dairy goods. This preservation strategy is cost-effective and environmentally beneficial, with no negative repercussions (Keyser et al., 2008). Commercial ultraviolet technology was designed for the pharma and fisheries industries, which cannot withstand disinfectants that contain chemicals.

The food industry became interested in using it to reduce heat-related issues during processing (López et al., 2005). UV light at shorter wavelengths (200–280 nm) disrupts microorganisms' DNA, changing metabolism and causing cell death. There are several mechanisms for the inactivation of microbial cells by using ultraviolet light, depending on the wavelength used for therapy. Microbial cells can be inactivated either indirectly or directly by absorbing light on their DNA. UV light primarily inactivates bacteria by causing DNA replication lesions (Brem et al., 2017; Gayán et al., 2014). UV radiation, which is the US Food and Drug Administration (FDA) and the European Food Safety Authority (EFSA) approved, can be used in conjunction with other interventions and therapies to enhance their effectiveness (Fan et al., 2017). UV light could be a viable option for the food sector to regulate contaminants in dairy products after processing (Koca, 2018, chap. 1). However, due to its low penetration, it has restricted applications. UV-C technology has low penetrating strength and requires direct exposure to inactivate bacteria, making it challenging for companies to utilize. Ensuring UV-C light exposure on all food surfaces remains a challenge (Fan et al., 2017). The energy utilization of a UV system depends on factors such as the variety and number of UV light sources, their flow rate, mixing efficiency, and food characteristics. The adoption of cutting-edge technologies in the food processing and beverage industry is influenced by industry characteristics such as their technological capabilities, market size, share, and demand. Modern technology includes growth and commercialization expenses, rewards, advantages, risks complexity, the value of the product, consumers' legitimacy, and environmental regulations and standards. Industries will adopt new technology if it offers cost and performance advantages over traditional methods (Priyadarshini et al., 2019). UV pasteurizing of milk is also impacted by factors that include low penetration, potential flavor changes, inability to remove the bacterial spores, resistance of some pathogens, and lack of an adequate and reliable indicator for productivity. Despite all the challenging issues, UV radiation is a cutting-edge food processing method that effectively eliminates harmful and spoiling microbes while preserving dietary and sensory quality. Furthermore, it is non-toxic and does not generate waste (Gayán et al., 2014). UV radiation is more efficient in terms of energy and economical as compared to other approaches. In the future thus, UV treatment is a promising approach for dairy processing, with the potential to improve sensory quality while reducing initial investment and operating costs.

4.2.4 Microneedle Technique

When integrated with advanced analytical methods, the recent research on microneedle (MN) technology provides accurate, non-destructive, and minimally obtrusive sampling in the field, allowing for the quick collection of many samples. This capacity improves the effectiveness of analyzing many food toxins quickly. The microneedle-assisted techniques greatly enhance the working process of conventional analytical methods and identify chemical as well as biological contaminants in food (Eş & Khaneghah, 2024). The microneedles are synthesized using

specialized techniques which include 3D printing (Krieger et al., 2019), photolithography (Eş et al., 2023; Roh et al., 2022), laser processing (Tu & Chung, 2016), two-photon polymerization (Faraji Rad et al., 2021) and various other methods (Nagarkar et al., 2020). MNs can be made from several materials, including titanium (Dong et al., 2023) and biocompatible polymers like silk (Wang et al., 2023). MNs allow for efficient and targeted sample extraction, safeguarding food quality and reducing contamination risks in the supply chain. Despite its advanced utility, significant challenges persist, one of which is extending MN-based sampling to diverse dietary matrices. This problem can be confronted with more research to create MN designs optimized for certain food kinds such as fruits and vegetables. Surface modifications, altering tip designs, and experimenting with different penetration depths can improve MN adaptation to different food matrices. Optimizing MN sample efficiency requires creative engineering solutions that account for various textures, moisture levels, and skin thicknesses in diverse food products. As innovation and collaboration propel the field ahead, MNs can play a revolutionary role in preserving food quality and safety through precision sampling.

4.2.5 Biosensor Technology to Detect Chemical Contamination in Food

Biosensor technology is gaining popularity among scientists in the food sector (Tripathi et al., 2023). Advancements in nanotechnology, biometrics, and materials are driving growth in the market. This new analytical technology offers numerous benefits for analyzing foods and is portable, making it easy to detect specific substances on-site. IUPAC defines biosensors as incorporated receptor-transducer platforms that provide quantitative or partially quantitative analytical data by using biological recognition. Biosensors are widely researched analytical devices that detect specific analytes. It integrates a biological recognizing component along with a physical and chemical transducer, which finally detect the analyte by converting the interactions between molecules into a recognizable signal (Pudake et al., 2021). Their fast, low-cost, sensitive, and selective nature has led to advances in next-generation medicine, including personalized healthcare and ultrasensitive point-of-care detection of disease markers. Biosensors are widely used in the food supply chain to provide prompt detection and treatment of food quality issues. One of the primary benefits of point-of-care (POC) technology is its simplicity, and economical sample preparation (Kaya et al., 2021). The primary problems in the food supply chain include food safety, security, nutrient monitoring, and eco-friendly production (Neethirajan et al., 2018). Biosensors have potential applications in food production and packaging design. Fruit ripening varies from fabricated ripening regarding the amount of nutrients, total soluble solids (TSS), titratable acidity (TA), and sensory qualities. Glucose biosensors can detect the glucose level in fruits and correspond it with the ripening state, determining shelf life (Haginoya et al., 2016). A biosensor was developed for food safety on forthcoming cyclo-olefin polymer packing film. They used an *E. coli*-specific RNA-cleaving fluorogenic DNzyme probe to determine the bacterial growth in multiple foods without removing any sample or sensing instrument. The package surface is specific, steady for at least 14 days under

various pH conditions (pH 3–9), and can detect *E. coli* (Yousefi et al., 2018). Currently, only a few sensors are utilized in high-value food packaging due to their high cost or lack of practicality. This is a critical issue that must be addressed in the future. This technology can be largely commercialized with cost reduction of the sensors and thus can be another player in food safety and control.

Magnetic nanoparticles are widely used in ultrasensitive biosensors for signal amplification, notwithstanding other detecting modalities. Ouyang et al., 2021, developed a colorimetric as well as fluorescent dual-mode nanoprobe biosensor for detecting *S. aureus* in meats. After microorganism growth and magnetic field separation, this method of detection achieved a low limit of detection. Under extreme conditions, molecular imprinting markers and high-affinity aptamers are the favored options. Additionally, the interaction with both the probe and tagging material is crucial for building a reliable biosensor (Tao et al., 2020). Nanotechnology, microfluidics, cell phones, and wireless networking can help researchers build and construct portable/smart biosensors.

5 Conclusion and Future Perspectives

The global food industry has led to increased demand for high-quality food with specific features, making food quality assurance and authenticity a major problem. More focus should be directed to provide researchers and industrialists with a foundation for future work involving HACCP and cutting-edge quality control and assurance systems in the food industry and challenges as well as possibilities for implementing HACCP in organizations should be identified. Future research in quality control and HACCP aims to enhance food safety, quality, and sustainability while adjusting to changing customer needs, risks, and regulations. Conventional procedures are insufficient to address emerging food fraud and safety threats. New strategies for detecting adulteration and exploring the link between endogenous chemicals and food quality should be developed. The research should emphasize the relevance of the food safety of the production of milk and dairy products, which are closely related in terms of assuring milk quality and minimizing milk spoiling. The dairy sector's management systems work for the safety and quality of food, milk, and dairy products, preventing microbiological contamination and chemical adulteration. Food-borne infections are a focus of public health initiatives, which are monitored for microbial contamination in milk products.

The advanced physiochemical, biochemical, and molecular-based techniques over conventional technical detection strategies offer promising capabilities for assessing food adulteration, safety, quality, and traceability. These methods outperform traditional vibrational spectrum-based approaches in terms of sensitivity, selectivity, and descriptors, allowing for more accurate categorization. Omics techniques have the potential to significantly affect microbiological food safety, but their implementation is still in its early stages in various sectors. Adopting

next-generation sequencing for epidemic identification and research in food microbiology requires both equipment and educated personnel. Microbiome profiling using 16S metagenomics can be a valuable forensic technique for the quality control and assurance of milk and dairy products. Scientists in microbiology, omics, and bioinformatics should be trained to improve existing technologies and investigate new applications in food and public health. Developing faster, less computationally intensive, and more user-friendly bioinformatics tools will be crucial. This plays an essential part in encouraging the use of omics tools and could potentially be of greater significance than future developments in genomic technology. Currently, research on lipids requires effective new computational and bioinformatic techniques that may elucidate their complexity and diversity. Their roles include both biochemical reactions and biophysical features, such as biological membrane structure. The other techniques described earlier in the chapter pulse electric field, a green technology used for food quality development and control focuses on the consumer needs for enhanced sensory and quality features, including flavor, extended storage, higher nutritional value, and environment-friendly processing. PEF-dependent food processing produces less industrial waste compared to conventional technologies. It offers improved food products with reduced energy consumption, water conservation, and little waste. Although the advancements in biosensors have shown promise in controlling the entire food supply chain, addressing inconsistencies and complexity it still needs enhancement in research and development, and explicitly in remodeling the published literature into portable on-site, usable in public domains. The development of next-generation approaches is constantly required for food assurance and quality, just as adulterants and scandals play a role in food safety.

Acknowledgments The authors acknowledge the funding support from the Department of Science and Technology (under Govt. of India) for the project (DST/WOS-A/LS-267/2019), under Women Scientist Scheme-A

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Chapter 4

Fluid Mechanics in Food & Dairy Processing



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1 Introduction

Fluid mechanics plays a crucial role in various aspects of dairy processing, ensuring efficient operation, product quality, and safety. Fluid mechanics principles are employed in designing pipelines and pumps for transporting milk from farms to processing plants. Fluid mechanics plays a vital role in various stages of dairy processing, from transportation and heat treatment to separation, mixing, and packaging, contributing to the efficiency, quality, and safety of dairy products. Understanding fluid flow helps in optimizing the layout, diameter, and pressure requirements of these systems to minimize energy consumption and maintain product integrity. Heat exchangers are used to pasteurize milk and other dairy products. Fluid mechanics governs the flow patterns inside heat exchangers, ensuring efficient heat transfer between the product and the heating or cooling medium. Design considerations include flow rates, turbulence, and pressure drops to achieve the desired pasteurization temperature while minimizing energy usage. Homogenization is a process that breaks down fat globules in milk to create a uniform product with a consistent texture and stability. Fluid mechanics principles guide the design of homogenizers, optimizing factors such as pressure, flow rate, and nozzle geometry to achieve the desired particle size reduction and distribution. Separation techniques such as centrifugation are used to separate cream from milk or to remove impurities.

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Understanding fluid dynamics is essential for optimizing centrifuge design and operation parameters to achieve efficient separation while minimizing product loss and energy consumption. Filtration processes remove impurities, bacteria, and particles from dairy products like milk and cheese whey. Fluid mechanics principles help in designing filtration systems that ensure proper fluid flow through filter media, maximizing filtration efficiency and product quality. Mixing and blending operations are crucial for achieving uniformity in dairy products such as yogurt, ice cream, and cheese. Fluid mechanics guides the design of mixing equipment, optimizing factors such as impeller design, agitation speed, and fluid viscosity to ensure thorough blending while minimizing energy input and processing time. Fluid mechanics is also relevant in packaging processes, where considerations such as fluid flow behavior during filling, sealing, and sterilization influence packaging design and integrity. Proper understanding of fluid dynamics helps prevent product contamination and packaging defects. Cleaning-in-Place (CIP) systems are used to clean processing equipment without disassembly, reducing downtime and labor costs. Fluid mechanics principles are applied to optimize CIP processes, ensuring efficient removal of residues and contaminants through proper selection of cleaning agents, flow rates, and temperature profiles. The characteristics of milk fat globules are affected by factors such as their size, surface layer, presence of fat crystals, and external parameters like agitation and air incorporation (Jukkola & Rojas, 2017). The stability of these globules against processes like creaming, coalescence, flocculation, and disruption depends on the presumed interaction energy between them and fat globule membrane properties. Homogenization significantly affects the fat globule membrane and size, leading to distinctions between homogenized, natural, and recombined fat globules (D’Incecco et al., 2018). In daily life, various substances, including milk, butter, cheese, cream, and even items like colored gems, boot polish, rubber, and ink, serve vital roles. These substances are colloidal solutions, where microscopic particles are evenly dispersed within a liquid, forming what is known as a colloidal suspension (Babick, 2016). Milk, for instance, is an aqueous solution containing primarily fat, proteins, lactose, and minerals. It serves as a crucial energy source for breast-fed infants, providing essential nutrients and bioactive compounds, with its fat content typically ranging from 3% to 5%, present in milk fat globules (Guo, 2020).

2 Milk Fat Globule Membrane (MFGM) as a Colloidal Structure

The milk fat globule membrane (MFGM) is a complex, multi-layered structure that surrounds the fat droplets in milk, stabilizing them as a colloidal dispersion. The MFGM is primarily composed of phospholipids, proteins, cholesterol and glycolipids. Phospholipids are amphiphilic molecules with a hydrophilic (water-attracting)

head and a hydrophobic (water-repelling) tail, forming the basic structure of the membrane. Various proteins, including enzymes, structural proteins, and glycoproteins, are embedded in the membrane. Cholesterol is the lipid component contributes to membrane fluidity and stability. Glycolipids are lipids have carbohydrate groups attached and play roles in cell recognition and signaling. Fat globules are synthesized in the mammary gland's epithelial cells, starting as small lipid droplets in the cytoplasm. As these droplets grow, they become enveloped by a monolayer of phospholipids and proteins derived from the endoplasmic reticulum. Upon secretion into the milk, these droplets acquire a bilayer membrane from the apical plasma membrane of the mammary epithelial cells, forming the mature MFGM.

The physico-chemical characteristics of the milk fat globule membrane have increased significant interest in the realm of food colloids, owing to the technological and nutritional significance of the MFGM. Milk fat globules represent unique colloidal formations, typically ranging from 0.1 to 20 μm in diameter, and are naturally occurring structures exclusively found in milk (Jukkola & Rojas, 2017; Mohan et al., 2021). These globules consist of highly intricate membrane structures that undergo various dynamic interactions. Processes employed within the dairy industries significantly influence the composition, functionality, and properties of the MFGM (El-Loly, 2011). The composition of natural milk fat globule membrane is presented in Table 4.1.

Milk is a naturally occurring emulsion, where oil is dispersed in water, primarily composed of fat globules ranging from 0.1 to 10 μm in diameter. These fat globules are shielded from enzymatic degradation and merging by MFGM, which functions as a natural emulsifier, enclosing the nonpolar triglyceride core (Zheng, 2014). Various substances exist in distinct particles, necessitating interactions with serum compounds to occur at the particle surfaces, potentially acting as a hindrance. Additionally, communication between fat globules is limited, preventing compounds in one globule from accessing another. Several physical attributes of milk,

Table 4.1 An approximate composition of natural milk fat globule membrane

Milk fat globule membrane component	Mg/100 g fat globules	Mg/ m ² fat surface	Membrane material percentage
Protein	1800	9.0	70
Phospholipids	650	3.2	25
Cerebrosides	80	0.4	3
Cholesterol	40	0.2	2
Monoglycerides	+	+	–
Water	+	+	–
Carotenoids + vitamin A	0.04	2×10^{-4}	0.0
Fe	0.3	1.5×10^{-3}	0.0
Cu	0.01	5×10^{-5}	0.0
Total	>2570	>12.8	100

Note: Various other components can be present in trace quantities

such as turbidity, and subsequently, color and viscosity, rely on its dispersion state. If particle aggregation takes place, viscosity is further impacted, often leading to gel formation (Sotomayor & Schalkwijk, 2020).

Colloids come in various forms, including sol, foam, emulsion, and aerosol. Sol refers to a colloidal suspension comprising solid particles dispersed in liquid. Emulsion occurs between two liquid phases. Foam arises when numerous gas particles become trapped within solid or liquid. Aerosol consists of smaller particles of solid or liquid dispersed within a gas phase (Schramm, 2014). An emulsion denotes a specific form of colloid, indicating tiny droplets of one liquid dispersed within another liquid. Milk serves as a prime illustration of an emulsion, with hydrophobic butterfat particles distributed within a water-based solution (Hugelshofer, 2001).

3 Classification of Colloids Solutions

Classification Based Upon Interaction, Colloidal solutions are categorized into two groups based on the interaction between the dispersed phase and the dispersion medium.

- (a) **Lyophilic colloids:** Lyophilic colloids, characterized by their affinity for the dispersion medium, entail dispersed phases that readily form colloidal solutions. Materials like gum, gelatine, and starch, when combined with a suitable dispersion medium, effortlessly transition into a colloidal state. Consequently, these solutions are easily created through direct contact between the dispersed phase and dispersion medium (Syal, 2007). Notably, lyophilic colloidal solutions exhibit reversibility, allowing for the straightforward separation of the dispersed phase and dispersion medium once formed. Upon separation, remixing the two phases regenerates the colloidal solution. These sols demonstrate significant stability. When water serves as the dispersion medium, they are classified as hydrophilic colloids (Ghosh, 2007; Goodwin, 2009).
- (b) **Lyophobic Colloids:** Lyophobic colloids, characterized by their aversion to the dispersion medium, involve dispersed phases lacking affinity for the dispersion medium. Metals such as gold, silver, and their hydroxides or sulfides, for instance, do not readily transition into a colloidal state when simply mixed with a dispersion medium. These sols necessitate special preparation methods. Unlike lyophilic colloids, they can precipitate readily, and once precipitated, they exhibit minimal tendency to return to the colloidal state, rendering them irreversible. Moreover, they typically lack stability and often require a stabilizing agent to maintain their colloidal form. When water serves as the dispersion medium, they are denoted as hydrophobic sols.

4 Surface Phenomena

Surface phenomena encompass a diverse range of physical and chemical processes occurring at interfaces between different phases, including gas-solid, liquid-solid, gas-liquid, and liquid-liquid interfaces. When one of these phases involved is a gas, typically air, the term “surface” is commonly used; otherwise, the term “interface” is more appropriate, though these terms are often used interchangeably. Of greater significance is the distinction between solid interfaces, involving at least one solid phase, and fluid interfaces between two fluid phases, such as liquid-liquid or gas-liquid interfaces. Surface phenomena associated with surface tension and resulting from the deformation of liquid boundary surfaces are often referred to as capillary phenomena (Dąbrowski, 2001; Sievers et al., 2016). These phenomena include the capillary absorption of liquids into a porous material, capillary condensation, and the determination of equilibrium shape of drops and gas bubbles (Streator, 2015).

4.1 Surface Tension

Surface tension, a characteristic property of liquids, is akin to the stretching of elastic material. It arises from cohesive forces among liquid molecules, playing a pivotal role in numerous behavioral attributes of liquids. The region of contact between two phases is termed the interface, referred to as the surface when one phase is gaseous. The characteristics of interfaces and surfaces hinge upon the composition, type, and arrangement of molecules within them. Surface tension governs the formation of liquid droplets. While solids also exhibit surface tension, it is not quantifiable (Nosonovsky & Ramachandran, 2015). Surface tension is described by the force per unit length or energy per unit area, denoted by symbol γ . It refers to the force acting along a unit length, parallel to the surface but perpendicular to the line. Its SI unit is newton/m and cgs unit is dyne/cm. Another definition equates it to work done per unit area, determined in SI units as joules/m² and in cgs units as ergs/cm² (Weijs et al., 2013).

Surface tension is a crucial property of liquids that reflects the cohesive forces at the surface, impacting various phenomena such as droplet formation, foam stability, and interactions with other substances. For milk and milk products, surface tension plays an important role in processing and quality. The surface tension of milk at room temperature (around 20 °C) typically ranges from 40 to 50 mN/m (millinewtons per meter). This value is lower than that of pure water (approximately 72 mN/m at 20 °C) due to the presence of milk fat, proteins, and other solutes that disrupt the hydrogen bonding network of water molecules. Factors affecting surface tension includes fat content, proteins, temperature, and processing conditions. Higher fat content generally reduces the surface tension of milk. Milk fat globules interfere with the cohesive forces among water molecules, lowering surface tension. Milk proteins, especially casein and whey proteins, can adsorb to the air-water interface,

stabilizing emulsions and foams, and reducing surface tension. Surface tension decreases with increasing temperature. Higher temperatures increase molecular motion, reducing cohesive forces at the surface. Homogenization, which breaks down fat globules into smaller sizes, can influence surface tension. Pasteurization and other heat treatments can also affect the protein structure and surface properties.

Different milk products exhibit varying surface tension values depending on their composition and processing. The surface tension of cream is lower than milk, typically around 25–35 mN/m. High fat content significantly reduces surface tension, which is crucial for whipping and forming stable foams. Surface tension of yogurt is similar or slightly lower than milk, depending on fat and protein content. Fermentation and thickening agents can influence the surface tension, affecting texture and mouthfeel. The surface tension of ice cream is lower than milk due to high fat and air incorporation. Surface-active agents and emulsifiers added during production further reduce surface tension, aiding in air incorporation and foam stability. The surface tension of skim milk is slightly higher than whole milk, around 50–55 mN/m. The reduced fat content means less disruption of cohesive forces among water molecules. The surface tension of condensed milk is lower than regular milk due to high sugar content and reduced water content. The increased viscosity and concentration of solutes lower the surface tension. Surface tension influences the ability to form and stabilize foams, essential for products like whipped cream and certain desserts. Lower surface tension aids in the formation of stable emulsions, crucial for products like cream and ice cream. Surface tension affects how milk spreads on surfaces, relevant in applications like milk coating or adhesion in dairy-based adhesives. Consistency in surface tension is important for maintaining product quality, texture, and stability.

4.2 Adsorption

Adsorption pertains to the accumulation of molecules on the internal or external surfaces, such as the walls of capillaries or crevices, of solids, or on liquid surface. In contrast, absorption, often mistaken for adsorption, involves the penetration of a substance into the actual interior of crystals, blocks of amorphous solids, or liquids. The term “sorption” is sometimes used interchangeably to indicate the uptake of a gas or liquid by a solid without specifying whether it involves adsorption or absorption. A substance that undergoes adsorption is referred to as a surfactant. Adsorption occurs because it results in a less surface free energy and, consequently, a reduction in surface tension. Additionally, substances in a gaseous phase, such as water vapors in air, can also adsorb onto a surface, exhibiting similar relationships (Filenko, 2009).

Adsorption in the context of milk refers to the process by which molecules from the milk (such as proteins, fats, or other solutes) accumulate on the surface of another phase, such as air bubbles, fat globules, or solid surfaces. This phenomenon is critical in various aspects of dairy science, including the stabilization of emulsions and foams, surface phenomena during processing, and interactions with

packaging materials. Caseins are the major proteins in milk that readily adsorb onto surfaces. They are particularly important in stabilizing casein micelles and in the formation of curds during cheese making. Whey proteins, such as beta-lactoglobulin and alpha-lactalbumin, also adsorb at interfaces, especially during heat treatment and processing. The milk fat globule membrane (MFGM) adsorbs proteins and phospholipids, stabilizing the fat globules and preventing coalescence. Sugars, minerals, and vitamins can also be involved in adsorption processes, although their role is less prominent compared to proteins and fats. Proteins adsorb to the surface of fat globules, forming a protective layer that prevents coalescence and stabilizes the emulsion. Casein micelles and whey proteins play a significant role in this process. During homogenization, the fat globules are broken down into smaller sizes, increasing the surface area and enhancing the adsorption of proteins, which stabilizes the emulsion. Proteins adsorb at the air-water interface, forming a film that stabilizes air bubbles.

Temperature, pH, and the presence of other solutes can affect the adsorption capacity of proteins and, consequently, the stability of foams. Higher temperatures can enhance the mobility of molecules, increasing the rate of adsorption. However, excessive heat can denature proteins, altering their adsorption properties. The pH of milk affects the charge and solubility of proteins, influencing their adsorption behavior. For example, at the isoelectric point of casein, the adsorption is maximized, leading to curd formation. The concentration of proteins, fats, and other solutes in milk can affect the extent and nature of adsorption. Higher concentrations can lead to more adsorption sites being occupied. The presence of salts, sugars, and other additives can influence the adsorption behavior by altering the interactions between molecules and the surface.

4.3 *Surfactants*

Surfactants represent a class of organic compounds with amphiphilic properties, consisting of hydrophobic and hydrophilic groups. Hydrophilic groups facilitate solubility in water, while hydrophobic groups promote solubility in nonpolar media. Consequently, at the interface within the adsorbing layer, amphiphilic molecules orient themselves optimally, with hydrophilic groups facing the polar (water) phase and hydrophobic groups facing the nonpolar (gas and hydrocarbon) phase (Lavanya & Machado, 2023). These versatile compounds play various roles, including reducing surface tension between different phases such as liquids, gases, and solids. Surfactants serve as wetting agents, foaming agents, emulsifiers, dispersants and detergents. Typically organic in nature, surfactants are characterized by their amphiphilic structure, comprising water-soluble heads and water-insoluble (or oil-soluble) tails. Upon introduction into water, surfactants diffuse and adsorb at the interface, such as between air and water or at an interface between oil and water. In the latter scenario, the water-insoluble hydrophobic group may extend into the air or

oil phase, while the water-soluble head group will remain in water phase (Khalfallah, 2023). Surfactants exist primarily in two forms: small-molecule amphiphilic compounds, commonly referred to as amphiphiles, and polymers, with proteins being a prominent example.

4.4 *Amphiphiles*

These compounds exhibit surface activity due to their amphiphilic nature. Their molecular structure consists hydrophobic tail, typically composed of fatty acid, and hydrophilic head group. While most of the amphiphiles have low solubility in water tending to aggregate into micelles above a critical concentration referred as the critical micellization concentration (CMC). At this concentration, the surface tension (represented by γ) also reaches a plateau. The CMC is affected by factors such as length and saturation of the fatty acid chain: longer and more saturated chains correspond to lower CMC values, higher surface activity, and lower Hydrophilic-Lipophilic Balance (HLB) numbers. HLB represents the balance between the hydrophilic and lipophilic properties of the molecules. Surfactants with an HLB value of 7 exhibit equal solubility in both oil and water; values lower than 7 indicate higher solubility in oil, while values higher than 7 signify greater solubility in water (Honciuc, 2021). Prominent examples of amphiphiles include monoglycerides and Spans, which are fatty acid sorbitan esters generally characterized by low to medium HLB values. Tweens, which are modified Spans with polyoxyethylene chains attached to the sorbitan group, have higher HLB values (Foo et al., 2020). In addition to these neutral or non-ionic surfactants, there are ionic surfactants such as sodium soaps, sodium dodecyl sulfate (SDS), and lactic acid esters, which are anionic and possess high HLB values. Phospholipids, another group of ionic surfactants, are mainly zwitterionic but are less soluble in water. All these surfactants, except for SDS, have various applications in food (Maher et al., 2023).

4.5 *Proteins*

These molecules are also amphiphilic, but their significant surface activity primarily stems from their large size. Upon adsorption, they tend to undergo conformational changes, with globular proteins often experiencing partial denaturation. For example, many enzymes undergo irreversible inactivation following adsorption at an oil-water interface. The process of conformational change typically occurs over an extended period, ranging from approximately 10 s for β -casein to 15 min for β -lactoglobulin. Consequently, it takes some time before reaching an equilibrium surface tension value (Satzer et al., 2016).

4.6 Functions of Surfactants

The primary role of a surfactant is to decrease surface tension, typically during the dissolution of liquids.

- (i) **Laplace pressure:** Laplace pressure typically decreases with the introduction of a surfactant, resulting in a reduction in surface tension. Consequently, this reduction results in fluid particle deformation, thereby promoting the formation of smaller particles during foam and emulsion formation (Langevin & Langevin, 2020).
- (ii) **Ostwald ripening:** This process experiences a decrease in its rate due to the reduction in interfacial tension. Additionally, in instances where proteins act as surfactants, the reluctance of proteins to undergo desorption further contributes to this deceleration (Wang et al., 2021).
- (iii) **Contact angle:** Surfactants play a role in altering contact angles, consequently influencing particle adhesion at interfaces and wetting process, such as the ability to clean solution to eliminate dirt from the solid surface. Additionally, variations in contact angles can impact the incidence or speed of partial coalescence (El-badawy et al., 2021).
- (iv) **Surface tension gradients:** Surface tension gradients are typically absent on an uncontaminated surface, but the introduction of surfactants can create variations in surface tension across different areas. This variation occurs when liquid flows along the surface, displacing surfactant molecules downstream and forming a surface tension gradient (denoted as dg/dx , where x is the distance). This gradient generates stress on the liquid. The liquid, in turn, exerts stress on the surface, with the stress magnitude determined by the product of viscosity and shear rate (Koch et al., 2011). When the surface tension gradient becomes significant, these stresses balance out, effectively stopping the surface from moving tangentially. This characteristic is crucial in technology as it aids in the formation of emulsions and foams. Without surfactants, liquid would quickly drain from the space between bubbles or drops, causing them to coalesce immediately. However, surfactants greatly slow down this drainage process (Wang & Yoon, 2008).
- (v) **Colloidal interaction:** The adsorption of surfactant onto particles typically results in a significant enhancement, in most instances, of the repulsive colloidal interaction forces among these particles. This phenomenon plays a crucial role in determining whether particle aggregation will occur or not. A primary function of surfactants is to hinder particle aggregation (Wang et al., 2020).
- (vi) **Coalescence:** Another key function of surfactants is to prevent the merging of emulsion droplets and foam bubbles. In many cases, this function relies significantly, although not entirely, on the colloidal repulsion they provide. Surfactants exhibit varying degrees of effectiveness in preventing coalescence,

with some even potentially promoting it under certain conditions. For example, small-molecule surfactants have the capability to displace proteins from an interface, potentially leading to instability (Langevin, 2019).

- (vii) **Micellization:** numerous small-molecule surfactants undergo micellization in water once the critical micelle concentration (CMC) is surpassed. These micelles have the ability to encapsulate lipid molecules within their interior, a crucial aspect of their detergent function (Hanafy et al., 2018).

5 Colloidal Interactions

Based on the Derjaguin–Landau–Verwey–Overbeek (DLVO) theory of colloid stability, it is postulated that two primary interactions govern the behavior of colloidal particles as they approach each other. These interactions include the electrostatic repulsion arising from the overlap of the electrical double layers surrounding the particles and the van der Waals attraction. The equilibrium between these opposing interactions dictates the stability of a suspension containing colloidal particles. This theory is applicable not only to rigid particles lacking surface structures but also to soft particles, such as polyelectrolyte-coated particles, which are often used as a model for biological cells (Ohshima, 2014).

5.1 Depletion Interaction

A repulsive interaction between polysaccharides and proteins induces an attractive force among globular proteins, termed the depletion interaction. For protein particles such as casein micelles in milk, a depletion layer forms when a polysaccharide does not bind to the casein micelle. This depletion interaction happens when colloidal particles are mixed with expanded polymer molecules, leading to the exclusion of the polymer's center of mass from a liquid zone near the surface of the rigid object. The thickness of this exclusion zone matches the polymer molecule's average effective radius. Within this depletion layer, the osmotic pressure is lower than in the bulk due to a reduced concentration of polymer segments (Semenova et al., 2014). Occasionally, the Brownian motion of casein micelles causes two depletion layers to overlap, increasing the bulk volume available to the polymer and reducing the system's free energy by a quantity known as P P V Overlap. As a result, colloidal particles aggregate, driven together by the unbalanced osmotic pressure difference. Asakura and Oosawa first described the depletion interaction between colloidal particles and non-adsorbing polymers, noting that the attractive force between particles is directly proportional to the polymer solution's osmotic pressure (Parakhonskiy et al., 2014).

5.2 *Van der Waals Attraction*

van der Waals forces, which are attractive, operate among all particles and molecules. For two identical particles with a radius of r dispersed within another medium, the attractive free energy is expressed as

$$V_{vdW} = -\frac{Ar}{12h}$$

provided $h \ll r$. The Hamaker constant A varies based on the particle material and the surrounding medium. For instance, in the case of milk fat globules in milk plasma, A is approximately 0.75 kT. The accumulation of fat crystals in oil occurs due to van der Waals attraction, with no repulsive force involved except for hard-core repulsion (Israelachvili, 2011).

5.3 *Other Interactions*

Particularly when particles are enveloped by a layer of hairy layer, various types of attractive interactions can ensue. Steric repulsion fails to hinder contact between these extended chains. Aggregation can occur if the surfaces or protruding chains have distinct negative and positive charges, due to electrostatic attraction. Even when all charges are negative, bridging can happen with the addition of a positively charged polymer or divalent cations like Ca^{2+} . Additionally, protein particles may aggregate during thermal treatment because of chemical cross-linking among exposed protein side groups. Typically, emulsion droplets coated with proteins aggregate under specific conditions, such as particular pH levels, where the protein becomes insoluble (Aguado et al., 2023).

6 *Fat Globule Size Distribution*

Milk fat primarily exists in spherical droplets ranging from less than 0.2 to approximately 15 μm diameter, with the majority of fat contained in globules measuring 1–8 μm in diameter. The observed size distributions may vary significantly depending on the method of measurement employed. Freshly drawn milk may contain a few globules ranging from 10 to a maximum of 15 μm , likely formed through the coalescence of smaller globules as they pass through the glandular ducts (Waldron et al., 2020). The particle size range is categorized into size classes of width Δd . In size class I , the number of particles with diameter d_i per unit volume of liquid, denoted as N_i , determines the number frequency as $N_i/\Delta d$ (dimension [length⁻⁴]) in relation to d . The volume frequency, representing the amount of dispersed material per particle of diameter d , is given by $\pi N_i d_i^3/6\Delta d$ (dimension [length⁻¹]).

This can also be expressed as a percentage of the total volume of dispersed material per unit class width. A size distribution cannot be adequately described solely by its mean value. The distribution's width is equally essential, with the relative width being more informative than the absolute width. The relative width, defined as cs , represents the standard deviation in particle size divided by d_{vs} .

Where, $N_i / \Delta d$ = number frequency; d = particle diameter; and L = length, and d_{vs} – Volume/surface average d .

6.1 Colloidal Solution

A colloidal solution is defined as a heterogeneous mixture where the particle size of the substance falls between that of a true solution and a suspension. Understanding the concept of colloidal solutions and distinguishing them from other types is essential, and they can be classified into True Solutions, Suspensions, and Colloids based on their distinct properties. Table 4.2 outlines the key properties and differentiation between each type of solution concerning various characteristics.

6.2 Difference Between True Solution, Suspension and Colloidal Solution

Figure 4.1 shows that particles size less than 10^{-7} cm are true solution and particles size between 10^{-7} cm and 10^{-5} cm are colloidal solution where size greater than 10^{-5} cm comes under suspensions.

Table 4.2 Comparison between true solution, suspension and colloidal solution

Property	True solution	Colloidal solutions	Suspension
Size of the particles	< 1 nm	1– 1000 nm	>1000 nm
Nature	Homogeneous	Heterogeneous	Heterogeneous
Filterability (diffusion via parchment paper)	Particles of a true solution diffuse rapidly via both parchment paper and filter paper	Colloidal particles pass via filter paper but not through parchment paper	Suspension particles do not pass via either parchment paper or filter paper
Visibility	Particles of a true solution are not visible to the naked eye	Colloidal particles are not visible to the naked eye but could be observed under an ultramicroscope	Suspension particles are large enough to be visible to the naked eye
Tyndall effect	True solutions do not exhibit the Tyndall effect	Colloids demonstrate the Tyndall effect	Suspension may or may not display the Tyndall effect
Appearance	Transparent	Translucent	Opaque

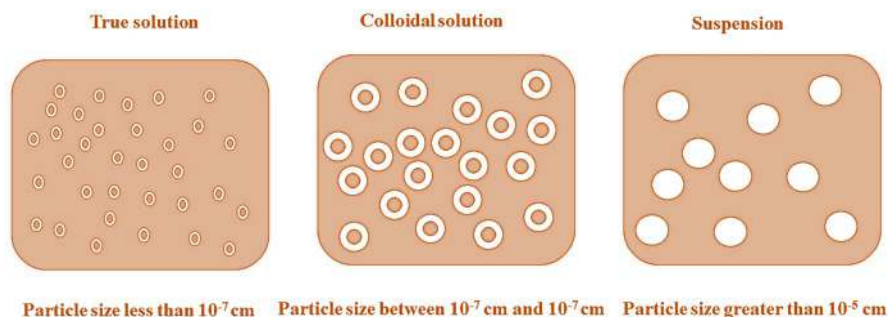


Fig. 4.1 Particles size of true solution, colloidal solution and suspensions

6.3 Creaming

Phospholipids play significant role in the oxidation process of milk. However, in cold raw milk, creaming occurs more rapidly than anticipated solely from this aspect. Immunoglobulin M (IgM), present in milk, interacts with lipoproteins to form a complex known as cryoglobulin, which then precipitates onto the fat globules, leading to flocculation. The process of homogenizing milk prevents this creaming phenomenon by lowering the diameter and size distribution of the fat globules, resulting in a similar rate of ascent for the majority of these globules. Additionally, homogenization facilitates the creation of a recombined membrane that closely matches the density of the continuous phase (Contarini & Povolo, 2013).

6.4 Effect of Homogenization

6.4.1 Surface Layers

The milk fat globule possesses a natural membrane acquired during secretion, composed of amphiphilic molecules with hydrophilic and hydrophobic segments. This membrane serves to decrease interfacial tension, thus enhancing emulsion stability. Upon homogenization, there is a significant expansion in surface area, leading to the loss of the native milk fat globule membrane (MFGM). Nevertheless, numerous amphiphilic molecules from the milk plasma, including partially dispersed whey proteins and casein micelles, are readily available for adsorption. Initially, the interfacial tension of raw milk ranges between 1–2 mN/m, which escalates to an unstable state at 15 mN/m immediately after homogenization, but stabilizes shortly thereafter (3–4 mN/m) due to protein adsorption. Protein transportation occurs predominantly through convection rather than diffusion. The rapid coverage process is typically accomplished in less than 10 s, albeit subject to some reorganization (Panchal et al., 2017).

6.4.2 Surface Excess

It quantifies the amount of protein adsorbed; for instance, 10 mg/m² corresponds to an adsorbed layer thickness of roughly 15 nm.

6.4.3 Acidity

The colloidal phosphate undergoes dissolution, which is completed at pH 5.25. Lowering the pH even further, below an isoelectric pH of casein, is necessary to remove all calcium. Essentially, calcium partially replaces calcium phosphate.

As the pH decreases, the negative charge on casein initially increases due to the dissociation of calcium ions from the micelles, but eventually decreases again as the casein associates with H⁺ ions. At low pH, casein becomes positively charged. This reduction in pH first causes the particles to swell and then to shrink significantly. For example, when the pH drops to around 5.3, a significant portion of the caseins goes into 'solution,' especially with increased hydrophobicity of the casein involved. This phenomenon occurs at 20 °C, with temperature variations affecting the impact—less at higher temperatures and more at lower temperatures, where some of the 'dissolved' casein becomes part of loose submicelles (Ye & Harte, 2013). The average particle size remains mostly unchanged within the considered pH range, but particles show notable differences at low and high pH values. At physiological pH, colloidal calcium phosphate mainly maintains micelle integrity. When the pH decreases, phosphate dissolution weakens the bonds, leading to micelle swelling and partial casein dissolution. At low pH, internal salt bridges between negative and positive protein groups enhance molecular cohesion. The overall attraction is particularly strong near the isoelectric pH of casein, around pH 4.6. Therefore, the number and strength of all types of bonds are weakest around pH 5.25, although this optimal pH can vary with temperature (McMahon & Oommen, 2008).

6.4.4 Colloidal Stability

The stability of colloidal solutions spans a broad spectrum, ranging from mere fractions of a second to several centuries. It is contingent upon numerous factors such as particle size, concentration, temperature during processing, and the presence of electrolytes. In lyophobic systems, the addition of electrolytes accelerates the rate of coagulation significantly. Conversely, incorporating a lyophilic colloid into a lyophobic sol can decelerate the coagulation process, yielding a kinetically stable colloidal system. Typically, colloidal particles exhibit instability due to thermodynamic factors, leading to their tendency to aggregate. However, the addition of a lyophilic colloid to a lyophobic sol can mitigate the coagulation process, resulting in a colloidal system that is kinetically stable (Yuan et al., 2022).

6.4.5 Viscosity

Viscosity defines the fluid's resistance to flow and deformation by shear or tensile stress. In fluid mechanics, it's essential to quantify viscosity to understand how fluids will behave under different conditions. There are two primary types of viscosity i.e. dynamic and kinematic viscosities. The dynamic and kinematic viscosities of milk are important properties that influence its flow behavior, processing, and stability.

Dynamic Viscosity (μ) is also known as absolute viscosity, it is the force per unit area needed to move one layer of fluid relative to another. This measure is expressed in Pascal-seconds (Pa.s) or poise (P), where 1 P equals 0.1 Pa.s. Dynamic viscosity measures milk's internal resistance to flow when an external force is applied. It quantifies the thickness or stickiness of milk. The dynamic viscosity of milk can vary depending on factors such as fat content, temperature, and the presence of other components (e.g., proteins, sugars). At 20 °C (68 °F), the dynamic viscosity of milk typically ranges from 1.5 to 2.0 mPa.s (millipascal-seconds). The viscosity of milk decreases as the temperature increases. For example, at higher temperatures, milk flows more easily because the internal resistance to flow is reduced. A general trend is that the dynamic viscosity of milk decreases by approximately 2–3% for every degree Celsius increase in temperature.

Kinematic Viscosity (ν) is defined as the ratio of dynamic viscosity to density of fluid ($\nu = \mu/\rho$), measured in square meters per second or stokes (St), where 1 St = 10^{-4} m²/s. Kinematic viscosity measures the milk's resistance to flow under the influence of gravity. It is the ratio of dynamic viscosity to the milk's density. The density of milk at 20 °C is approximately 1030 kg/m³. Given the dynamic viscosity range of 1.5 to 2.0 mPa.s, the kinematic viscosity of milk at 20 °C is 1.46×10^{-6} m²/s and 1.94×10^{-6} m²/s respectively. Therefore, the kinematic viscosity of milk at 20 °C typically ranges from approximately 1.46 to 1.94 cSt (centistokes), since 1 cSt = 10^{-6} m²/s.

Higher fat content increases the viscosity of milk. Whole milk has a higher viscosity compared to skim milk due to the presence of milk fat globules. As mentioned, higher temperatures reduce viscosity. For instance, milk stored at refrigeration temperatures (4 °C or 39 °F) will have a higher viscosity than milk at room temperature. Homogenized milk has fat globules broken down into smaller sizes, resulting in a more uniform and stable suspension. This process can slightly increase the viscosity compared to non-homogenized milk. Processing methods (e.g., pasteurization) and additives (e.g., stabilizers) can also influence the viscosity of milk.

Fundamental Equation for Viscosity

Viscosity for a Newtonian fluid can be described using Newton's law of viscosity, which establishes a linear relationship between shear stress and shear rate:

$$\tau = \mu \frac{dy}{du}.$$

Where τ is the shear stress (Pa), μ is the dynamic viscosity (Pa.s), $\frac{dy}{du}$ is the velocity gradient perpendicular to the direction of shear (s⁻¹). This equation

indicates that the shear stress between adjacent fluid layers is directly proportional to the rate of change of velocity between those layers. The proportionality constant, μ , represents the viscosity (Špet'uch et al., 2015).

6.4.6 Flow Behaviour

Newtonian & Non-Newtonian Fluids

The rheological behavior of milk and its products is essential for processing, quality control, and consumer satisfaction. Understanding these properties helps in designing appropriate handling and manufacturing processes to ensure product consistency and quality.

Newtonian Fluids maintain a constant viscosity regardless of the shear rate (e.g., water, milk). In these fluids, the stress is directly proportional to strain rate. For a Newtonian fluid, the constitutive equation which explains the flow behaviour is straight forward:

$$\tau = \mu \frac{dy}{du}. \quad (4.1)$$

Where τ is the shear stress (Pa), μ is the dynamic viscosity (Pa.s), $\frac{dy}{du}$ is the velocity gradient perpendicular to the direction of shear (s^{-1}).

Milk and milk products exhibit a range of rheological behaviors, which can be classified as either Newtonian or non-Newtonian depending on their composition and processing. A fluid is considered Newtonian if its viscosity remains constant regardless of the applied shear rate. In other words, the fluid's flow behavior does not change with different rates of stirring or mixing. Fresh milk and skim milk typically exhibits Newtonian behavior. Their viscosity remains constant at a given temperature and composition, regardless of the shear rate applied. When fresh milk is stirred in a glass, the resistance felt remains the same regardless of how fast or slow the stirring is done.

Non-Newtonian Fluids have a viscosity that changes with the shear rate. This category can be further divided into sub-types explained below.

- (i) *Shear-Thinning Fluids (Pseudoplastic)*: These fluids experience a decrease in viscosity as the shear rate increases. Examples include ketchup and paints.
- (ii) *Shear-Thickening Fluids (Dilatant)*: These fluids demonstrate an increase in viscosity with an increasing shear rate. A common example is cornstarch mixed with water, also known as oobleck.
- (iii) *Bingham Plastic*: Behaving like a solid until a critical stress threshold is surpassed, at which point it flows like a fluid. Examples include toothpaste and mayonnaise.
- (iv) *Thixotropic Fluids*: These fluids experience a reduction in viscosity over time under constant shear, but regain their original viscosity once the shear force is removed. Examples include yogurt and certain paints.

- (v) *Rheopectic Fluids*: These fluids demonstrate an increase in viscosity over time under constant shear. Examples are rare in everyday use but include some lubricants.
- (vi) *Viscoelastic Fluids*: Displaying both viscous and elastic properties depending on conditions. Examples include human blood and molten polymers (Kuimov et al., 2023).

Non-newtonian fluids can exhibit various behaviors, such as shear thinning, shear thickening, thixotropy, or rheopecty. Many milk products exhibit non-newtonian behavior due to their complex composition and processing. Yogurt, certain types of cream, and concentrated milk shows shear thinning (pseudoplastic) behavior. In these products viscosity decreases with increasing shear rate. When you stir yogurt, it becomes thinner and flows more easily. Some concentrated milk products and high-fat creams might exhibit shear thickening (dilatant) behavior under certain conditions, though it is less common in dairy products. In shear thickening the viscosity increases with increasing shear rate. Some types of yogurt and fermented milk products are thixotropic in nature. In thixotropic fluid viscosity decreases over time under constant shear and recovers when the shear is removed. Stirring these products can make them flow more easily, but they thicken again when left to stand. Certain specialized dairy gels or custards may exhibit rheopectic behavior. In rheopectic fluid viscosity increases over time under constant shear. The various Rheological behavior of milk products is presented in Table 4.3.

Case Study I *A sample of milk with a viscosity of 1.5 cP (centipoise) at a certain temperature. We want to calculate the shear stress when this milk flows through a pipe with a shear rate of 100 s^{-1} .*

Step 1 To calculate the shear stress (τ) exerted by the milk, we can use the equation for Newtonian fluids:

$$\tau = \mu \frac{dy}{du}$$

Where

- τ is the shear stress (in pascal, Pa),
- μ is the dynamic viscosity of the fluid (in pascal-second, Pa.s),
- $\frac{dy}{du}$ is the shear rate (in reciprocal seconds, s^{-1}).

Step 2 Given that the viscosity of milk is 1.5 cP, which is equivalent to 0.0015 Pa.s, and the shear rate is 100 s^{-1} , we can calculate the shear stress:

Step 3 $\tau = \mu \frac{dy}{du}$

$$\tau = (0.0015 \text{ Pa.s}) \times (100 \text{ s}^{-1})$$

Table 4.3 Rheological behavior of milk products

Milk products	Behavior	Description
Fresh milk	Newtonian	Constant viscosity under different shear rates
Skim milk	Newtonian	Similar to fresh milk, with a lower viscosity due to reduced fat content
Whole milk	Slightly non-Newtonian	Can exhibit minor shear thinning due to the presence of fat globules, but generally behaves as a Newtonian fluid
Cream	Shear thinning	Higher fat content leads to a decrease in viscosity with increasing shear rate
Yogurt	Shear thinning and thixotropic	Viscosity decreases with stirring and can recover over time when left to stand
Cheese	Non-Newtonian, complex viscoelastic properties	Soft cheeses can exhibit shear thinning, while hard cheeses have a more solid-like behavior
Ice cream	Non-Newtonian, complex behavior	Exhibits shear thinning during mixing and scooping, influenced by temperature and composition
Condensed milk	Non-Newtonian	Can show shear thinning due to the high concentration of sugars and milk solids

$$\tau = 0.15 \text{ Pa}$$

So, the shear stress exerted by the milk as it flows through the pipe at a shear rate of 100 s^{-1} is **0.15 Pa**.

Reynolds Number

Newtonian fluids exhibit either laminar or turbulent flow based on their Reynolds number, which is a dimensionless parameter. This number aids in predicting flow behaviors in various fluid flow scenarios. It is determined by comparing the ratio of inertial forces to viscous forces, playing a crucial role in predicting whether the flow will be laminar or turbulent.

Laminar Flow (low Reynolds number) This type of flow is characterized by smooth and orderly movement, typically preferred in applications where shear sensitivity is a concern, such as handling delicate food products.

Turbulent Flow (high Reynolds number) This type of flow is marked by chaotic and mixed motion, which can be advantageous for enhancing heat transfer and mixing efficiency but may potentially cause damage to sensitive products or result in inconsistent outcomes.

Reynolds number, a dimensionless number calculated as:

$$N_{Re} = \frac{D\rho v}{\mu}$$

Where ρ is the fluid density, v is the velocity of the fluid, D is a characteristic linear dimension (e.g., pipe diameter), μ is the viscosity of the fluid.

Case Study II *A dairy plant is processing milk through a pipe with a diameter of 0.1 m. The milk has a density of 1030 kg/m³ and a dynamic viscosity of 0.0015 Pa.s. If the milk flows through the pipe at a velocity of 0.5 m/s, calculate the Reynolds number for the flow.*

Step 1 The Reynolds number (Re) is given by the formula:

$$R_e = \frac{D\rho v}{\mu}$$

Where

- ρ is the fluid density.
- v is the velocity of the fluid.
- D is a characteristic linear dimension (e.g., pipe diameter).
- μ is the viscosity of the fluid.

Step 2 Let's assume the following values for our calculation:

- Milk density(ρ): 1030 kg/m³
- Milk viscosity(v): 0.5 m/s
- Pipe diameter (D): 0.1 m
- Milk dynamic viscosity (μ): 0.0015 Pa.s

Step 3 Substituting these values into the formula, we get:

$$R_e = \frac{D\rho v}{\mu}$$

$$R_e = \frac{(0.1\text{m})(1030\text{kg / m}^3)(0.5\text{m / s})}{0.0015\text{Pa.s}}$$

$$R_e = \frac{(0.1\text{m})(1030\text{kg / m}^3)(0.5\text{m / s})}{0.0015\text{Pa.s}}$$

$$R_e = 34333.33$$

So, the Reynolds number for milk flowing through the pipe under these conditions is approximately 34333.33. This value indicates that the flow of milk through the pipe is likely turbulent.

7 Overall Mass Balance and Continuity Equation

The core principles of overall mass conservation and the continuity equation are essential in dairy engineering. In dairy processing, the application of overall mass balance and continuity equations is essential for ensuring efficient production and quality control. These equations are fundamental tools used to track the flow of mass through various stages of processing, from raw materials to finished products. Imagine a dairy processing plant as a complex system of interconnected pipes, tanks, and equipment, where milk and other ingredients undergo a series of transformations to produce a range of dairy products like cheese, yogurt, and butter. At each stage of this journey, it's crucial to maintain a balance between the incoming raw materials and the outgoing products, while accounting for any losses or changes in mass due to processing operations.

Let's consider an example scenario for the production of cheese. At the beginning of the process, milk is received and stored in tanks. The overall mass balance equation for this stage would involve accounting for the incoming mass of raw milk, any additions of starter cultures or enzymes, and losses due to evaporation or spillage. This equation can be represented as:

$$\text{Incoming mass} = \text{Mass of milk} + \text{Mass of additives} - \text{Losses}$$

As the milk undergoes various processing steps such as pasteurization, coagulation, and whey separation, it's crucial to track the flow of mass accurately. Continuity equations are applied to ensure that mass is conserved throughout these processes. For instance, during cheese production, the continuity equation for mass might be expressed as:

$$\text{Mass in} = \text{Mass out} + \text{Accumulation}$$

This equation ensures that the mass of milk entering the cheese-making process equals the mass of cheese produced, accounting for any accumulation of solids or liquids during processing. Furthermore, these equations are not only useful for tracking mass but also for optimizing processes and troubleshooting. By analyzing deviations from expected mass balances, operators can identify potential issues such as leaks, equipment malfunctions, or variations in ingredient quality.

7.1 Overall Mass Balance

The concept of mass balance asserts that within an isolated system, mass remains constant—it neither appears nor disappears. In the context of a processing system, this means that the total mass entering a system must equal the total mass leaving

the system, while also accounting for any accumulation of mass within the system over a defined period. The general mass balance equation can be expressed as:

$$\text{Input} - \text{Output} + \text{Generation} - \text{Consumption} = \text{Accumulation} \quad (4.2)$$

For a system where there is no mass being generated or consumed (such as in many physical processes), the equation simplifies to:

$$\text{Input} - \text{Output} = \text{Accumulation} \quad (4.3)$$

In fluid dynamics, where flow rates are typically considered under steady-state conditions, the principle dictates that the rate of input equals the rate of output, given that there is no accumulation of mass over time and thus,

$$\text{rate of input} = \text{rate of output (steady state)} \quad (4.4)$$

If the fluid enters with the average velocity v_1 m/s and density ρ_1 kg/m³. The cross-sectional area is A_1 m², the fluid leaves with the average velocity v_2 . The mass balance, equation becomes

$$m = \rho_1 u_1 A_1 = \rho_2 u_2 A_2 \quad (4.5)$$

where $m = \text{kg/s}$, ρv is expressed as $G = \rho v$, where G is mass velocity or mass flux in kg/s m².

7.2 Principle of Continuity Equation

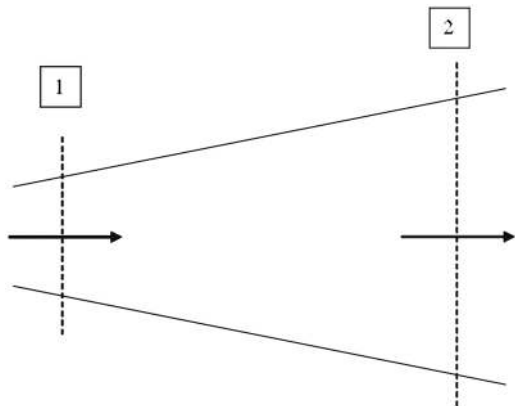
Studying fluid dynamics is intricate, but significant insights can be obtained by examining an ideal fluid and employing mass and energy conservation principles. An ideal fluid, also known as inviscid, is characterized by its lack of viscosity and uniform velocity throughout a given cross-section of the flow channel. Referring to Fig. 4.2 and equating the mass flow rate at points 1 and 2 yields:

$$\rho_1 u_1 A_1 = \rho_2 u_2 A_2 + \frac{d(\rho_{av} V)}{dt} \quad (4.6)$$

where A represents the cross-sectional area, and ρ and u denote the density and velocity of the fluid at points 1 and 2, $\rho_{av} V$ is the average density, and V is volume of the flow channel between points 1 and 2.

The differential term shows the accumulation of mass. This result is referred as the principle of continuity. At steady state, there is no mass accumulation and equation becomes

Fig. 4.2 Principle of continuity



$$\rho_1 u_1 A_1 = \rho_2 u_2 A_2 \quad (4.7)$$

The density of liquids typically stays relatively stable despite changes in pressure, especially within the pressure ranges commonly encountered in food processing. Consequently, a liquid behaves akin to an incompressible fluid, where the density remains constant ($\rho_1 = \rho_2$) and Eq. can now be written as

$$u_1 A_1 = u_2 A_2 \quad (4.8)$$

Clearly, gases are compressible and the gas laws should be used to determine the relationship between ρ_1 & ρ_2 .

The principle of continuity equation in milk processing is based on the conservation of mass, stating that the mass of milk entering the process should be equal to the mass of milk leaving the process, accounting for any accumulation or depletion in the system. This principle is crucial for maintaining control over the flow of milk and ensuring that processing operations are efficient and effective. In milk processing, the continuity equation is applied to various stages of production, from raw milk reception to the production of final dairy products like cheese, yogurt, or butter. When raw milk is received at the processing plant, the mass of incoming milk must be equal to the mass of milk stored in tanks or silos, accounting for any losses due to spillage, sampling, or evaporation. The continuity equation for this stage ensures that all incoming milk is properly accounted for and none is lost during storage. During pasteurization, milk is heated to a specific temperature to destroy harmful bacteria while preserving its quality. The continuity equation ensures that the mass of milk entering the pasteurization unit equals the mass of milk exiting the unit, accounting for any changes in temperature or volume due to heating. In processes such as cream separation or whey separation, the continuity equation ensures that the mass of milk entering the separator equals the mass of separated components (e.g., cream, skim milk, whey) plus any losses or accumulations. This equation helps monitor the efficiency of separation and ensures that no milk is

unaccounted for. In cheese making, the continuity equation is applied at various stages, including coagulation, curd cutting, whey drainage, and pressing. It ensures that the mass of milk and curd entering each stage equals the mass of cheese and whey exiting the stage, accounting for any changes in moisture content or volume. When milk or dairy products are packaged for distribution, the continuity equation ensures that the mass of product entering the packaging line equals the mass of packaged product leaving the line, accounting for any losses or rejects. By applying the principle of continuity equation in milk processing, producers can monitor the flow of milk through each stage of production, identify potential inefficiencies or losses, and ensure the consistency and quality of dairy products.

7.3 Overall Energy Balance

The second property addressed in the overall balances on a control volume is energy. By integrating the energy conservation equation with the first law of thermodynamics, the comprehensive energy balance equation can be derived.

First law of thermodynamics is expressed as:

$$\Delta E = Q - W \quad (4.9)$$

where ΔE represents the total energy per unit mass of the fluid, Q is the heat absorbed per unit mass of the fluid, and W is the work done per unit mass of fluid on the surroundings. Each term in equation must be expressed in J/kg (SI).

The overall energy balance is a fundamental concept in dairy engineering, ensuring that energy input into dairy processes equals energy output, accounting for any changes in energy storage within the system. This principle is crucial for optimizing energy usage, minimizing costs, and ensuring the efficiency of dairy processing operations. Heat is a primary form of energy used in dairy processing for pasteurization, sterilization, and other heat treatment processes. The overall energy balance ensures that the heat energy supplied to heat exchangers or other heating equipment equals the heat energy absorbed by the dairy product and the surrounding environment, accounting for any losses due to heat transfer inefficiencies. In processes such as cooling of milk or dairy products after pasteurization, the overall energy balance ensures that the energy removed by cooling equipment equals the heat energy released by the product, accounting for any changes in temperature and phase. Steam is often used for various purposes in dairy processing, such as heating, sterilization, and cleaning. The overall energy balance ensures that the energy input in the form of steam equals the energy absorbed by the process, accounting for any losses due to steam leaks or condensation. Refrigeration systems are employed in dairy processing for chilling milk, storing dairy products, and maintaining cold storage facilities. The overall energy balance ensures that the energy consumed by refrigeration equipment equals the heat energy removed from the product and the environment, accounting for any losses due to heat infiltration or equipment

inefficiencies. In some dairy processing plants, energy recovery systems may be implemented to capture and reuse waste heat or energy from various processes. The overall energy balance ensures that the recovered energy is properly accounted for and utilized to offset energy requirements in other parts of the system. By analyzing the overall energy balance of dairy processing operations, engineers can identify opportunities for process optimization, such as adjusting operating parameters, improving equipment design, or implementing energy-efficient technologies.

7.4 Velocity Profile in Laminar Flow

The primary relationship crucial for understanding fluid transport in pipelines is the correlation between flow rate and the pressure gradient driving the flow. Numerous food liquids exhibit high dynamic viscosity, often resulting in laminar flow. In cases of laminar flow, it's feasible to establish a precise connection between flow rate and pressure.

Figure 4.3 depicts a cylindrical segment of fluid with radius r inside a circular pipe of radius r_1 and length L . The pressure drop caused by friction between the fluid and the pipe wall is denoted as ΔP . It is assumed that the pressure gradient along the pipe is uniform and has a specified value. If the fluid's momentum remains constant, the net force acting on the fluid must be zero. This condition implies that the shear force acting on the curved surface of the element equals the difference between the forces acting on the respective ends of the cylinder. This latter force is the result of multiplying the pressure difference ΔP by cross-sectional area r^2 . Thus,

$$2\pi rLR = \pi r^2 \Delta P \quad (4.10)$$

where R is the shear stress at a radius r and $2\pi rL$ represents the curved surface of the element. Consequently

$$R = \frac{r}{2} \frac{\Delta P}{L} \quad (4.11)$$

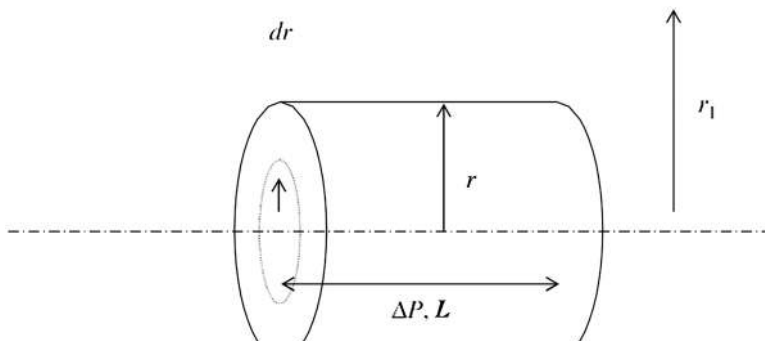


Fig. 4.3 Laminar flow in a pipe

but from Eq. the shear stress equates to the product of viscosity and velocity gradient, in this case $\frac{du_r}{dr}$ where u_r is velocity in the direction of flow, at a radius r . Hence

$$\frac{r}{2} \frac{\Delta P}{L} = -\mu \frac{du_r}{dr} \quad (4.12)$$

By separating the variables and integrating from $r = r_1$ (at the pipe wall where the fluid is stationary) to $r = r$ (where the velocity is u_r), gives

$$\mu \int_0^{u_r} du_r = -\frac{\Delta P}{2L} \int_{r_1}^r r dr \quad (4.13)$$

and the result

$$u_r = \frac{\Delta P}{4L\mu} (r_1^2 - r^2) \quad (4.14)$$

Equation (4.14) represents a parabolic equation. Upon observation, it's apparent that the velocity reaches its maximum when $r = 0$ and drops to zero when $r = r_1$ (at the pipe wall). Now, consider replacing the cylindrical element in Fig. 4.3 with an annulus of radius r and thickness dr . The volumetric flow rate V is determined by multiplying the velocity [as per Eq. (4.14)] by the cross-sectional area $2\pi r dr$ and integrating across the pipe radius. Thus,

$$V = \int_0^{r_1} 2\pi r \frac{\Delta P}{4L\mu} (r_1^2 - r^2) du_r \quad (4.15)$$

which on integration produces

$$V = \frac{\pi \Delta P}{2L\mu} \frac{r_1^4}{4} \quad (4.16)$$

and in terms of the pipe diameter d the volumetric flow rate is now

$$V = \frac{\pi \Delta P d^4}{128L\mu} \quad (4.17)$$

This result is referred as Hagen-Poiseuille relationship and in terms of a mean velocity over the cross-section $\frac{\pi d^2}{4}$ becomes

$$u = \frac{\Delta P d^2}{32L\mu} \quad (4.18)$$

The velocity profile in laminar flow is a fundamental concept in fluid dynamics that explains how the velocity of a fluid changes across the cross-section of a pipe or channel. In industrial processes like pasteurization or sterilization, milk passes through heat exchangers where it undergoes heating or cooling. The velocity profile plays a crucial role in determining how heat is distributed within the milk. In laminar flow, the velocity profile is parabolic, with the highest velocity occurring at the center of the pipe and gradually decreasing towards the walls. This affects the heat transfer rate, as the milk near the walls may experience less heat exchange compared to the milk at the center. In mixing operations, such as blending additives or ingredients into milk, the velocity profile determines the degree of mixing achieved. The parabolic velocity profile in laminar flow results in a layered flow pattern, which may require longer mixing times to achieve uniform distribution of additives throughout the milk. In processes involving separation, such as cream separation or whey separation, the velocity profile influences the efficiency of separation. Understanding the velocity profile helps in designing separation equipment such as centrifuges to optimize separation efficiency while minimizing energy consumption. In pipelines used for transporting milk within a processing plant, the velocity profile affects the frictional losses and pressure drop along the pipeline. Engineers need to consider the velocity profile when designing pipelines to ensure efficient transportation of milk while minimizing energy requirements. Understanding the velocity profile in laminar flow is essential for conducting fluid mechanics analysis and predicting flow behavior in various processing equipment. Computational fluid dynamics (CFD) simulations often rely on accurate representations of velocity profiles to model fluid flow and optimize equipment design. Overall, the application of velocity profile in laminar flow in milk processing helps in optimizing heat transfer, mixing efficiency, separation processes, transportation, and equipment design. By considering the velocity profile, engineers can improve the efficiency, quality, and safety of milk processing operations.

8 Conclusion

In conclusion, fluid mechanics plays an essential role in the manufacturing of food and dairy items, where precise control and optimization of fluid processes are vital for efficiency and product excellence. Viscous fluids are commonly employed, highlighting the importance of maintaining equipment cleanliness for smooth transportation. Computational fluid dynamics and advanced modeling methods have become indispensable tools for designing and refining processing equipment and systems, allowing for the simulation of fluid flow, heat transfer, mass transfer, and chemical reactions. Additionally, considering the intricate nature of food systems, it is important to consider the impacts of structural alterations and physicochemical reactions on product quality from a thermodynamic standpoint. Moreover, comprehension of fluid and solid rheology is fundamental for equipment design and operation in the food, beverage, and dairy sectors. By harnessing these principles and techniques, these industries can achieve heightened efficiency and consistently deliver high-quality products.

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Chapter 5

Heat Transfer and Pasteurization Techniques in Food and Dairy Processing



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1 Introduction: Heat Transfer

Food processing includes a wide range of procedures aimed at converting raw ingredients into consumable goods with increased safety, shelf life, and sensory properties. For determining the safety and quality of processed food heat transmission is very important. In food processing, heat is a kind of energy that may be controlled and utilized to accomplish a variety of goals, from texture alteration to microbial inactivation. Heat is the transitional form of thermal energy which dynamically flows from one region or body to another, where the former is at higher temperature than the later. This phenomenon is called heat transfer which continues until thermal equilibrium is attained (Alanazi, 2022; Allende et al., 2022) and the of heat transfer rate is primarily determined by temperature gradient between two regions or bodies; the higher the gradient, the faster will be the heat transfer. Thus, any positive increase in temperature that exists between heat source and heat receiver, acts as driving force of heat transfer (Alpas et al., 2000). Besides temperature gradient, heat transfer rate is impacted by the medium through which it travels as it resists the flow of thermal energy. State and nature of medium greatly influence heat transition between bodies (Atilgan et al., 2020).

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1.1 Types of Food for Heat Processing

Foods falling into the acidic and low-acid groups are typically thermally processed. The acidity of food can be determined by the pH scale, where 1 denotes an extremely high acidity and 4 denotes low acidity. pH 4.6 is the line that separates acidic and low-acid meals. Acidity is a determining factor for selecting the severity of thermal processing to which the food is to be subjected. Foods having high acidity do not require higher temperatures and can be preserved at 100 °C. However, foods with low acidity need to be processed under pressure-canning at temperatures up to 115 °C. *Clostridium botulinum*, a spore forming bacteria which produces lethal toxins, cannot thrive at pH lower than 4.6. Whereas, several spoilage bacteria cannot develop in pH range 1–4.6. Yeasts and moulds being acid-tolerant are often found to be the spoilage-causing microorganisms in acidic foods.

- *Acidic foods*: Foods having a high acid concentration contain a high concentration of natural acids, which prevent some bacteria that cause spoiling from growing. Thus, only boiling temperatures are high enough to render such foods with microbiologically safe level.
- *Low acid foods*: Vegetables and animal products are examples of low-acid foods that contain lesser amounts of natural acids. Therefore, in order to eliminate any spoilage related to *Clostridium botulinum*, temperatures greater than boiling water are employed for their processing. Water is placed under pressure to facilitate boiling at higher temperature than its boiling temperature. Under 1.0 kg/cm² pressure, water boils at 115 °C instead of 100 °C. Food processing at this level efficiently eliminates any possible spores responsible for botulin poisoning.

1.2 Characteristics of Heat Transfer in Food

The rate at which heat penetrates food and the degree of heat resistance exhibited by microbes or enzymes are critical information for determining the processing time of food. Heat enters in the food container through the lid from steam or pressurized water. Heat transfer is often not limited by the coefficient of surface heat transfer, which is typically extremely high. A food's ability to absorb heat is affected by the following: Product kind (i) container size (ii), container agitation (iv), retort temperature (v), and container shape. Convection currents are facilitated by tall containers when food is heated convectively. (vi) Type of container. Metal has a different thermal conductivity from glass or plastic, heat penetrates through it more quickly. It's critical to comprehend how food products' thermal properties affect the amount and penetration of heat. When assessing heat penetration, thermal conductivity and thermal diffusivity are two crucial thermal parameters. When estimating the amount of heat needed for the process, specific and latent heat are significant factors:

- *Thermal conductivity*: The characteristic that shows how quickly heat moves through food is called thermal conductivity. Heat can move freely through a product with high thermal conductivity while it can be hindered by an insulator, or substance with poor thermal conductivity. Temperature variations are possible, however for a given material, in many applications, it can be considered a constant. Foods have thermal conductivities ranging from 0.6 to $0.7 \text{ J m}^{-1} \text{ s}^{-1} \text{ }^{\circ}\text{C}^{-1}$ above Zero $^{\circ}\text{C}$ because many foods include a large amount of water. Meals served at room temperature have a lower thermal conductivity than meals that are frozen.
- *Thermal diffusivity*: The real capacity of a meal to transmit heat to nearby molecules is known as thermal diffusivity. As a result, m^2/s is how thermal diffusivity is measured. Accelerated heat penetration is correlated with higher thermal diffusivity values.
- *Specific heat*: The amount of energy supplied to remove from a unit mass of material to change its temperature by $1 \text{ }^{\circ}\text{C}$ is determined by a critical characteristic called specific heat. Thus, knowing a substance's specific heat is crucial when developing procedures like freezing, cooling, heating, sterilizing, and cooking. The SI unit of a specific heat is $\text{kJ}/(\text{kg. K})$.
- *Phase transitions*: A temperature at which a transition takes place, the enthalpy varies that goes along with it, the kind of transition (endothermic or exothermic), and the amount of material that goes through it are all crucial. We shall take the melting and crystallization of food ingredients as an example. Heat is absorbed or released by a substance when it melts, or turns from a liquid to a solid (crystallization). Heat-evolving processes are exothermic processes, whereas heat-absorbing processes are endo-thermic.

1.3 Principles of Heat Transfer

The study of energy production, transformation, transfer, and application as thermal energy through several systems is known as heat transfer in thermodynamics. A thorough grasp of the many mechanisms through which heat is carried, including conduction, convection, and radiation, is essential for the successful design of any device involving thermal energy. For this reason, it is critical to research and evaluate heat transmission in all applications.

Food processing procedures such as evaporation, drying, freezing, refrigeration, heat sterilization, pasteurization, etc. all involve heating and cooling processes that are grouped together under a single operation called heat transfer, which is frequently utilized by food engineers. Food engineers must have a fundamental understanding of heat transfer concepts in order to either build thermal process equipment and operate it for optimal performance or alter the design of the current process. There are three ways that thermal energy can move: conduction, convection, and radiation. Convection and conduction, however, are the two primary heat-transfer techniques employed in the dairy sector. Furthermore, the kind of heating—direct

or indirect—is a powerful guiding principle when choosing appropriate techniques for heating a variety of dairy products.

- *Direct heating*: Placing the object to be heated in close physical contact with the heating or cooling medium is how it is accomplished. Transfer of heat is mediated through conduction and convection. On industrial scale, products like curd can be heated by adding hot water to it to make specific kinds of cheese; also, milk can be directly sterilized by either infusing it with steam or by injecting it in steam chambers (Barbosa-Canovas et al., 2000). For quick heating, the technique for direct transmission of heat works efficiently.
- *Indirect heating*: In dairy industries, heat transfer that occurs indirectly is the most widely employed technique. In this method, the product and the heating or cooling media are separated by a divider or plate. The heat was transferred to the product by conduction using the divider or plate (Bergman et al., 2011). These plates satisfactorily facilitate the heat exchange between the products and medium by preventing the content's mixing. This concept is adopted in the construction and working of a plate heat exchanger. The cold milk on the other side of the plates cools the water more closely when it is near it. Convection and conduction carry heat into the boundary layer (Cengel & Boles, 2010). When information is transferred from the boundary layer on one side of the wall to the boundary layer on the other, conduction is crucial and both conduction and convection are used to move the material further to the milk in the channel's centre zone.

1.4 Mechanism of Heat Transfer

Food processing industries, techniques employing transfer of thermal energy are essential for turning raw components into finished goods that are microbiologically safe, organoleptically appetizing, and shelf-stable. The quality, safety and efficiency of products are dependent on the comprehension of concepts related to heat transfer, which is applied to all processing techniques such as cooking, pasteurization, sterilization, and freezing (Das, 2005). Conduction, convection, and radiation are the three primary methods of heat transport (Fig. 5.1 and Table 5.1).

Conduction

The transmission of vibrational energy from one molecule to the nearby molecules that are tightly related to a solid mass is the cause of heat transfer. In a system, free electrons may transport electrical and thermal energy at the molecular level, but conduction does not cause physical movement of the body. One example of this is the heating of a metal body.

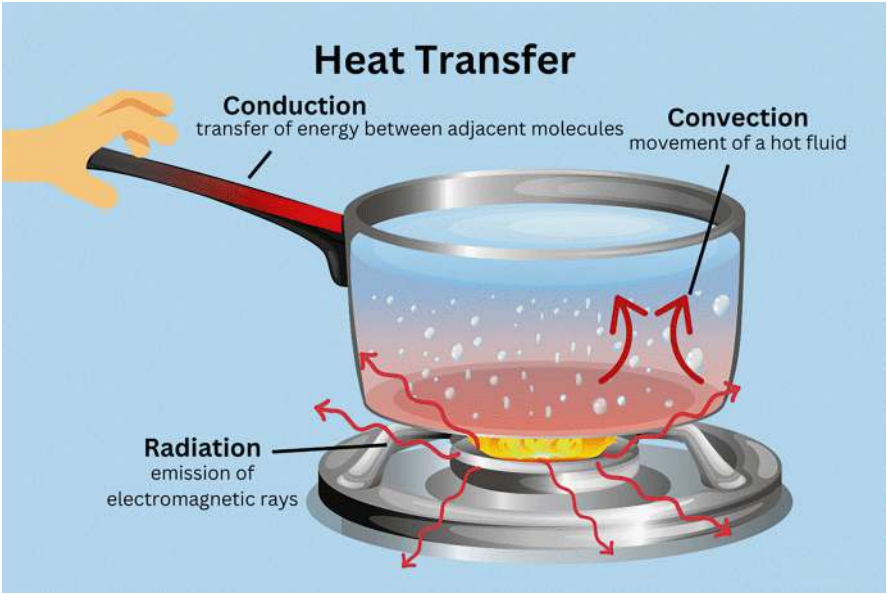


Fig. 5.1 Modes of heat transfer

Table 5.1 Methods of heat transfer

Heat transfer methods	Definitions	Equations	Example
Conduction	The energy tends to move from hotter to colder regions with subsequent transfer of molecular energy to adjacent molecules at lower energy levels	$Qx = -kA dT$	The movement of heat through a refrigerated store's solid walls.
Convection	Convection is the method by which heat is transferred by the movement of fluid when hot air or steam surrounds food during food processing	$Q = hA\Delta T$	Boiling, frying, and baking is convection
Radiation	The process by which heat is transferred in radiation is comparable to the way electromagnetic light waves transfer light energy from one body to another	$q = A \sigma t^4$	Microwave heating

Conduction happens when the thermal energy is transferred through or between materials placed in direct contact; when a material is subjected to heat at one end, it gradually gets heated at the other end as well. The atomic or molecule collision that creates kinetic energy within the material is what causes the slow process of heat transmission (Charm, 1978).

When temperature gradient per unit length = dt/dx , resistance provided by medium = $1/ka$, and rate of conductive heat transfer = dQ/dt . The reciprocal of resistance is known as conductance (ka). The conductive heat transfer equation is therefore

$$dQ = -dt / dx, \text{ or } qx = -kA dTs$$

Where, q = Rate of heat transfer (J/s or W), and $dt = 1/kA$, K is the body's thermal conductivity (W/mK or W/m°C). A = cross-sectional area perpendicular to the direction of heat flow. For heat conduction, the formula is referred to as Fourier's equation (Hottel, 1930).

A negative temperature gradient, or the movement of heat from a hot body to a cold body, is what happens. Thus, the Fourier equation has a negative sign. Fourier's equation of heat conduction, which describes how a substance behaves when transferring heat, may be used to quantify thermal conductivity. The rate of heat transport increases with increasing thermal conductivity. Thermal conductivity is regarded as a substance's constant thermal property even though it fluctuates slightly with temperature. The thermal conductivity of metals is strong, that of liquids is comparatively low, and that of gases is considerably lower.

Convection

It is concerned with heat transmission by the movement of fluids (liquids or gases). This movement can be forced by an outside source, like a pump or fan, or it can be natural, driven by density changes brought on by temperature variations (Holman 2009). Convection is the movement of molecule clusters in a fluid that transfers heat. The molecular groups might be moved by the forced motion of the fluid or by changes in density (Tao et al., 2019). When cooking food in a jacketed pan, natural convection—which transfers heat—occurs due to density changes that happen in the absence of a stirrer. Forced convection when a stirrer is present (Kakac & Liu, 1998). Four general categories can be used to categorize theoretical understanding of convective heat transfer enhancement techniques: increasing turbulence strength, producing swirling and secondary flow, destroying, and weakening boundary layers, and increasing the heat transfer area (Bergles & Manglik, 2013; He & Tao, 2014; Tao et al., 2019).

The convective heat transfer rate is expressed as follows: $Q = hA\Delta T$

- Q = heat transfer rate.
- For convection, h is the heat-transfer coefficient.
- Surface area exposed (A)
- ΔT = difference in temperature

Radiation

Radiation is defined as the transfer of heat energy via electromagnetic waves. In contrast to conduction and convection, radiation can occur in a vacuum and does not need a medium to propagate. The quantity and wavelength of thermal radiation emitted by any object that is warmer than absolute zero are determined by its surface characteristics and temperature (Fellows, 2022). Radiant heat transmission occurs, for example, when food is transported beneath a bank of red-hot electric resistance heaters. Processes with little temperature changes, including freeze-drying and cold stores, can benefit from the use of radiation (Holman, 2009; Naik et al., 2024). Moreover, it is employed significantly in processes with larger temperature changes. In such processes, the radiation mechanism is of foremost importance to facilitate heat transfer, as in radiant dryers and bakers' ovens. Howell et al. (2020) stated The Stefan-Boltzmann Law as under, $q = A \sigma T^4$, is the fundamental formula for radiant heat transmission. The temperature T is the absolute temperature in degrees Kelvin (K) in the SI system, determined from the temperature at -273°C , the absolute zero. The Stefan-Boltzmann constant, denoted as σ (sigma), is $5.73 \times 10^{-8} \text{ J m}^{-2} \text{ s}^{-1} \text{ K}^{-4}$.

$K = (^\circ\text{C} + 273)$, formula used to compute the absolute temperatures.

For the heat to mediate from one body to another, the temperature gradient between these two bodies is necessary. Also, the medium assisting the transmission must let heat to pass through it. Thus, the temperature gradient acts as driving force for the heat transfer and the resistance of heat flow provided by a medium as the retarding force (Green & Perry, 2007). Therefore, the general equation for heat transmission rate can be stipulated as follows.

Rate of heat transfer = temperature difference/resistance offered by medium

The driving force alter because of fluctuations in the body temperature at any stage throughout processing. This results into the unsteady state heat transfer. Heat-transfer of cans in retorts is suitable exemplification of an unstable condition. Heat transfer calculations in unsteady state are rather complex than in a steady state which involves constant temperature conditions throughout (Heldman & Lund, 2007).

2 Pasteurization

2.1 Introduction

Pasteurization entails heating food (often below 100°C) to eliminate important pathogens and germs as well as to reduce the growth of spoiling organisms that may occur during distribution and storage (Anderson, 2019) of processed foods. Today, pasteurization is widely recognized as an effective food preservation technique that

Table 5.2 Details of food pasteurization

Aspect	Details
Definition	Heating food and beverages to eliminate hazardous bacteria while preserving quality.
Types of pasteurization	High temperature short-time (HTST) – temperature and duration: 72 °C (161 °F) for 15 s. Milk and fruit juices are examples of common uses. Ultra-high temperature (UHT): 135 °C (275 °F) for 2–5 s. Milk, cream, and fruit juices are among its most common applications. Shelf life: Lasts longer without refrigeration until opened. Low-temperature long-time (LTLT): 63 °C (145 °F) for 30 min. Common applications: Some dairy products and liquid eggs. Flash pasteurization temperature and time are higher than HTST for a few seconds. Fruit juices and beverages are examples of common uses.
Effects on foods	Nutrient retention: The majority of nutrients are retained, but vitamin C and B vitamins may be significantly reduced. Flavor and texture: While UHT generally retains flavor and texture, it can add a somewhat cooked taste. Microbial reduction: Lowers harmful bacteria, increasing shelf life and safety. Enzyme inactivation is the process of deactivating enzymes that may degrade food.
Advantages	Safety: Reduces harmful microbes. Shelf life: Increases the shelf life of perishable items. Quality maintenance: Maintains taste, texture, and nutritional value. Economic: Decreases food waste by extending shelf life.
Disadvantages	Nutrient loss: Heat-sensitive nutrients are slightly reduced. Energy is required for heating. Initial investment: Expensive equipment and process setup. Flavor may be slightly altered in some circumstances (for example, with UHT).

eliminates microorganisms while maintaining the desired level of food quality (Table 5.2).

In pursuit of improving the safety and shelf life of different liquid foods like milk, juice, beer, and wine, this technique is frequently used in food industry. For instance, raw milk may contain dangerous germs like *Listeria*, *Salmonella* and *E. Coli* that can lead to major health issues, particularly for the elderly, small children, and pregnant women. Pasteurization of milk destroys these harmful bacteria and makes the milk safe for consumption. Similarly, fruit juices and other beverages are also prone to spoilage by harmful microorganisms. Pasteurization of these products destroys any pathogens present and extends their shelf life by preventing spoilage caused by bacterial growth. In addition to ensuring food safety, pasteurization also helps to maintain the nutritional quality of liquid foods. Pasteurization can get rid of dangerous microorganisms while retaining the nutritional value, flavour, and texture of the product by using specific temperature and time parameters.

French scientist Louis Pasteur used the term “sterilization” to refer to the method of quickly heating beverage such as beer or wine upto 55 °C in order to prevent them from drying up. (Acuff et al., 2020). The National Advisory Committee on Microbiological Criteria for Foods (NACMCF), USA has established the scientific constraints needed to launch equivalent another pasteurization methods. This term includes a wide range of thermal (steam and infrared processing, hot water heating, ohmic heating, microwave heating) and non-thermal (UV radiation, chemical treatments, ultrasound, filtration, High-pressure processing, irradiation, Pulsed Electric Field, etc.) technologies that can be used alone or in combination to pasteurize different foods. (Andrews & Fuchs, 1944).

2.2 Purpose of Pasteurization

Food is heated below 100 °C in a relatively mild heat treatment called pasteurization. It is commonly utilized in the food industry and is frequently included as a CCP in various HACCP systems (Baro et al., 2011). This unit action can be used in food processing to remove enzymes and mild temperature-sensitive microorganisms (such as moulds, yeasts, and non-spore-forming bacteria. The food’s pH has a significant impact on the degree of treatment and consequent improvement in shelf life (Brennan et al., 1990). Foods with a pH of less than 4.5 are primarily meant to remove hazardous microbes; below that point, the aim is typically to deactivate enzymes. (Burgwald, 1939).

The enzyme or bacteria that is most heat-resistant among those that are able to be identified will be indicated by the D value, which denotes the amount of time needed to reduce the population by a factor of 10% or 90% of the initial load and indicates the necessary degree of heat treatment. (Bylund, 2003).

2.3 Types of Pasteurization Methods

Depending on the heating method used for the liquid food product, pasteurization techniques can be generally divided into thermal and non-thermal methods in Table 5.3.

Thermal Pasteurization:

Thermal pasteurization means use of heat to destroy harmful microorganisms in the product. These methods are further classified into low-temperature and high-temperature. In cases where phosphatase activity is detected, pasteurization is considered insufficient. Pasteurization is often used to remove or decrease the number of spoilage microorganisms in specific foods, such as vinegar, or to sterilize milk containing all pathogenic germs (Charm, 1978).

Table 5.3 Different types of pasteurization processes

Criteria	LTLT	HTST	UHT
Process	Batch	Continuous	Continuous
Temperature and duration	30 min at 65 °C	72 °C for 15–30 s	135–150 °C for a few seconds
Preserved foods	Butter-milk and sour cream	Raw Milk, desserts, fruit juices, etc	Raw Milk
Duration of shelf life	Several days	2–3 weeks	6–9 months
Microorganism eliminated	Pathogens	Pathogens	All bacteria and spores

Both pasteurization methods, namely continuous and batch, holding or low temperature long time (LTLT), high temperature short time (HTST) methods, are associated with heat treatment. The batch method allows milk to be heated in a vat or container to 63 °C. It is stirred with a stirrer and hot water or steam jacket for 30 min before being partially cooled in a batch pasteurizer (Dag et al., 2020). This is a surface/plate cooler that provides additional cooling. Plate heat exchangers (PHE) are used to heat, store and cool milk (Doll et al., 2017).

Batch Pasteurization

Batch pasteurization is an important process, especially in the production of dairy products, juices, and some dishes. Singh and Heldman (2009), this method removes harmful microorganisms from consumable products without significantly changing their taste, consistency, or nutritional value. This method preserves the product's quality by quickly cooling it after heating it to a predefined temperature for a predetermined amount of time.

The basic principle of batch pasteurization is to remove any harmful bacteria, yeast or mold from the food or beverage. To get the right temperature, which is normally between 145 °F and 165 °F (63 °C and 74 °C), the product must be heated for a set amount of time, usually 15–30 min. Once microbial loads are reduced to safe levels, the goal is to maintain the desired product properties (Anderson, 2019). The final product is safe to consume because the temperature and time of use are sufficient to kill most harmful bacteria.

The fundamental advantage of batch pasteurization is its flexibility and adaptability to different production capacities. For manual production or small facilities, batch pasteurization is a viable option over continuous pasteurization methods, which are more suitable for larger operations (Czaplicki, 2007). Greater control over the process allows manufacturers to make the necessary adjustments to ensure consistent quality and safety standards.

The batch pasteurization technique usually includes the following important steps:

1. **Preheating:** To achieve the temperature required for pasteurization, the product is gradually heated. In addition to helping to avoid thermal shock, this step also ensures uniform heating throughout the batch.
2. **Holding:** After reaching the target temperature, the product is held at the specified temperature for a predetermined period. This retention period is important to achieve the desired level of microbial reduction and minimize the impact on product quality.
3. **Cooling:** The product is cooled quickly after storage to avoid overcooking or spoilage. While maintaining product freshness and flavour, quick freezing prevents the growth of heat-resistant bacteria.
4. **Packaging:** After the pasteurization process is finished, the food is hygienically packaged to preserve its quality and safety. Two other benefits of good packaging are longer product shelf life and reduced risk of contamination during pasteurization (Gao et al., 2011). Fruit juices, sauces, some soups, drinks, and dairy products including yogurt, cheese, and milk are all produced using batch pasteurization.

It is especially useful for products whose natural flavour and nutritional content must be preserved through gentle processing. Although effective in reducing microbial contamination, batch pasteurization has several disadvantages (Singh & Heldman, 2009). It is difficult to maintain a consistent temperature throughout the batch, which may not be suitable for granular products or very viscous ingredients. Production costs and efficiency can also be affected by batch processing, which is often more labour-intensive and time-consuming than continuous processes. In summary, batch pasteurization is an important method used in the food industries that balances the need for effective microbial control and preservation of product quality (Allende et al., 2022). By continuously adjusting temperature, time and other process parameters, manufacturers can ensure product integrity and safety while meeting consumer expectations for flavour, texture, taste, structure, and nutritional value.

High-Temperature Short-Time (HTST) Pasteurization

In this process, the product is heated quickly to temperature between 71.7 and 74 °C (161–165 °F) in 15–30 s, and it is then swiftly cooled (Donalisio et al., 2018). Dairy products, fruit juices, and liquid egg products are often pasteurized using HTST, which reduces heat damage and successfully eliminates germs. The method used to effectively reduce bacterial contamination while preserving the nutritive value and sensory appeal of perishable food is long-term pasteurization. In order to assure microbiological safety without compromising the product's overall quality, high temperature short time (HTST) (Escuder-Vieco et al., 2018) entails heating the product to a certain temperature for a brief period of time and cooling it swiftly. The food sector frequently uses HTST pasteurization to lower the quantity of dangerous bacteria in liquids like milk, juices, and other drinks. Before the liquid is pumped into a holding tube and heated with hot water or steam to the appropriate temperature, it

is first preheated to around 60 °C (140 °F). The liquid is quickly cooled to stop any additional heat damage once the holding tube keeps it at this temperature for the necessary amount of time. To avoid recontamination by any leftover microbes, the liquid is usually stored in sterile containers after pasteurization.

UHT pasteurization, also known as Ultra High-Temperature pasteurization or Ultra By sterilizing liquid food goods, the process of pasteurization is utilized to increase their shelf life. The liquid is heated to an extremely high temperature between 135 and 150 °C (275–302 °F) for a limited amount of time throughout this process—typically 2–5 s. The liquid is heated using direct or indirect heat during UHT pasteurization; this is usually accomplished by putting the liquid through a heat exchanger or injecting it with steam. All dangerous microorganisms, such as molds, yeasts, and bacteria, as well as spores that are frequently resistant to conventional pasteurization techniques, are destroyed by the high temperature. Additionally, the quick heating and cooling procedure minimizes any deterioration to the product's sensory and nutritional aspects. After pasteurization, the liquid is typically packaged in sterile containers, such as Tetra Pak or aseptic cartons, which are designed to prevent any further contamination. These containers are then filled with the sterilized liquid in a sterile environment, using a sterile filling machine. The process destroys nearly all microorganisms present in the liquid, including spoilage bacteria and spores. In ultra-pasteurization, the liquid food is first preheated to about 80–90 °C (176–194 °F) before it enters a high-temperature holding tube. Steam or Hot water is inserted into the liquid, rapidly raising the temperature to above 135 °C (275 °F). The liquid is held at this high temperature for 1–2 s before it is rapidly cooled down to below 4 °C (39 °F) using a heat exchanger. It is used for dairy products like milk, cream, and flavour-infused dairy drinks as well as non-dairy milk alternatives like soy milk and almond milk. This is one of the key benefits of the process (Fig. 5.2).

Low-Temperature Long-Time (LTLT) Pasteurization

LTLT pasteurization stands for Low-Heat The process of long-term pasteurization lowers the quantity of dangerous germs in liquid food products. The dairy industry frequently uses this procedure to pasteurize milk, cream, and other dairy products. The process comprises heating the liquid to a lower temperature compared to HTST or vat/batch pasteurization, typically around 63 °C (145 °F), but for a longer period of time, usually between 30 min to an hour.

This lower temperature and longer heating time are used to minimize any damage to the nutritional and sensory qualities of the product while still reducing the number of harmful microorganisms. The liquid is heated using indirect heat during LTLT pasteurization, usually by running it through a heat exchanger that heats it with steam or hot water. After the heated liquid reaches the proper temperature, it must be maintained there for the necessary amount of time before being quickly cooled to avoid further heat damage.

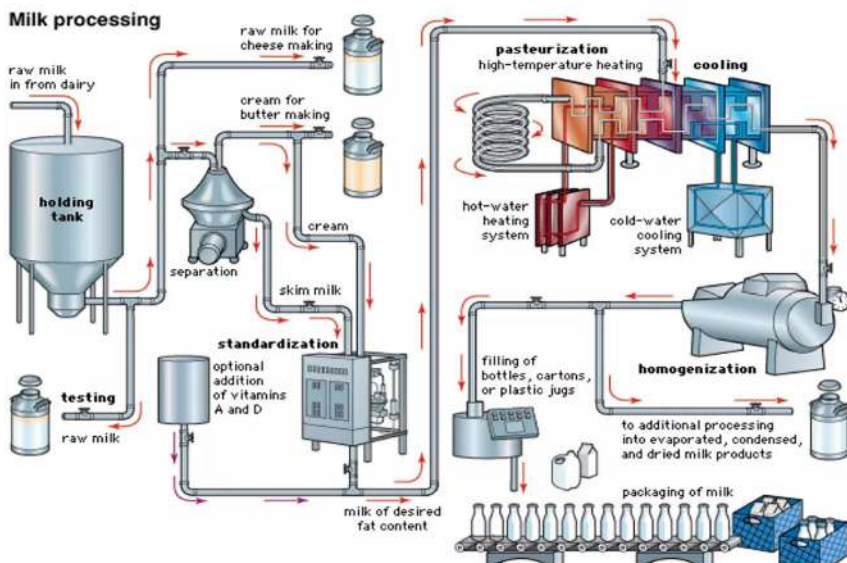


Fig. 5.2 High-Temperature Short-Time (HTST) Pasteurization (www.pmg.engineering)

After pasteurization, the liquid is typically packaged in sterile containers and stored under refrigeration until it is ready for distribution. While limiting any potential harm to the product's nutritional value and sensory appeal, LTLT pasteurization is an efficient way to lower the number of dangerous germs in liquid food products.

However, the longer heating time and lower temperature required for this method may result in higher energy consumption and production costs compared to HTST or VAT/batch pasteurization.

LTLT pasteurization differs from HTST in that it uses lower temperatures, typically 63°C or 145°F , for long periods of time (30 min to 1 h). When the product's organoleptic qualities must be preserved, this method is frequently applied to delicate liquids like wine, beer, and various dairy products (Franklin, 1965). Long-time low-temperature (LTLT) pasteurization is common method in the food industry to minimize bacterial contamination while having the least negative impact on nutritional content and appeal sensory aspects of perishable products (Giribaldi et al., 2016; Grant et al., 1999; Grant et al., 1996). LTLT pasteurization, as the name implies, entails heating the product for a longer amount of time at a lower temperature than traditional pasteurization techniques. This meticulous approach aims to preserve the nutritional value, flavour and freshness of the food or beverage without compromising its microbiological safety (Hamad, 2018) (Figs. 5.3 and 5.4).

The liquid is heated using direct or indirect heat during UHT pasteurization; this is usually accomplished by putting the liquid through a heat exchanger or injecting it with steam. All dangerous microorganisms, such as Molds, yeasts, and bacteria, as well as spores that are frequently resistant to conventional pasteurization

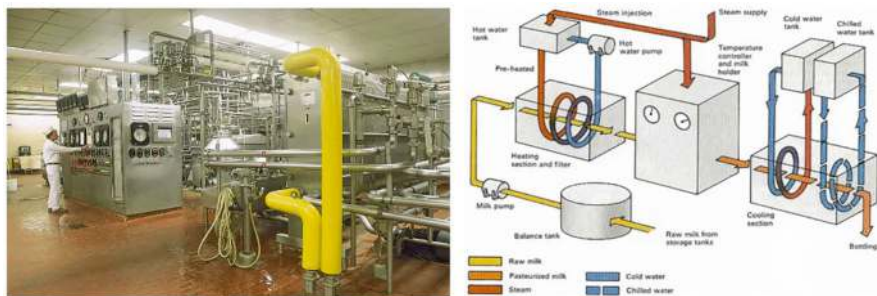


Fig. 5.3 Flow-diagram of LTLT Process (Right: Diagram of the milk pasteurization process)

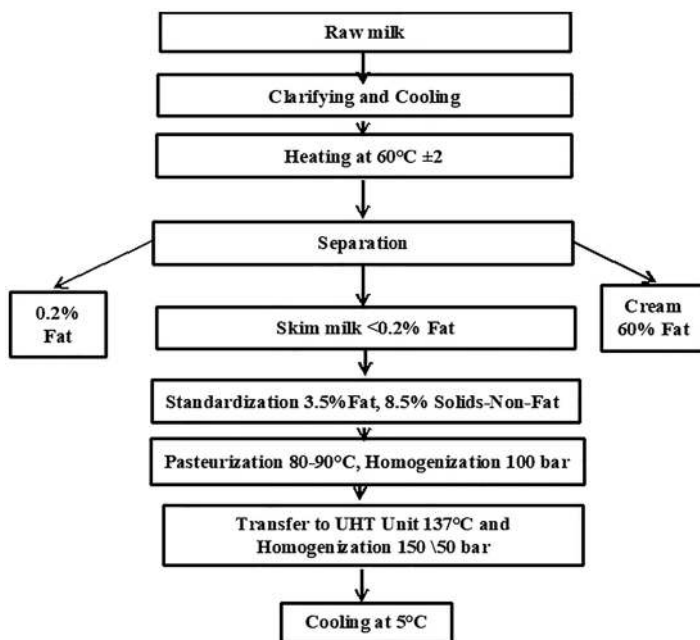


Fig. 5.4 Ultra-high Temperature “UHT” “Processing of Milk (Hamad, 2018)

techniques, are destroyed by the high temperature. Rapid heating and cooling also contributes to minimizing any damage to nutritional and sensory qualities of product. After pasteurization, liquid is typically packaged in sterile containers, such as Tetra Pak or aseptic cartons, which are designed to prevent any further contamination. These containers are then filled with the sterilized liquid in a sterile environment, using a sterile filling machine.

Similarly, Ultra-pasteurization is an another HTST process that comprises heating liquid foods to temperatures above 135 °C (275 °F) for 1–2 s, followed by rapid cooling. The process destroys nearly all microorganisms present in the liquid,

including spoilage bacteria and spores. In ultra-pasteurization, the liquid food is first preheated to about 80–90 °C (176–194 °F) before it enters at a high-temperature holding tube. Steam or hot water is injected into the liquid, rapidly raising the temperature to above 135 °C (275 °F). The liquid is held at this high temperature for 1–2 s before it is rapidly cooled down to below 4 °C (39 °F) using a heat exchanger. This is one of the key benefits of the process. This makes it an ideal method for producing long-lasting, shelf-stable products that can be stored and distributed without the need for refrigeration, such as milk, cream, and other dairy products, as well as fruit juices, soups, and sauces. However, one potential disadvantage of UHT pasteurization is that it can result in a slightly cooked or burnt taste in the product due to the high temperatures used.

UHT milk can have a lengthy shelf life by being used for a brief period of time at 135–140 °C (Fitria et al., 2015). According to Rauh et al. (2014), use of UHT treatment reduced or eliminated the growth of harmful bacteria and spoilage of milk. UHT milk is highly popular (Chove et al., 2013; Chavan et al., 2011). Pulkkinen (2014) state that UHT milk has a six-month shelf life. However, this can vary depending on quality of the milk, the storage situations used and the physico-chemical and biochemical processes. Shelf life depends greatly on time and temperature. According to Lacroix et al. (2008), there are two forms of heat treatment utilized in the UHT process: direct and indirect. When indirect heating is used, heat exchange occurs when steam is introduced into the milk during direct heat treatment and not when the product and heating liquid come into direct contact (Panchal et al., 2020). According to Perkins et al. (2005) the effects of the two treatments on milk are different. However, one potential disadvantage of UHT pasteurization is that it can result in a slightly cooked or burnt taste in the product due to the high temperatures used.

2.4 *Non-thermal Pasteurization*

Non-thermal pasteurization methods use non-heat physical or chemical treatments to destroy harmful microorganisms in the product. These methods are further classified into several categories, including: High-pressure processing (HPP): In order to eradicate microorganisms, the liquid is subjected to high pressures of up to 600 MPa.

Pulsed electric field (PEF) involves exposing the liquid to high-intensity electric pulses to kill microorganisms. Ultraviolet (UV) treatment involves exposing the liquid to UV radiation to kill microorganisms. Chemical treatments, such as ozone and hydrogen peroxide, which are used to kill microorganisms in the liquid. Membrane filtration involves filtering the liquid through a membrane to remove microorganisms. Each of these non-thermal pasteurization methods has its benefits and drawbacks, and their effectiveness may depend on the type of liquid products being treated (Fig. 5.5).

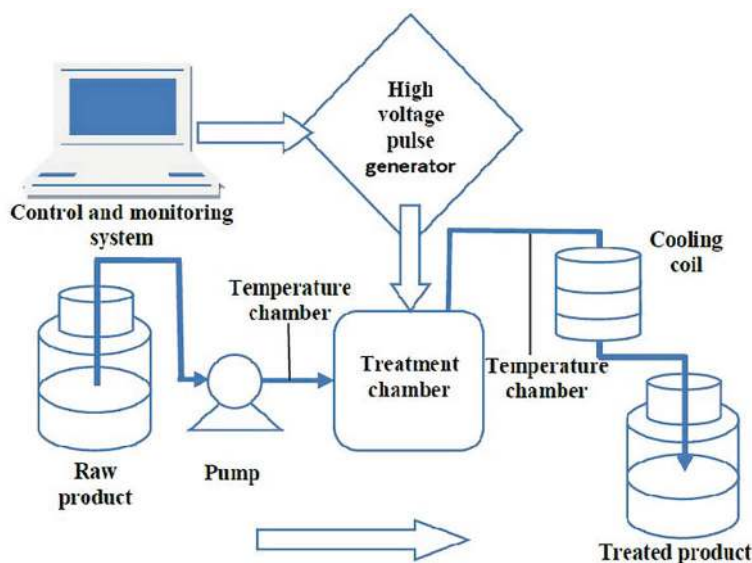


Fig. 5.5 Flow- sheet of Pulsed electric field for food (Mohammed & Amer Eiss, 2012)

High-pressure processing (HPP) as a minimum process to increase the microbiological safety and shelf life of pasteurised foods. It is applied at pressures up to 400 MPa using a modified homogenizer. According to Escuder-Vieco et al. (2018), the number of following processing cycles, the inlet temperature, and the operating pressure are the critical processing variables. After milk was treated with HPP, psychotropic bacteria were reduced by four logs and were not present. (Fitria et al. 2015) reported that the HPP action of soy and almond milks resulted in complete bacterial suppression at 200 MPa and 75 °C or 300 MPa and 65 °C. Also, these goods' colloidal stability improved compared to when they were conventionally pasteurised, which experienced issues with particle sedimentation during storage. In order to attain a deeper penetration depth during processing, volumetric and continuous microwave

systems—which are relatively new—need a special microwave energy delivery technique (Ahmed and Ramaswamy, 2020) (Fig. 5.6).

The technology can also be used to pasteurize goods like sauces and soups that include particles and are difficult to treat with conventional heat exchangers (Stratakos et al., 2016).

UV light can be used as a germicidal medium during the processing of fresh food products to reduce the number of germs that could result in food poisoning.

UV light is a germicidal medium used to reduce the burden of bacteria in fresh food products. UV radiation has been shown to cause cell death and inhibit cell development, with the most fatal effects occurring at 254 nm. UV treatment may have more of a fresh-like quality than thermal pasteurisation, and photo reactivation may happen if light with a wavelength longer than 330 nm is applied to UV-C

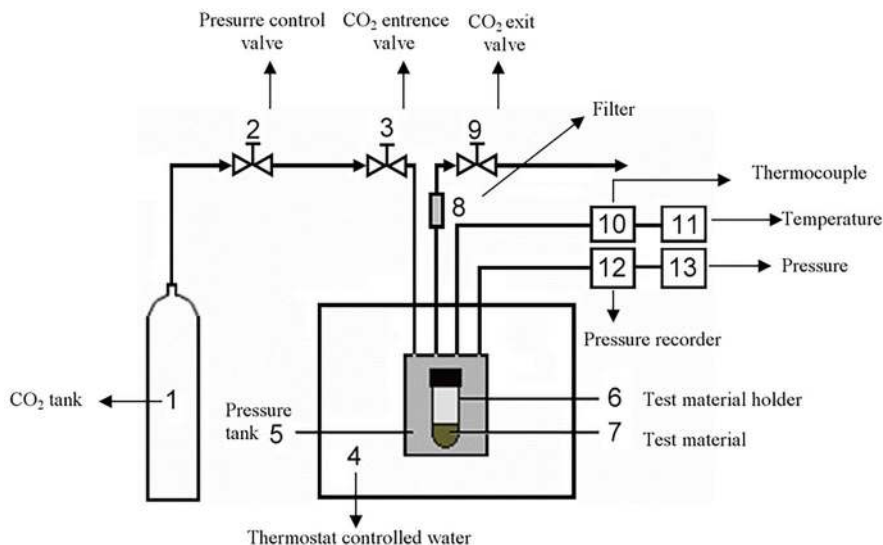


Fig. 5.6 Flow-sheet of High-pressure processing (Evrendilek, 2017)

damaged cells (Liltved and Landfald, 2000). Due to their large suspended particles, juices have limited UV penetration, making them challenging to UV-treat. To achieve the necessary reductions, tropical and orange juices require higher UV dosages (Keyser et al., 2008). Juices with high suspended particle content and poor UV transmittance have been cured using a variety of techniques in recent years, such as turbulent flow UV reactors and ultra-thin film UV reactors (Oteiza et al., 2005; Tran and Farid, 2004). Mixing and flow rates in a turbulent flow UV reactor affected the inactivation of microorganisms (Koutchma et al., 2004). *Saccharomyces cerevisiae* KE162 and the yeast cocktail in apple juice were less sensitive to UV radiation than *E. coli* ATCC 35218 and its cocktail (Char et al., 2010). Orange juice's inactivation action has been enhanced and made more effective all at once by combining UV light with sonication, but potential for flavour and colour variations in some juice products is a drawback. Additionally, furan is produced during UV exposure.

2.5 Dimensioning Data for a Heat Exchanger

The design and required dimensions of heat exchanger are established with consideration of several variables which involve complex computations. The important considerations in such computations are the rate of product flow, physical characteristics of liquid, program for temperature-dependent pressure drops, and design with ease of cleaning. The following general formula can be used to determine any heat exchanger's necessary size or heat transfer area:

$$A = \frac{V \times \rho \times C_p \times \Delta t}{\Delta t_m \times k}$$

Where;

A = Area required heat transfer.

V = Product flow rate, ρ = Density of product, C_p = Specific heat of the product, Δt = Temperature change of the product, Δt_m = Logarithmic mean temperature difference (LMTD).

k = Overall heat transfer coefficient.

- *Output Flow Rate:* Capacity of dairy facilities determines flow rate, and there is a correlation between the flow rate and necessary heat exchanger size.
- *The Liquids' Physical Importance:* One can obtain the density figure, ρ , based on the outcome. The product also establishes the specific heat value or c_p . A substance's specific heat indicates how much heat is needed to raise its temperature by one degree Celsius. Viscosity is another physical attribute of importance that influences the total heat transfer coefficient. The temperature program transferring heat from a given input temperature to a given output temperature involves a specific quantity of a product, like milk, being heated or cooled. A heat exchanger uses a heating or cooling medium, like water, to help achieve this. When milk is heated, hot water is used, causing the milk's temperature to increase accordingly. Several factors related to the temperature program need to be considered, including temperature variations, relative temperatures of liquids, and the direction of their flow.
- *Change in temperature:* Inlet and output temperatures of product are influenced by the consecutive steps that a process involves. In the preceding generic formula, the product temperature change is denoted by Δt . The formula is:

$$\Delta t_1 = t_{o1} - t_{i1}$$

The heating or cooling medium's input temperature is influenced by processing circumstances. It is possible to calculate the temperature of the outgoing medium using an energy balance calculation. The energy losses of a contemporary heat exchanger to the ambient air are negligible and should be disregarded. Consequently, there is an energy balance when the heat energy emitted by the heated liquid and the heat energy received by the chilled liquid are equal. It is expressed by the following formula:

$$V_1 \times \rho_1 \times C_{p1} \times \Delta t_1 = V_2 \times \rho_2 \times C_{p2} \times \Delta t$$

2.6 Systems for Heating of Food Products

In food industry, equipment with precise functioning is used for heating or cooling food products. These are known as heat exchangers which based on construction and working principles, are categorized into two groups: contact type and non-contact type. A non-contact type heat exchanger maintains the product's physical isolation from the heating or cooling media by utilizing a thin wall or plate. Conversely, the product is in close physical touch with the heating or cooling streams when using contact-type heat exchangers (Fig. 5.7).

- **Plate Heat Exchanger (PHE):** In this heat exchanger, heat is exchanged between two fluids by means of metal plates and thus it is also called plate heat exchanger (PHE). Owing to its small size and high efficiency, its applications are wide in several industrial sectors such as in food and beverage processing, electricity generation and chemical processing. However, PHE can be specifically used for the processing of foods with low viscosity (~ 5 Pa s) having particulates with a comparable diameter of <0.3 cm as suspended solids. This is because there is a possibility for larger particles to “burn on” in the heating area by bridging over the plate contact points. In industrial-sized PHE, the product flow can be attained at a maximum level of 5000–20,000 kg/h. However, the flow rate can be affected by the solids deposition on the surface of plates due to burn on during processing such as of milk proteins, which is known as fouling. To avoid this, build up the plates of PHE are dismantled and cleaned occasionally to ensure the efficient working of the process. The processing time is frequently restricted to 3–4 h for dairy products since they need to be processed at extremely high temperatures (Fig. 5.8).

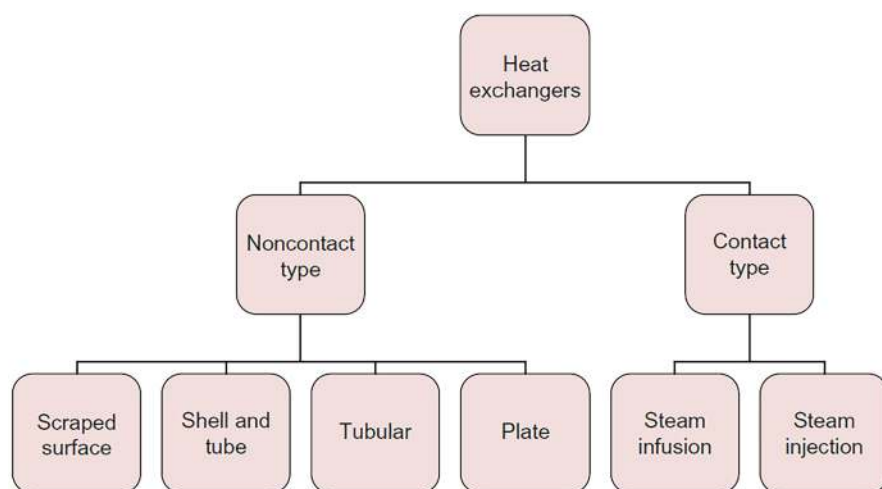


Fig. 5.7 Classification of heat exchangers

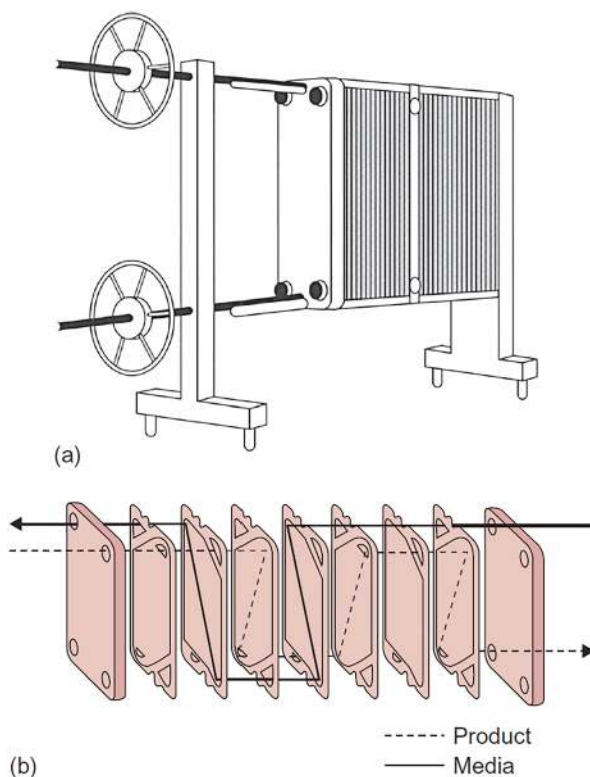


Fig. 5.8 (a) Plate heat exchanger. (b) Fluid flow between plates. (Courtesy of Cherry-Burrell Corporation)

• *Tubular Heat Exchanger:*

A double-pipe heat exchanger is the most basic type of non-contact heat exchanger. It is made up of one pipe that is concentrically positioned inside another pipe. The two fluid streams i.e., the product and the heating or cooling medium, flow in the cavity of inner pipe and annular space, respectively. There are two possible directions for the streams to flow: parallel flow and counter-flow (Fig. 5.9).

A schematic of a counter-flow double-pipe heat exchanger is shown in Fig. 5.10a. A slight variation of a double-pipe heat exchanger is shown in Fig. 5.10b: a triple-tube heat exchanger. In this type of heat exchanger, the heating/cooling medium flows in the outer annular space and the inner tube, while the product flows in the inner annular space. The heat transmission and turbulence can be improved by making impediments in the innermost tube. The following industrial applications make use of triple-tube heat exchangers.

- (i) Heating 4–93 °C orange juice at one strength and then cooling it to 4 °C.
- (ii) Lower the cottage cheese water's temperature from 46 to 18 °C using cooled water

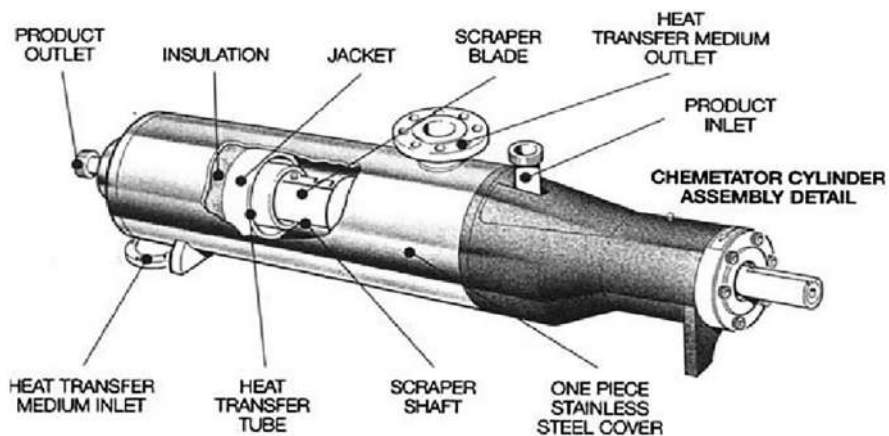


Fig. 5.9 Tubular heat exchanger (Maurya, 2017)

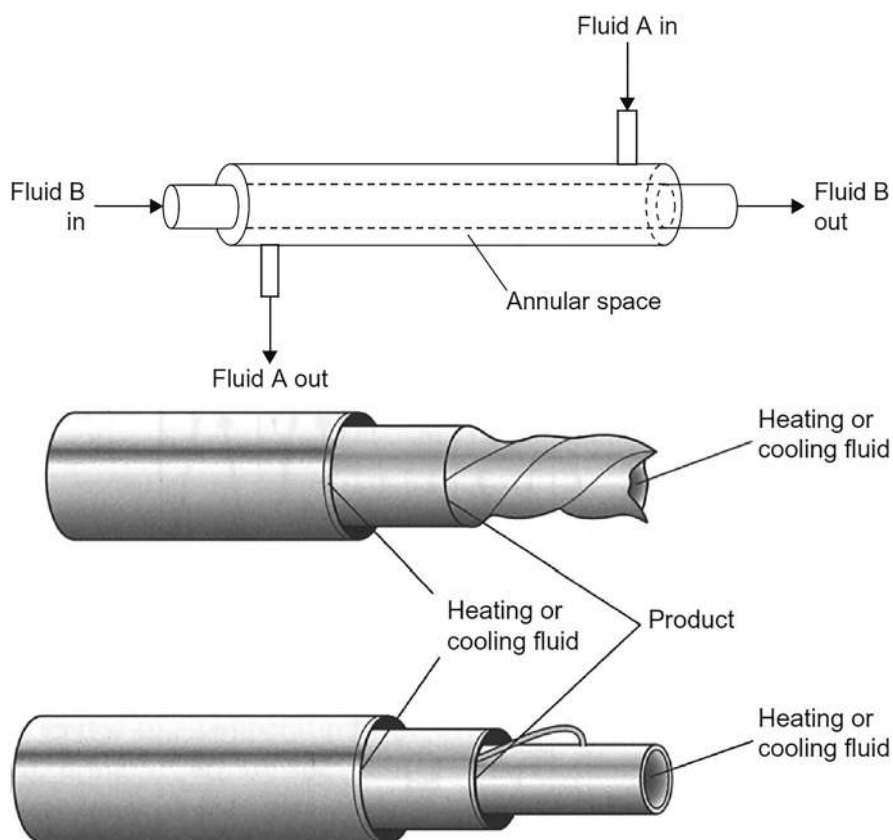


Fig. 5.10 (a) Diagrammatic representation of a heat exchanger with tubes. (b) A triple tube heat exchanger's schematic drawing. (Source: Paul Mueller Company)

(iii) Using ammonia to cool ice cream mixture from 12 to 0.5 °C.

- *Shell and Tube Heat Exchanger:*

- This type of heat exchanger is most frequently used in large chemical processes, such as oil refineries. A bundle of tubes is housed inside a shell, or huge vessel. Within the heat exchanger, two fluids with varying initial temperatures circulate. There are two distinct forms of fluid flow: the shell side flows outside the tubes, and the tube side flows through the tubes. Heat can be transferred between fluids via the tube walls in both directions, or from the shell side to the tube side. On either side of tube or shell, the fluids might be either liquids or gases. There are several tubes because an extensive heat transfer area must be utilized for effective heat transmission. Heat exchangers with a single phase (gas or liquid) on each side are referred to as “one-phase” or “single-phase” heat exchangers. Phase changes in two-phase heat exchangers often occur on the shell side. Boilers are devices that heat a liquid until it turns into a gas (vapor); condensers are devices that cool a liquid until it condenses back into a liquid. Steam engine locomotives use large, frequently cylindrical shell-and-tube heat exchangers as boilers. The exhaust steam from the turbine is condensed into condensate water by large steam-driven shell-and-tube condensers; this water can then be recycled to be converted back into steam, perhaps in a shell-and-tube type boiler. This considerably aids in energy conservation by regenerating the waste heat for future purposes (Fig. 5.11).

- *Scraped-Surface Heat Exchanger:* Heat transmission to a fluid stream in typical tubular heat exchangers is impacted by hydraulic drag and heat resistance brought on by fouling or film build-up on the tube wall. To reduce heat resistance, a mechanical device can be constructed which continuously scrapes the inside surface of the tube wall. Rapid heat transfer is made possible by the scraping movement for a comparatively small product volume. Figure 5.12 illustrates a design of a scraped-surface heat exchanger used in food preparation. Scraped-surface cylinders with food contact parts can be built of any corrosion-resistant material, pure nickel, hard nickel coated with chromium, or stainless steel (type 316). The blades of rotor are covered in plastic laminate or mould plastic. The rotor speed can be varied by adjusting in the range of 150–500 rpm. Increased rotation speed facilitates improved heat transmission, but it also runs the risk of macerating the treated product, which might lower its quality. As a result, for the product being processed, carefully choose the rotor speed and annular distance between rotor and cylinder. The cylinder with product and rotor is covered by an outer jacket, as shown in Fig. 5.5. This outer jacket gets its heating/cooling medium from outside sources. A refrigerant, steam, boiling water, or brine are examples of often employed media. In scraped-surface heat exchangers, the typical processing temperature ranges from 235 to 190 °C. The scraped-surface heat exchanger’s continuous mixing action is frequently preferred to improve the consistency of the product’s flavour, colour, fragrance, and textural qualities. The food processing industry uses scraped-surface heat exchangers for temperature regulation, pasteurization, sterilisation, whipping, gelling, emulsification, plasticizing, and crystallization.

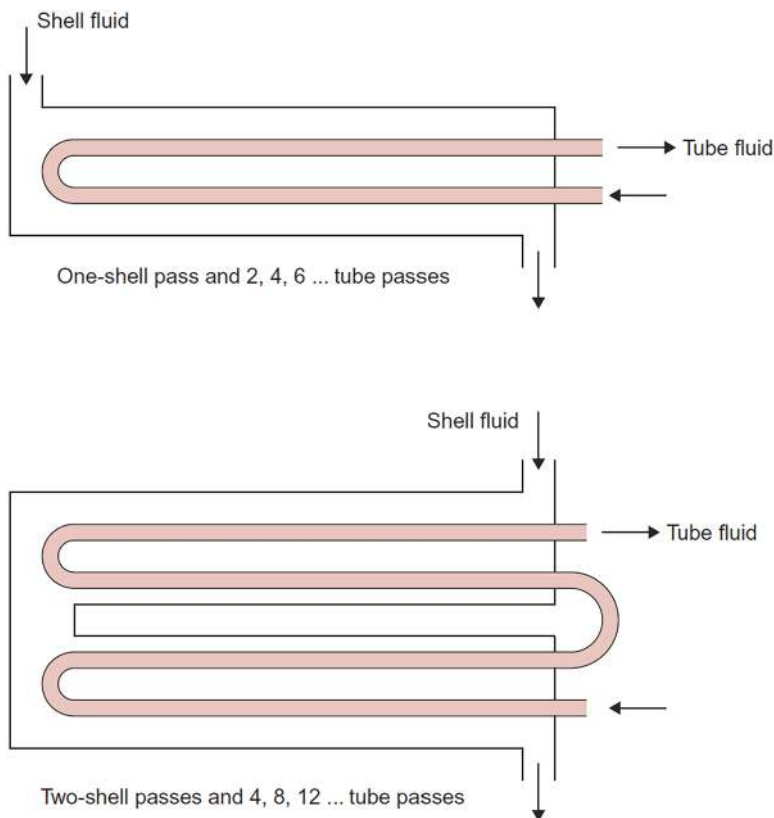


Fig. 5.11 Shell-and-tube heat exchanger

- *Steam-Infusion Heat Exchanger:*
- A heat exchanger that infuses steam directly into the product to allow direct steam-to-product contact. After being propelled to the top of the heat exchanger, the liquid product is let to flow into the heating chamber in thin sheets. The spreaders' size is determined by the liquid's viscosity. Products with specific functionality can manage products that contain particles, like chopped vegetables, cereals, and pieces of meat. Steam and small food droplets come in physical contact to transfer heat at high rates. Steam condensation causes the product's temperature to rise extremely quickly. The bottom chamber releases the condensed steam-filled hot items. A specific amount of liquid is maintained at the chamber's bottom for the appropriate cooking. For example, the temperature differential between the product's input and output during the deodorization of milk ($76.7\text{--}82.28\text{ }^{\circ}\text{C}$) may be as low as $5.58\text{ }^{\circ}\text{C}$ in the heating chamber. Alternatively, it can sterilize puddings for aseptic packaging at $96.78\text{ }^{\circ}\text{C}$, which is the difference in temperature between 48.9 and $145.68\text{ }^{\circ}\text{C}$ (Fig. 5.13).

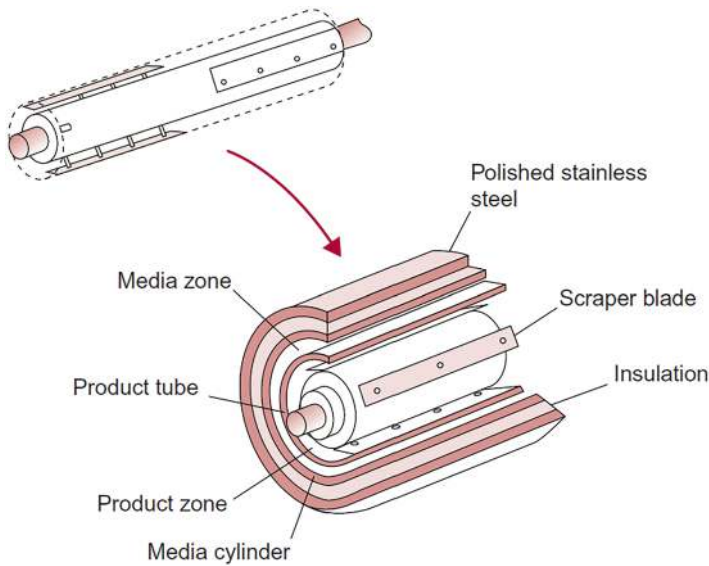


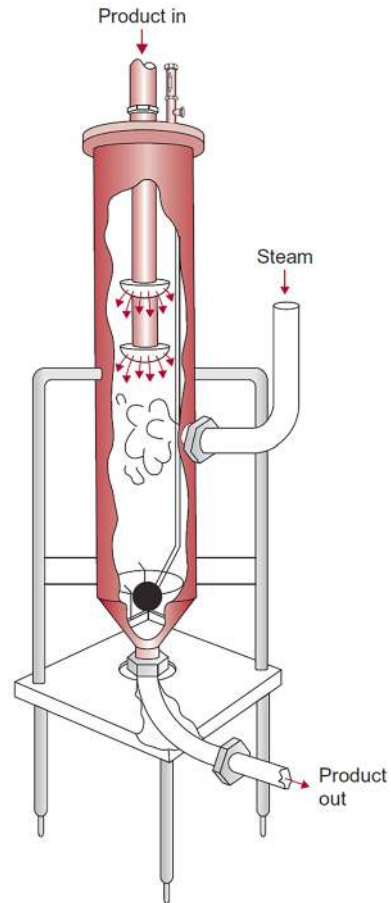
Fig. 5.12 A scraped-surface heat exchanger with a section removed to reveal different parts. (Courtesy of Cherry-Burrell Corporation)

2.7 Applications of Heat Exchangers in Food Industry

Heat exchangers are a promising piece of equipment in the food processing industry that can be used to heat or cool a variety of food products. Den Braven & Nielson (1998) well explained that products like hazelnut paste must be heated or cooled to be processed further. Therefore, to process foods efficiently where heating or cooling is involved, heat exchangers can be employed to use.

Applications in food industries	
In dairy	Heating or cooling milk and during processes like evaporation, freezing, or crystallization that are utilized in the production of dairy products including ice cream, yogurt, cream, and milk powder (Whitaker, 1977).
In juices	Fruit juices are largely processed using hot fill processing which involves subjecting juice to high temperatures for heating followed by filling into containers. The heat prolongs shelf life of juice and additionally sanitizes the container. (Fellows, 2022). In fruit juice processing, heat exchangers are frequently used to effectively exchange heat between juice and heating or cooling medium, like steam or chilled water, to attain the desired temperature at subsequent processing steps (Holman, 2009; Sweat, 1974).
In sea foods	In the processing of seafood, effective heating or cooking must be ensured to achieve safe internal temperatures, desired protein denaturation, and enhanced texture and flavour. Despite the type of cooking method applied, whether grilling, boiling, frying, or baking, adequate heat transfer is the foremost parameter to be considered (He & Tao, 2014). The key objective of thermal processing of marine items is to destroy <i>clostridium botulinum</i> spores, which can only be accomplished by regulating heat transfer.

Fig. 5.13 A steam-infusion heat exchanger.
(Courtesy of
CREPACO, Inc)



2.8 Pasteurization Plant and Its Operations

To ensure product sterility during the HTST pasteurization process, a specified temperature of $72\text{ }^{\circ}\text{C}$ is maintained for 15 s. To make milk, fruit juice and beer safe for consumption, this technique aims to eliminate bacteria that may be present. This also allows you to drink milk longer. Bylund (2003) has given a general diagram of milk pasteurization in Fig. 5.1a, which also explains the heat treatment of whole milk before it is sold to consumers. According to Gao et al. (2011), the HTST pasteurizer with padded plate heat exchanger (PHE) is the most used method. By using strategies such as white box, black box and grey box, mathematical models of these PHEs can be created. To achieve the above goals, precise temperature control and accurate mathematical modelling are beneficial (Martin et al., 2018). This ensures efficient optimization, process security, scaling and quality control (Fig. 5.14).

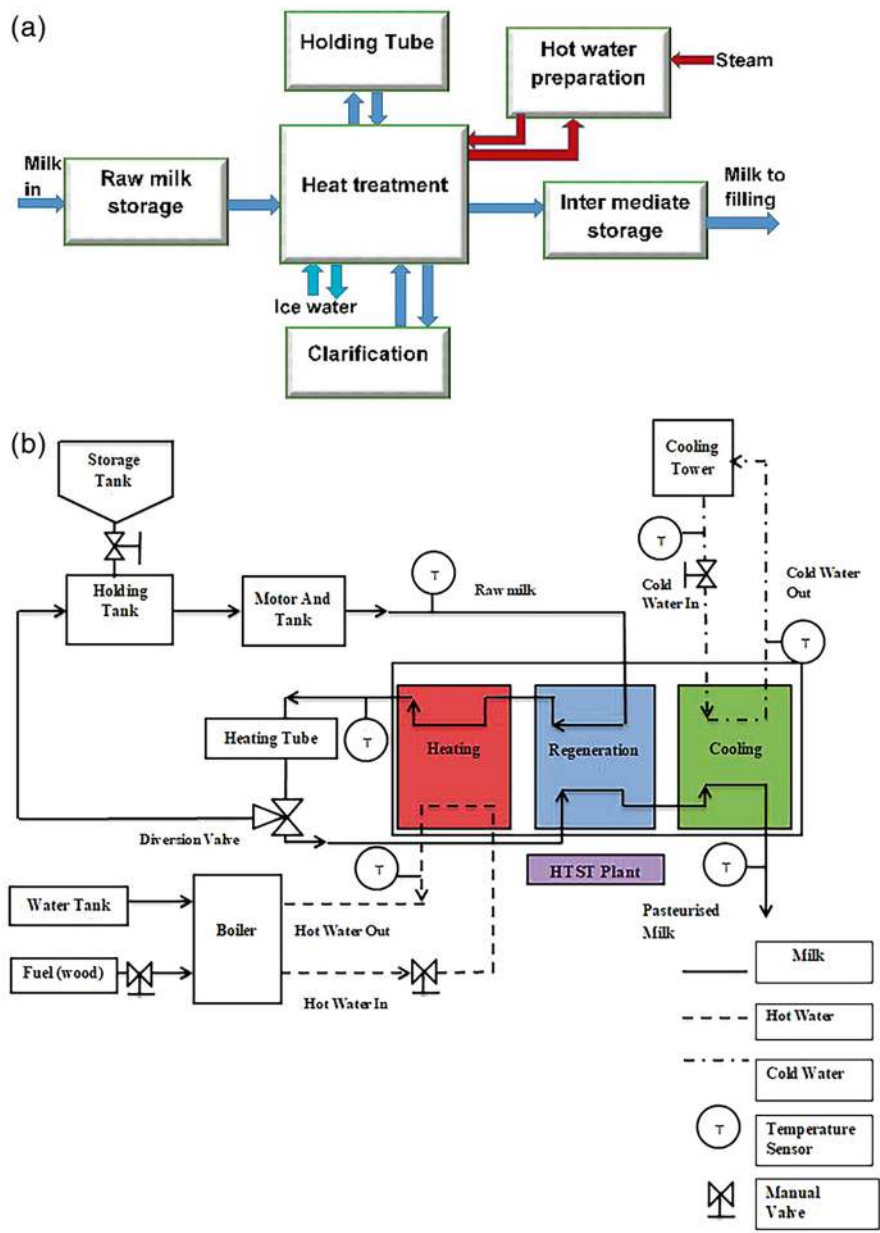


Fig. 5.14 (a) Flow chart of milk pasteurization. (b) Schematic diagram of the HTST Pasteuriser Plant (Indumathy et al., 2020)

2.9 Advances in Application of Pasteurization in Food Industry

- **Milk:** Modern dairy operations rely heavily on pasteurization, which is essential to produce indigenous and Western dairy products. Microorganisms grow best in milk and the growth of harmful organisms can lead to diseases such as typhus and tuberculosis. Pasteurization makes milk safe for consumption by eliminating disease-causing microorganisms spread through milk. Louis Pasteur, a famous French scientist, was the one who coined the name “sterilization.” Generally, it involves heating milk or its derivatives to a temperature that eliminates virtually all microorganisms present without changing the composition or properties of the product.

S.N.	Food	Main purpose	Sub-purpose	Conditions of processing
1	Juice from fruit (pH < 4.5)	Inactivation of enzymes (polygalacturonase, pectin-esterase)	Elimination of bacteria that cause spoiling (<i>Cryptosporidium parvum</i> , <i>salmonella enterica</i>)	Temperatures: 65 °C for 30 min, 77 °C for 1 min, and 88 °C for 15 s.
2.	Beer (pH less than 4.5)	Elimination of microorganisms that cause spoilage, such as residual yeasts and saccharomyces species and wild yeasts.	Destroy spoilage-causing bacteria.	Temperatures: 65 °C–68 °C for 20 min (in bottle); 72 °C–75 °C for 1–4 min at 900–1000 kPa.
3.	Milk with a pH higher than 4.5	Pathogen destruction: <i>Brucella abortus</i> , mycobacterium tuberculosis, and <i>Coxiella burnetti</i>	Destroy spoilage-causing bacteria (<i>streptococcus lactis</i> , <i>streptococcus cremoris</i>) and enzymes.	Temperatures used: 63 °C for 30 min, 71.5 °C for 15 s, and 64.4 °C overall.
4.	Egg liquid	Pathogen destruction (<i>salmonella seftenberg</i>)	Microorganisms that cause spoiling are destroyed	60 °C for 3.5 min and 64.4 °C for 2.5 min
5.	Ice cream	Elimination of bacteria that cause spoiling.	Pathogens are destroyed	Temperatures used: 65 °C for 30 min, 71 °C for 10 min, and 80 °C for 25 s.

Therefore, it is essential to monitor the pasteurization process, as poorly pasteurized or unpasteurized milk may contain harmful bacteria (Pandey & Gupta, 1983). The first federal standard for milk pasteurization was developed in 1924 with the purpose of eradicating *Mycobacterium tuberculosis*. It gives the method at 61.7 °C/30 min (Meanwell, 1927). Three varieties of dairy products, ice cream, chocolate milk mixture, and ice cream, were later discovered to require more stringent pasteurization procedures (Burgwald, 1939). The study by Fitria et al. (2015) on this topic revealed that particle diameter has very little effect on the thermal

process used to pasteurize milk. Therefore, flocculation of *Mycobacteria paratuberculosis* cells, proposed as a method for the organism to survive pasteurization, is unlikely to reduce the effectiveness of standard pasteurization procedures (Hope et al., 1997). To accurately assess the heat provided, the experimental methodologies for evaluating heat resistance must be outlined and understood. If this is not done, incorrect conclusions may be drawn and increase the likelihood that the experiment will have errors and variations.

- **Seafood**

The FDA regulates the pasteurization of seafood in accordance with the Seafood Product Risk and Control Guidelines. For seafood pasteurized, FDA believes that the 6D technique (6 log reduction) is generally appropriate. Pasteurized fish and fish products can reduce *C. botulinum* type E spores in up to 10 min with a minimum total cumulative bactericidal rate of F 90 °C or equivalent cumulative time at 90 °C, in when performing heat treatment. Items containing substances such as lysozyme, which can help pathogens recover from heat injury, require higher temperatures.

- **Egg and egg products:**

As a USDA Food Safety and Inspection Service (FSIS) regulations define pasteurization as “subjecting each particle of egg products to heat or other treatments to destroy harmful viable microorganisms.” Moreover, regulation defines as “Salmonella negative product” and specifies specific time and temperature requirements for liquid egg products. According to FDA regulations, the Egg Products Inspection Act mandates that egg products be processed using as “process that achieves at least a 5-log destruction of *Salmonella* for shell eggs.” conditions unique to the processing of eggs and egg products (Wilbey, 2014).

- **Juice:**

Hazard Analysis and Critical Control Point (HACCP) systems, as well as FDA rule 21 CFR 120, apply to juice pasteurization. A strategy that lowers a pertinent pathogen—defined as the most resistant microorganism by a minimum of five logs must be put into place. The juice product and procedure determine which bacteria are the target, which could be *Salmonella*, *Cryptosporidium parvum*, *E. Coli* O157:H7 or *C. botulinum*. Pathogen hazards to be concerned about include *C. botulinum*, which can thrive in low-acid juices like carrot juice and generate toxins; *Cryptosporidium parvum*, *E. Coli* O157:H7 and *Salmonella* can grow in acidic juices (pH less than 4.6) and cause significant outbreaks of foodborne illness. The American understanding of pasteurization is, all things considered, very broad. The specific product, the packing technique, and the processing conditions all influence the regulations and recommendations for pathogens of concern and pasteurization processing parameters. There was no “one size fits all” approach to accomplishing microbiological safety in food pasteurization in the USA. The process of pasteurizing fruit juices by applying high hydrostatic pressure and carbon dioxide. The results implied that low-medium

acid fruit and vegetable juices might be preserved at relatively low pressures when dissolved CO₂ was combined with HHP treatment.

HHP alone was able to effectively eradicate bacteria from high-acid fruit juice. Kong et al. investigated how different pasteurization temperatures affected reconstituted pomegranate juice (RPJ) (2020). RPJ was subjected to thermal treatments including high-temperature pasteurization (HTP) at 95 °C and mild-temperature pasteurization (MTP) at 80 °C for 30 s. An assessment of the influence on physicochemical qualities, which included antioxidant activities and microbial inactivation, revealed that both HTP and MTP can meet the standards for microbiological safety and comparable physicochemical features.

According to a study by Telis-Romero et al. (1998) on how it changes the sensory qualities and nutritional profile of orange pulp by-products, pasteurization is the preferred procedure before aseptically packing and maintaining under refrigeration. The effects of pasteurization on the functional, sensory, and chemical properties were evaluated in this study. It is not a good idea to retain the orange pulp by-product for use in making food products that are different from juices or other drinks since pasteurization changes the sensory profile of an added-pasteurized-pulp juice.

2.10 Effect of Pasteurization on Foods

Most foods undergo a relatively gentle heat treatment called pasteurization, which alters their nutritional value and sensory appeal. Still, pasteurized goods often only have a few days or weeks longer shelf life than they would have with the more intense heat treatment sterilization, as opposed to many months. Pasteurization has little effect on the colour of plant or animal products.

Fruit juices can be kept coloured by deaerating them to remove oxygen before pasteurization, which prevents enzymatic browning caused by polyphenol oxidase. The homogenization process is what makes pasteurized milk whiter than raw milk. By itself, pasteurization has no discernible impact. Pasteurization destroys volatile aroma molecules, which can also bring out other “cooked” smells in juices, degrading their quality. Rather than pasteurization, deaeration causes fruit juices to lose volatile components. Though it can be used to produce premium juices, volatile recovery is not commonly used due to its higher expense. A blander product is produced when the volatiles in raw milk are eliminated, eliminating the hay-like smell. The only dietary alterations that pasteurized foods go through are heat-labile vitamin losses. As an illustration, milk has 7% less thiamine, 2025 percent less vitamin C, 0% folate, 1% vitamin B12, 5% less blood proteins, and so on. After being deaerated, fruit juices lose less of their beta-carotene and vitamin C.

3 Conclusion

The discovery that heats treatment can help preserve food products dates to the late 1800s. Heating can cause both desirable and undesirable chemical changes. Desired changes can enhance the product's value, but unfavourable changes may alter the nutrition profile and sensory quality. To maximize microbial destruction and reduce undesired ones, it is necessary to carefully optimize the heat procedures. The dairy sector uses a variety of thermal processing techniques in a range of modes and equipment, based on factors such as heat transfer phenomena, reaction kinetic analysis of thermal processes, time-temperature combinations, etc. Additionally, research is being conducted to present novel thermal processing techniques. Pasteurization has significantly altered our connection with food, making it safer, more enduring, and more accessible. The core values of pasteurization—ingenuity, diligence, and a dedication to public health—will continue to direct us toward a future in which access to healthy food is a fundamental human right as we face the problems of the twenty-first century and beyond. Safety regulations of pasteurized liquid foods In the USA, pasteurization is defined by the FDA is the process of heating each particle of milk or milk product to at least 161 °F (71.7 °C) for at least 15 s, or at least 145 °F (62.8 °C) for at least 30 min. For other liquid foods, such as juices and non-dairy beverages, the pasteurization process may vary depending on the type of food and the intended use. In the European Union, pasteurization is defined by the European Food Safety Authority (EFSA) as a process of heating food to a temperature of at least 72 °C for a minimum of 15 s. However, depending on the food product and its intended use, several combinations of temperature and time may be utilized. The Food Safety and Standards Authority of India (FSSAI) defines pasteurization as heating milk to a minimum temperature of 63 °C for 30 min or to a minimum temperature of 72 °C for 15 s in India. The US Food and Drug Administration (FDA) has created laws for pasteurizing certain liquid goods, such as milk, juice, and shell eggs, to assure their safety for ingestion. The particular standards depend on the type of food and its intended use. The FDA requires that every juice sold in interstate commerce be pasteurized or processed to produce a 5-log reduction in the specified microorganism.

The specific process and time-temperature combination used for pasteurization depends on the type of juice and the method used. For example, orange juice can be pasteurized using the HPP method at 87,000 psi for 3 min, or using the UHT method at 280 °F (138 °C) for 2 s. Shell eggs: The FDA requires that all shell eggs sold in interstate commerce be washed and sanitized, and that eggs intended for consumption without cooking be pasteurized. Pasteurized shell eggs must be cooked, utilizing the hot water immersion method, to a minimum of 135 °F (57.2 °C) for at least 75 min or, using the HTST method, to a minimum of 140 °F (60 °C) for at least 3.5 min. In addition to these regulations, the FDA requires that makers of pasteurized liquid meals establish and maintain a Hazard Analysis and Critical address Points (HACCP) program to identify and address any hazards that could compromise product safety.

To protect customer safety, the European Union (EU) has set rules for the production, labelling, and marketing of pasteurised liquid foods. General guidelines for food safety are outlined in the EU's General Food Law Regulation, which also stipulates that all food sold must be secure.

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Chapter 6

Separation Technologies: Filtration and Centrifugation for Food and Dairy Processing



Ranjana Verma, Nilakshi Chauhan, Diksha Sharma, Kanchan Thakur, and Farhan M. Bhat

1 Introduction

The food and dairy industry is a vital sector that encompasses the production, processing, distribution, and consumption of various food products derived from agricultural commodities such as grains, fruits, vegetables, meat, and dairy. With a global population exceeding 7 billion and steadily growing, the demand for safe, nutritious, and diverse food products continues to escalate. In this context, separation technologies play a crucial role in ensuring the quality, safety, and efficiency of food and dairy processing operations. The food and dairy industry is a multifaceted sector with a vast array of products catering to diverse consumer preferences and dietary requirements. From staple foods like bread, rice, and pasta to indulgent treats such as chocolates, ice creams, and confectioneries, the industry offers a wide spectrum of choices to consumers worldwide. Similarly, the dairy segment encompasses various products ranging from milk and cheese to yogurt, butter, and ice cream, each with its unique manufacturing processes and market dynamics.

In the dominion of food and dairy processing, for ensuring the product quality, safety and efficiency, the application of separation technologies plays a pivotal role. These technologies are essential for extracting desired components, removing impurities, and achieving desired textures and consistencies in various food and dairy products.

Separation technologies refer to a diverse set of techniques and processes used to isolate, extract, purify, or concentrate specific components or substances from a mixture. These technologies are employed across various industries, including food and dairy processing, pharmaceuticals, chemicals, environmental remediation, and

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more. The primary objective of separation technologies is to achieve the desired separation of components based on their physical or chemical properties, such as size, density, solubility, or affinity.

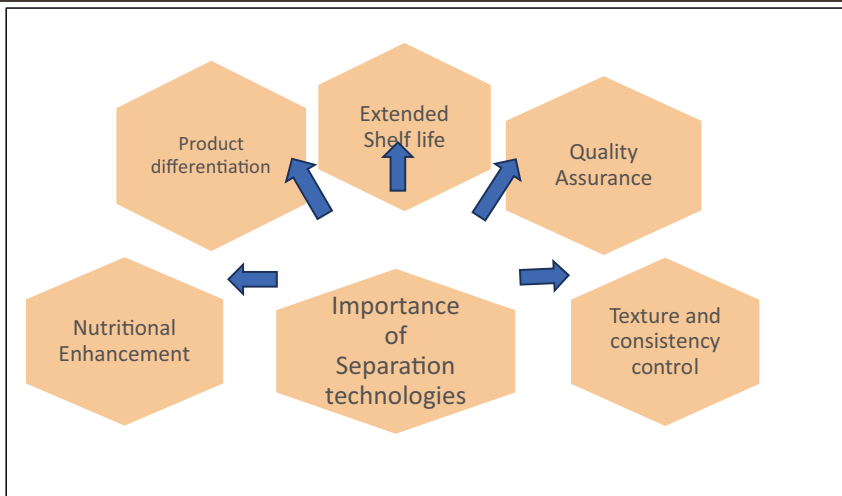
2 The Importance of Separation Technologies

1. **Quality Assurance:** Separation technologies enable the removal of unwanted components such as impurities, contaminants, and undesirable flavours, thereby ensuring the overall quality of the final product.
2. **Product Differentiation:** By selectively isolating specific components, separation technologies allow for the creation of specialized products with unique characteristics, flavours, and nutritional profiles, catering to diverse consumer preferences.
3. **Extended Shelf Life:** Separation processes such as filtration and centrifugation aid in the removal of microorganisms and enzymes that contribute to spoilage, thus enhancing the shelf stability of food and dairy products.
4. **Nutritional Enhancement:** Certain separation techniques facilitate the concentration of nutrients, vitamins, and minerals in food products, enhancing their nutritional value and contributing to consumer health and well-being.
5. **Texture and Consistency Control:** Separation technologies are instrumental in achieving desired textures and consistencies in food and dairy products, crucial for sensory appeal and consumer satisfaction (Table 6.1).

Table 6.1 Separation technologies commonly employed in food and dairy processing

S No	Technique employed	Principles	Widely used for
1	Filtration	Involves the passage of a liquid or slurry through a porous medium to separate suspended solids or particles from the liquid phase	Clarifying juices, removing particulates from milk, and purifying beverages.
2	Centrifugation	Utilizes centrifugal force to separate components of different densities in a liquid or suspension	Separation of cream from milk, clarification of fruit juices, and extraction of oils from seeds
3	Membrane separation	Involve the selective passage of components through semipermeable membranes based on size, charge, or solubility	Concentration, purification, and fractionation of proteins, fats, sugars, and other compounds in food and dairy processing.
4	Extraction	Involves separation of components from a solid or liquid matrix utilising solvents or supercritical fluids.	Extracting flavours, aromas, colours, and bioactive compounds from natural sources such as herbs, spices, and fruits
5	Distillation	Involves thermal separation process that exploits differences in the boiling points of components to separate them from a liquid mixture	Production of concentrated flavours, essences, and alcoholic beverages.

Separation technologies are indispensable in the food and dairy industry



3 Fundamental of Filtration and Centrifugation

Centrifugation and filtration stand as fundamental techniques in the realm of food processing, serving critical roles in the separation, clarification, and purification of various food components. These techniques are indispensable in the quest to produce high-quality food products that meet stringent standards of safety, purity, and consumer satisfaction.

3.1 Filtration

Principle of Filtration

Filtration is based on the principle of separating solid particles or impurities from liquid or gas components of food substances. This procedure involves passing the food mixture through a porous media or filter, which holds the solid particles while allowing the liquid or gas to pass through. The choice of filter medium depends on different factors like size of particles to be removed, the desired clarity of the final product, and the properties of the food substance (Liderfelt & Royce, 2018).

Key aspects of filtration in food and dairy processing include:

- **Particle Size Exclusion:** Filtration selectively traps particles based on their size, averting bigger particles from passing through the filter while allowing smaller molecules to flow through.
- **Adsorption and Depth Filtration:** In addition to size exclusion, filtration may involve particles adhering to the surface of the filter (adsorption) or being retained within the porous structure of the filter medium (depth filtration).
- **Filter Medium Selection:** The filter medium used is determined by criteria such as particle size, desired final product clarity, and the qualities of the food substance being processed.
- **Efficiency and Operating Conditions:** The efficiency of filtration is influenced by parameters such as the flow rate of the food mixture, the pressure or vacuum applied during filtration, and the characteristics of the filter medium.
- **Applications in Food and Dairy Processing:** Filtration is widely used in food and dairy processing for various applications, including clarifying fruit juices, removing sediment from dairy products, purifying oils and fats, and sterilizing liquids.

The effectiveness of filtration in food processing is determined by a variety of parameters, including the type of filter material employed, flow rate of the food mixtures, and the operating conditions, such as pressure or vacuum applied during filtration. The goal of filtration in food processing is to produce food products that meet quality standards by removing impurities, particulates, or contaminants from the liquid or gas components.

3.2 Centrifugation

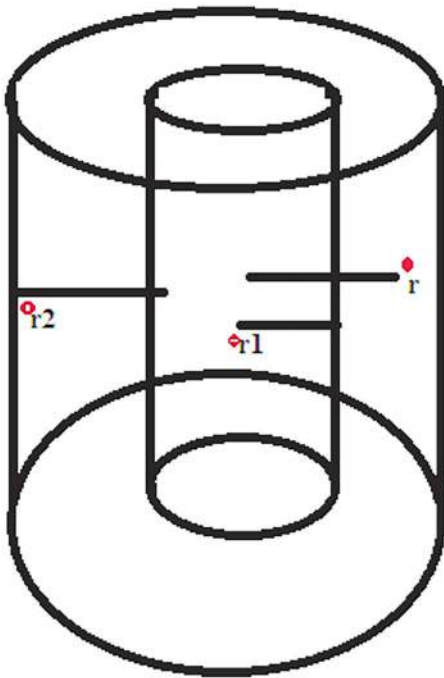
Principle of Centrifugation

The principle of centrifugation in food processing revolves around the separation of components within food mixtures based on differences in their densities. When a mixture is subjected to centrifugal force by spinning rapidly, denser particles tend to migrate outwards towards the periphery of the centrifuge while lighter particles remain closer to the center (Sood et al., 2023). Centrifugation is the accelerated separation based on centrifugal principle that is to separate heterogeneous mixtures differing in their phase densities. Centrifuges despite their costly maintenance in terms of initial investment as well as ongoing operating costs including energy usage, component wear and tear, and robust design against shear stress are finding widespread applications in dairy and food processing industries. The process of separation of cream and whey from curd in cheese making along with whole milk from skimmed milk is the most applied usage of centrifugation in dairy industries technically known by the name of Separators for centrifuges used for this purpose. Centrifugation is finding wide application in clarification process of Fruit juices and

oil processing by reducing the fines and suspended solids due to accelerated decantation. The speed centrifugation applied in bactofugation process is carried in clarifiers to remove bacterial cells and spores from chesses and fermented milk to extend their shelf life and sensory appeal.

Mechanism of Centrifugation in Dairy and Food Industries

The centrifugal force acting on any particle is determined by its density, rotational speed and radius. In case of emulsions, the forces exerted on each phase layer is being governed by liquid densities, pressure gradients between layers and rotational speed.



Consider a particle at a distance r from the centre of axis in rotational bowl of centrifuge; the radial speed will vary from distance r_1 representing central wall of rotating bowl to exterior body wall (r_2). Let ω be the radial velocity and ρ_s, ρ_t be the density of solid and liquid phase, assume the particle be spherical, then the terminal sinking velocity is being given as per stokes law as

$$u = \frac{dp^2 (\rho_s - \rho_t) \omega^2 r}{18\mu}$$

The radial velocity will be given by $u = \frac{dr}{dt} = \frac{dp^2 (\rho_s - \rho_t) \omega^2 r}{18\mu}$

The velocity of centrifugal separator u will increase with increasing distance from central axis

$$\text{Rearranging the above equation, } dt = \frac{dp^2 (\rho_s - \rho_t) \omega^2 r}{18\mu dr}$$

The residence time for retention will be find out by integrating dt along with radius from r_1 to r_2 as follows

$$\int dt = \int_{r_1}^{r_2} \frac{dp^2 (\rho_s - \rho_t) \omega^2 r}{18\mu dr}$$

This will give the expression of residence time as

$$t = \frac{dp^2 (\rho_s - \rho_t) \omega^2}{18\mu} \ln \frac{r_2}{r_1}$$

Thus the centrifugation used in any dairy and food processing will be determined by its geometry (r_1 and r_2) along with the speed of rotation ω .

Key aspects of centrifugation in food processing include:

- **Density Gradient:** Centrifugation takes advantage of variations in density among components in food mixtures. For instance, in milk processing, centrifugation separates cream from skim milk due to the lower density of cream.
- **Centrifugal Forces:** High-speed rotation of the centrifuge generates centrifugal force, which causes the denser particles to move outward and accumulate at the periphery, forming distinct layers or zones.
- **Separation Efficiency:** Centrifugation efficiency depends on factors such as the speed of rotation, the design of the centrifuge, and the properties of the mixture being processed. Optimal conditions are necessary to achieve effective separation without compromising the integrity of the components.
- **Versatile Applications:** Centrifugation is employed in various aspects of food processing, including the clarification of fruit juices, separation of solids from liquids, and concentration of liquids.
- **Diverse Centrifuge Types:** Different types of centrifuges, such as batch, continuous, and decanter centrifuges, are utilized based on specific processing requirements and the characteristics of the food mixture.

Types of Separation Equipment

Separation

Separation of components from complex mixtures is a crucial step in many industrial operations, particularly in the food and dairy industries. It has numerous applications in a variety of industries, including agricultural commodities, food production, development of health-promoting ingredients and high-value-added goods. The use of separation technology enables the recovery of vital components such as oil, protein, antioxidants, and flavours. The fundamental goal of separation operations, often known as “downstream processing,” is to use scientific and engineering concepts to successfully separate and purify diverse components in the food industry (Chang et al., 2008). Additionally, these processes are necessary for removing pollutants and impurities from food materials, resulting in safe and high-quality goods. Moreover, separation techniques play an important role in enhancing the overall efficiency and sustainability of the food and dairy industries. By selectively separating components, these processes enable better utilization of resources, reduction of waste, and optimization of production processes. As a result, separation technologies not only contribute to the creation of innovative food products but also uphold food safety standards and promote environmentally friendly practices (Shi et al., 2012).

Primary Separation Techniques Utilized in Food and Dairy Industry Operations

The process of separation, such as extraction, concentration, purification, and fractionation, are crucial in obtaining valuable end products from agricultural materials. These processes revolve around using variations in the physical and chemical properties of components inside mixes (Heldman et al., 1981). Common properties include particle or molecular size and shape, density, solubility, and electrostatic charge. It is not uncommon for multiple properties to be involved in a single operation of separation. This process is an essential component of value-added food processing, acting as a major unit activity. This science of separation encompasses various methods, including mechanical, equilibrium, and chromatographic approaches. By incorporating these processes, a wide range of high-quality products can be derived from agricultural sources (Herrero et al., 2004).

Different Mechanical Separation Processes

1. Centrifugation

Centrifugation is a technique that uses centrifugal force to separate immiscible liquids or solids from liquids. It entails rotating a settling tank at high speeds to substitute gravity with controlled centrifugal force. This approach is often employed in

solid-liquid or liquid-liquid separation processes that rely on density differences between components. In the food sector, it is frequently used to separate suspended particles or liquids from the fluid phase.

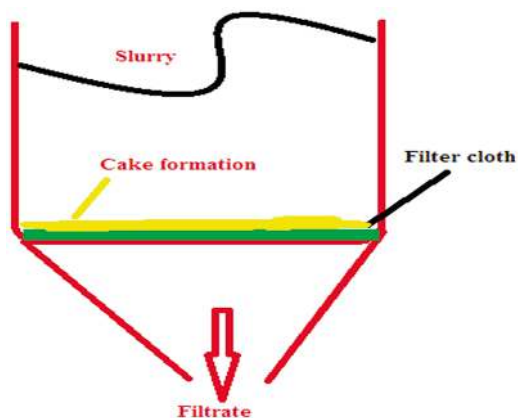
2. Filtration

The process of filtration involves passing a mixture through a porous material to separate solid particles or liquid droplets from the continuous phase. It is used in many stages of food production and biotechnology, including the refinement of edible oils, the clarification of syrups, juices, vinegar, wine, and beer, and the recovery of cells from fermentation broths. It can be classified as standard or unconventional. Conventional filtration uses coarse selectivity filtration media to separate solid, immiscible particles from liquid streams.

Mechanism of Filtration in Dairy and Food Industries

The process of filtration is mainly governed by the separation of solids from liquid and gas by passing through porous membrane. The capacity of any filtration process is being characterised by the volume of filtrate obtained per unit time as given by Darcy law

$$\text{Filtrate flow rate}(Q) = \frac{dv}{dt} = \frac{A \Delta P}{\mu R}$$



Where A represents the filter area, ΔP is the pressure gradient, μ is the viscosity and r depicts the resistance of bed to flow. The resistance to flow is being determined by the filter membrane and the cake formation on the membrane that impede the filtration rate

That is $R = R_c + R_f$

Therefore,

$$Q = \frac{dv}{dt} = \frac{A \Delta P}{\mu(Rc + Rf)}$$

The pressure gradient needed to increase filtration rate can be achieved by applying Centrifugal force, a vacuum at the filtrate side, or positive pressure at the feed side

$$\text{Rate of filtration} = \frac{\text{Driving force (Pressur drop across membrane)}}{\text{Resistance to flow}}$$

3. Membrane Separation

Nonconventional filtration procedures rely mainly on membrane separation. This technology makes use of membranes with regulated pore size and structure to maximise filtration area while minimising unit volume. Membrane separation procedures rely on the capacity of components to pass from the pores of a barrier. They are classed as microfiltration, nanofiltration, ultrafiltration, or reverse osmosis based on membrane's pore size.

4. Ion-Exchange and Electrodialysis

The two independent separation processes viz. Ion-exchange and electrodialysis rely on the molecular electrostatic charge. While they differ from centrifugation and filtration, these processes play a role in separation techniques in various fields.

(a) Ion-Exchange

Using solid ion-exchange medium charged molecules are preferentially extracted from one liquid phase and transmitted to another liquid phase in the ion-exchange process. The electrostatic attraction of opposing charges possessed by solutes along with ion exchanger forms the basis of this process. The separated species are recovered via desorption after the feed solution has been washed off, producing a pure solution. Ion exchange is extensively employed in many different industries, such as the dairy industry for the separation of proteins and amino acids, sugar production, and water treatment. The isolation and purification of enzymes, antibodies, electrolytic solutions and biochemical substances are other typical applications for it.

(b) Electrodialysis

Membranes based on ion-selection capability comprising bundles of ion-exchange resin, have applications in electrodialysis. This technique facilitates the interchange of ions between solutions as well as the separation of electrolytes and nonelectrolytes in a solution. Ions are separated across charged, ionically selective membranes via electrochemical separation, which makes use of an electrical potential gradient. Ionic species separation is accomplished in the food and biotechnology sectors by electrodialysis. It has been extensively utilized in the food industry

for a number of motives, including deionizing whey from dairy products, controlling pollution, and removing salt from brackish water.

5. Solid-Solid Separation

A common mechanised separation approach in the processing of separation facilities is solid/solid separation. Using this method, items are separated based on their particle size, which may differ from large feed units to molecules. Specific gravity, shape, electrostatic charge, and moisture content are among the parameters that can influence the separation process. To attain particle size uniformity screening with perforated beds—such as wire mesh or cloth screens—is frequently used. Grains, fruits, and vegetables are among the foods that are often classified and graded via screening. The food processors use a various separating tools, including flat bed and rotating fixed variable aperture screens, to separate solids.

6. Sedimentation

The mechanism, that occurs when solids pass into liquids as a result of gravity is called sedimentation. It is a lengthy procedure that is frequently applied in operations that treat waste water and water.

7. Magnetic Separation

Magnetic separation makes use of how individual particles behave when subjected to magnetic forces. Ferromagnetic materials are drawn along magnetic force lines from low to high field intensifying regions.

8. Equilibration Separation Processes

Equilibration separation procedures are often seen in the food industry that include a balance of solid and liquid phases.

(a) Adsorption

Adsorption is the means through which a material builds up on a solid's surface. Through this technique, desirable ingredients are extracted and purified from an amalgamation of liquids. Adsorption is a widely applied technique for isolation of antibiotics, enzymes and elimination of pigmented compounds. Low-quantity pollutants are generally removed from industrial streams by means of liquid-phase adsorption.

(b) Evaporation

The technique of removal of water or any other solvent from a solution with the intent to raise its concentration referred to as evaporation. The efficiency of this technique is determined on the material's heat sensitivity. Vacuum conditions allow lowering boiling temperatures. Commercial evaporators typically run between 40 and 90 °C, reducing the amount of time spent in the vaporising operations. It additionally makes it feasible to concentrate volatile flavoring compounds and aromatic

solutions, as well as heat-sensitive liquid meals. Liquid usually represents the end product of an evaporation operation.

Crystallization

Crystallisation procedures are used to separate liquids from solids. This process involves developing crystal nuclei to the desired size from a supersaturated solution, separating components and generating solid particles with specific shape and size. In isolating biological macromolecules, crystallization is frequently used as a high-resolution, finishing step. Cooling or evaporation can start the process, leading to in a highly saturated solution wherein crystal nuclei can form. Sometimes seeding the solution with solute crystals is required. Commercial food manufacturing use both batch and continuous crystallisation techniques.

Drying or Dehydration (Dewatering)

The process of dewatering yields solid products by removing water from solids, slurries, and solutions.

Separators or Clarifiers (Centrifugation)

With the aid of size, shape, and density, a centrifuge can separate particles, suspensions, or macromolecules from liquids. This tactic subjected distributed systems to artificial gravitational fields, or centrifugal force. Immiscible liquids can be separated via centrifugation. There are mainly two types of commercial centrifugation: (1) sedimenting and (2) filtration. The sedimenting centrifuge separates the components of the mixture according to variations in specific gravity, or density. In fact, depending on the specific gravity of the components, rotating materials around a fixed axis can produce a centrifugal force up to 10,000 times stronger than gravity. Particles with greater density are forced towards the edge of the centrifuge bowl because they require more force to remain near the rotating axis than do lighter particles.

According to Kessler (2002), this centrifuge can separate combinations of solids and liquids with gravitational differences as low as 100 kg/m^3 . In contrast to sedimentation centrifuges, filtration centrifuges have perforated bowls and are only intended to separate mixes of solid and liquid materials. The liquid phase is able to pass through the porous wall holding the solids thanks to this kind of centrifugal separation. With the filtering centrifuge, soluble solids can be separated independently of density variations, in contrast to the sedimenting centrifuge. But particles larger than 10 microns are needed for filtration (Brennan et al., 2006). Therefore,

solid-liquid and liquid-liquid separations can be accomplished through centrifugation. This can be seen in the processing of dairy products, where cream, or milk fat, can be simultaneously extracted and clarified. Juices, oils, and beers can all be processed using centrifugal clarifying.

Recently, a process called bacto-fugation—high-speed centrifugation—has been utilized to reduce the number of bacteria present in raw milk, allowing for the production of milk with an extended shelf life (Chandan & Kilara, 2013).

Different Centrifugal Equipment's

1. Liquid-Liquid Centrifugal Separators

- (a) **Tubular Bowl Centrifuge:** It is a type of centrifuge in which a tall, narrow bowl rotates vertically within a stationary casing. The bowl's diameter ranges from 10 to 15 cm, with a length-to-diameter ratio of 4–8. The feed enters the bowl from the bottom through a fixed pipe and is accelerated by vanes or baffles to match the bowl's speed. The light and dense phases pass through a weir system at the bowl's top and into stationary discharge covers. Depending on the task, a gravity disc of the right size is attached to the dense phase exit. The bowl's spinning speed varies between 15,000 rpm for larger models and 50,000 rpm for smaller ones.
- (b) **Disc Bowl Centrifuge:** It is another kind that has a wide, shallow bowl that rotates within a stationary frame. The bowl normally has a cylindrical body, a conical top, and a diameter ranging from 20 cm to 100 cm. Inside the bowl, there is a stack of truncated metal cones known as discs, which spin with the bowl. The spaces between the discs are typically 50–130 metres wide. These discs contain matching perforations, which form vertical channels within the stack. The feed enters the bowl at the bottom, then travels via these channels into the spaces between the discs. Centrifugal force causes the dense phase to slide along the underside of the discs towards the bowl wall, while the light phase flows over the top of the discs towards the centre of rotation. As a result, each pair of discs serves as a miniature centrifuge. In disc bowl machines, the distance that liquid droplets must travel is quite short, and there is significant shearing at the interface between the two streams of liquid, which contributes to emulsion breakup. The phases exit the bowl via a weir system with a gravity disc and flow to stationary discharge covers (Pouliot et al., 2014).

2. Solid-Liquid Centrifugal Separators

Within specific constraints, tubular bowl and disc bowl centrifuges can be used to separate solids and liquids respectively. In this particular task, the dense phase outlet is blocked, and the clear liquid exits the bowl via the middle light phase outlet. The solid particles separate from the liquid and accumulate as a

deposit on the bowl's wall. As a result, these centrifuges operate on a batch principle and must be periodically stopped and cleaned. Tubular bowl machines have a relatively small solids capacity, making them suitable for feeds with low solids content (less than 0.5%). However, due to their high operating speeds, they are particularly effective in removing very fine solids. On the other hand, disc bowl machines have a capacity for solids up to five times greater than tubular bowl centrifuges. Nonetheless, to minimize cleaning frequency, they are primarily used for feeds with relatively low solids content (less than 1.0%).

- (a) **Solid Bowl Centrifuge (Clarifier):** It is used to separate solid particles that settle relatively easily. It has a conical bowl without perforations or filter media. The solids accumulate on the inside of the bowl wall, while the clear liquid overflows the top rim into the outer casing. Periodically, the feed is stopped, and the solids are removed through an opening at the bottom of the bowl using a knife or plow. This type of clarifier can handle feeds with solids content up to 2.0%.
- (b) **Nozzle-discharge Centrifuge:** Includes arrangements for continuous discharge of both solids (sludge) and clear liquid. Numerous designs exist, but one example is a disc bowl machine with two to twenty-four nozzles placed around the bowl. The nozzle sizes range from 0.75 to 2.00 mm, depending on the solid particle size in the feed. Approximately 5–50% of the feed is continuously discharged as a slurry through these nozzles, and the slurry can contain up to 25% volume/volume solids. By recycling some of the slurry, the solids content can be increased, with up to 75% of the slurry being recycled and the solids content reaching up to 40%.
- (c) **Self-opening Centrifuge:** It operates by periodically opening ports to discharge the slurry under pressures of up to 3500 kN m^{-2} . The timing of port openings may be controlled by timers, and self-triggering ports are also available. These centrifuges monitor the solids buildup within the bowl and generate a signal to trigger port openings. The slurry discharged from these self-opening centrifuges usually has a higher solids content compared to that continuously discharged through open nozzles.
- (d) **Decanting Centrifuge:** It is ideal for meals with a high solids content. The device features a solid bowl with a screw conveyor that rotates on a horizontal axis. Both the bowl and the conveyor rotate in the same direction but at different speeds. The feed enters the bowl through the conveyor axis, where solids are flung against the bowl wall and transported to one end, up a conical section, before being ejected. The clear liquid is released through an adjustable weir at the opposite end of the bowl. These machines can process feeds containing up to 90% (v/v) of relatively large solid particles. Particles $2 \text{ }\mu\text{m}$ or smaller in diameter are typically not removed from the liquid. If needed, the liquid output from decanting centrifuges can be further filtered using tubular or disc bowl centrifuges.

4 Filtration Techniques in Food and Dairy Processing (Table 6.2)

FILTRATION TECHNIQUES IN FOOD AND DAIRY PROCESSING

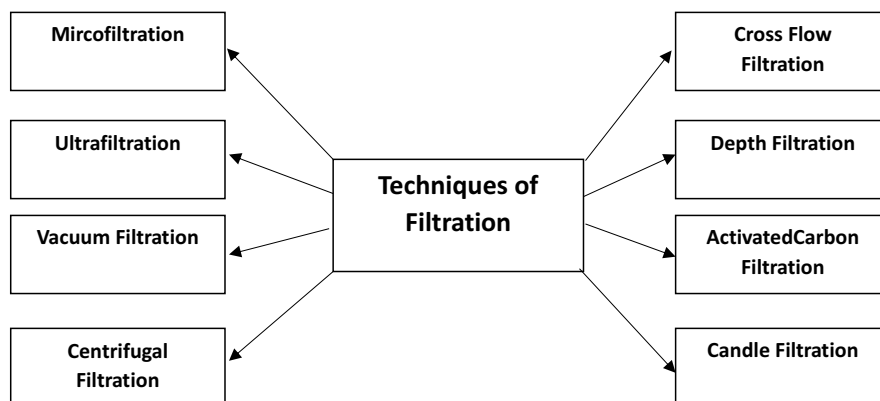


Table 6.2 Different filtration techniques along with principles employed in food processing sectors

Filtration techniques	Filter	Principle
Microfiltration	Membrane	Size exclusion: Uses membranes with pores (0.1–10 μm) to separate particles from liquids.
Ultra filtration	Membrane	Size exclusion: Employs membranes with smaller pores (0.001–0.1 μm) to separate macromolecules.
Vacuum filtration	Filter paper, Büchner funnel, vacuum pump	Pressure difference: Utilizes negative pressure to draw liquid through a filter medium.
Centrifugal filtration	Centrifuge	Centrifugal force: Separates particles from liquids by spinning them at high speeds.
Cross flow filtration	Filter membrane	Tangential flow: Involves continuous flow parallel to the membrane surface to prevent clogging.
Depth filtration	Filter medium (e.g., diatomaceous earth, activated carbon)	Depth filtration: Captures particles throughout the depth of the filter medium.
Activated carbon filtration	Activated carbon medium	Adsorption: Utilizes activated carbon to trap impurities and contaminants onto its surface.
Candle filtration	Candle filter	Depth filtration: Uses cylindrical filter elements to capture particles and impurities.

4.1 Microfiltration

Microfiltration (MF) is a filtration process widely used in food and dairy processing for separating suspended solids, bacteria, and other microorganisms from liquids. It employs membranes with pore sizes typically ranging from 0.1 to 10 micrometers (Anis et al., 2019). It primarily uses a sieving mechanism, in which particles bigger than the pore size are trapped on the membrane surface or within the membrane matrix, while smaller particles and liquids flow through (Fig. 6.1).

Principles of Microfiltration

- **Size Exclusion:** Microfiltration membrane pore diameters typically range from 0.1 to 10 micrometres. These holes are large enough to pass solvents and tiny solutes but small enough to keep particles, germs, and microbes suspended in the liquid.
- **Sieving Mechanism:** Microfiltration works primarily through a sieving process. As the liquid passes across the membrane, particles bigger than the pore size are trapped on the membrane surface or within the membrane matrix, whereas smaller particles and solvents pass through (Baker & Sirkar, 2017).

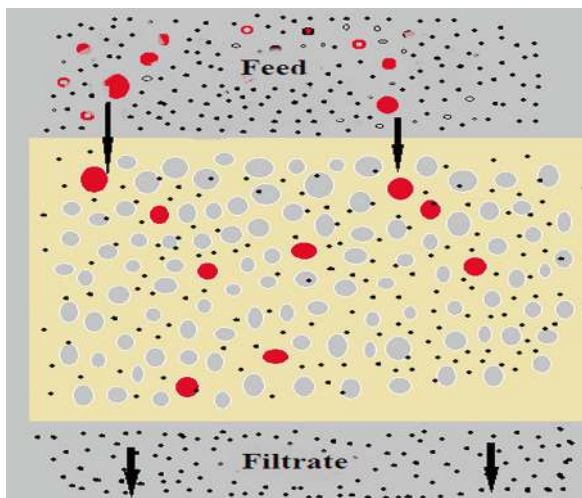


Fig. 6.1 Sieve mechanism for filtration of particles

Components of Microfiltration Systems

Microfiltration systems consist of microfiltration membranes made from materials like polymers or ceramics, a feed system, pressure control mechanisms, and retentate/permeate collection systems (Ferreira et al., 2010).

1. **Microfiltration Membranes:** These membranes are usually made of materials like polymeric films or ceramics. They are engineered to have precise pore sizes and structural integrity suitable for specific applications in food and dairy processing.
2. **Feed System:** The liquid mixture to be filtered is introduced into the microfiltration system through a feed system, which may include pumps, pipes, and valves.
3. **Pressure Control Mechanism:** Microfiltration systems may operate under different pressure conditions, including gravity-driven flow, pressure-driven flow, or a combination of both. Pressure control mechanisms ensure optimal filtration rates and prevent membrane damage.
4. **Retentate and Permeate Collection System:** The retentate, containing concentrated particles and microorganisms retained by the membrane, is collected separately from the permeate, which consists of the filtered liquid passing through the membrane.

Mechanism of Microfiltration

- Particles bigger than the pore size are physically blocked and held on the microfiltration membrane's surface or matrix when the liquid mixture runs through.
- The retained particles form a filter cake layer on the membrane surface, which enhances filtration efficiency and prolongs the membrane's lifespan.
- Meanwhile, the filtered liquid, known as permeate, passes through the membrane, leaving behind the particles and microorganisms (Tiwari & Abughannam, 2010).

Applications of Ultrafiltration in Food and Dairy Processing

1. **Protein Concentration:** Ultrafiltration is used to concentrate proteins, enzymes, and peptides from milk, whey, and other dairy products, allowing for the production of high-protein ingredients and supplements (Pabby et al., 2008).
2. **Fractionation of Milk Components:** Ultrafiltration separates milk components such as casein and whey proteins, lactose, and minerals, enabling the production of specialized dairy products with customized compositions and functionalities (Pabby et al., 2008).
3. **Removal of Colloids and Microorganisms:** Ultrafiltration removes colloidal particles, bacteria, and microorganisms from milk, fruit juices, and beverages, enhancing product shelf life and ensuring food safety (Pabby et al., 2008).

4. **Wastewater Treatment:** Ultrafiltration is employed in wastewater treatment processes to remove suspended solids, organic matter, and contaminants from process streams, enabling the recovery and reuse of water resources and minimizing environmental impact (Pabby et al., [2008](#)).

4.2 Vacuum Filtration

Vacuum filtration is a widely used technique in food and dairy processing industries to separate solids from liquids using reduced pressure. It operates based on the principle of pressure difference, where a vacuum is applied to one side of a filter medium to draw the liquid through while retaining the solids. Vacuum filtration operates by applying negative pressure to draw the liquid through a filter medium, typically a filter paper or membrane, while retaining solid particles (Karvonen et al., [2018](#)).

Principles of Vacuum Filtration

- **Pressure Difference:** Vacuum filtration relies on the creation of a pressure difference between the upstream and downstream sides of a filter medium. By providing vacuum pressure to the downstream side, the liquid is driven through the filter medium while the particles remain.
- **Size Exclusion:** The filter material used in vacuum filtering typically has pore diameters that are tiny enough to hold solid particles while large enough to enable liquid passage.

Components of Vacuum Filtration Systems

In vacuum filtration setups, each component plays a crucial role in facilitating the filtration process. Here's an explanation of each component:

1. **Vacuum Pump:** The vacuum pump is the heart of the vacuum filtration setup. It creates a negative pressure or vacuum within the system, which allows the liquid to be drawn through the filter paper and funnel while leaving the solid particles behind. The vacuum pump can be either a rotary vane pump, diaphragm pump, or other types suitable for generating the necessary vacuum pressure.
2. **Filter Flask:** The filter flask, also known as the vacuum flask, is a thick-walled glass container designed to withstand the negative pressure generated by the vacuum pump. It holds the liquid mixture that needs to be filtered. The top of the filter flask is typically equipped with a ground glass joint to securely connect it to the Büchner funnel.
3. **Büchner Funnel:** The Büchner funnel is a specially designed funnel used in vacuum filtration. It is made of porcelain, glass, or plastic and has a perforated

plate or fritted glass disc at the bottom. The Büchner funnel allows the liquid to pass through while retaining the solid particles on top of the filter paper.

4. **Filter Paper:** Filter paper is placed inside the Büchner funnel to serve as the actual filtration medium. It acts as a barrier that allows the liquid to pass through while trapping solid particles, precipitates, or contaminants. Filter papers come in various pore sizes and materials, such as cellulose, glass microfiber, or qualitative and quantitative grades, depending on the filtration requirements.
5. **Receiving Flask:** The receiving flask is placed below the Büchner funnel to collect the filtered liquid, also known as the filtrate. It is connected to the Büchner funnel via a vacuum-tight hose or tubing. The receiving flask should have sufficient capacity to hold the entire volume of the filtrate.
6. **Rubber Stopper and Tubing:** A rubber stopper is used to seal the connection between the filter flask and the vacuum pump. Tubing or hoses are used to connect the vacuum pump to the filter flask and provide a pathway for the air and liquid to flow out of the system.

Mechanism of Vacuum Filtration

- The liquid mixture to be filtered is poured into the filtration flask or funnel, which is placed on top of the filter assembly.
- The vacuum pump is turned on, creating a pressure difference between the top and bottom of the filter medium.
- The pressure gradient forces liquid through the filter media, leaving solid particles on the surface or in the matrix.
- The filtered liquid, known as the filtrate, collects in the filtration flask or funnel, while the solids accumulate on the filter medium as a filter cake.

Applications of Vacuum Filtration in Food and Dairy Processing

1. **Clarification of Fruit Juices and Beverages:** Vacuum filtration is used to remove suspended solids, pulp, and particles from fruit juices, wines, beers, and other beverages, resulting in clearer and visually appealing products.
2. **Separation of Curds and Whey:** In dairy processing, vacuum filtration is employed to separate curds and whey during cheese production. The whey, containing soluble proteins and lactose, is drawn through the filter medium, leaving behind the curds.
3. **Removal of Residual Solids:** Vacuum filtration helps in the removal of residual solids, sediment, and impurities from liquid dairy products like milk and cream, ensuring product quality and extending shelf life.
4. **Filtration of Clarifying Agents:** Vacuum filtration is used to filter clarifying agents and fining agents used in the clarification and stabilization of beverages and liquid food products.

4.3 *Centrifugal Filtration*

Centrifugal filtration uses centrifugal force to separate particles from liquids. This method is based on the sedimentation principle, in which solid particles are driven to the bottom of a container by centrifugal force while liquid remains above (Pouliot et al., 2014).

Principles of Centrifugal Filtration

- **Centrifugal Force:** Centrifugal force is generated by spinning a container containing a mixture of solids and liquids at high speeds. This force causes the denser solid particles to move outward towards the walls of the container while the lighter liquid remains in the center.
- **Density Difference:** The separation is based on the difference in density between the solid particles and the liquid. Heavier particles experience a greater centrifugal force and settle at the bottom of the container.

Components of Centrifugal Filtration Systems

Centrifugal filtration systems consist of centrifuges equipped with appropriate rotors and tubes for separating solid-liquid mixtures.

1. **Centrifuge:** The centrifuge is the primary component of a centrifugal filtration system. It consists of a rotating drum or bowl where the mixture to be separated is placed. The centrifuge rotates at high speeds, generating centrifugal force.
2. **Rotor:** The rotor is the part of the centrifuge that spins at high speeds and holds the containers or holders containing the mixture. It is designed to withstand the high centrifugal forces generated during operation.
3. **Containers or Holders:** These are vessels or holders that hold the mixture to be separated. They are placed in the rotor and subjected to centrifugal forces during operation.
4. **Sealing Mechanism:** Centrifuges often feature sealing mechanisms to prevent leakage of the liquid during centrifugation. This ensures efficient separation without loss of liquid or contamination.

Mechanism of Centrifugal Filtration

- The mixture to be separated is placed into containers or holders, which are then loaded into the rotor of the centrifuge.
- The centrifuge is started, and the rotor begins to spin rapidly, generating centrifugal force.

- The influence of centrifugal force allows solid particles in the mixture to move outward and settle at the bottom of the containers or holders.
- The liquid, which is lighter, remains in the center and can be decanted or collected separately.

Applications of Centrifugal Filtration in Food and Dairy Processing

1. **Clarification of Fruit Juices and Beverages:** Centrifugal filtration is used to remove pulp, solids, and suspended particles from fruit juices and beverages, producing clear and visually appealing products.
2. **Separation of Milk and Cream:** In dairy processing, centrifugal filtration is employed to separate milk and cream. The denser cream is forced to the outer walls of the centrifuge, while the lighter milk remains in the center.
3. **Separation of Whey and Curds:** Centrifugal filtration is used during cheese production to separate whey and curds. Whey, containing soluble proteins and lactose, is separated from the curds under centrifugal force.
4. **Clarification of Liquid Ingredients:** Centrifugal filtration is utilized to clarify liquid ingredients such as stocks, broths, and sauces by removing suspended solids and impurities.

4.4 Cross Flow Filtration

Crossflow filtration involves the continuous flow of liquid parallel to the membrane surface. A portion of the liquid passes through the membrane, while the remaining liquid and particles flow tangentially along the membrane surface, preventing clogging (Charcosset, [2021](#)).

Principles of Cross Flow Filtration

- **Tangential Flow:** Unlike conventional filtration methods where the liquid flows perpendicular to the filter membrane (dead-end filtration), crossflow filtration involves the liquid flowing parallel to the membrane surface. This tangential flow reduces the buildup of particles on the membrane surface, leading to more efficient filtration.
- **Hydrodynamic Shear:** The tangential flow creates hydrodynamic shear forces along the membrane surface. These shear forces help prevent the accumulation of particles and contaminants on the membrane, maintaining its efficiency over time.

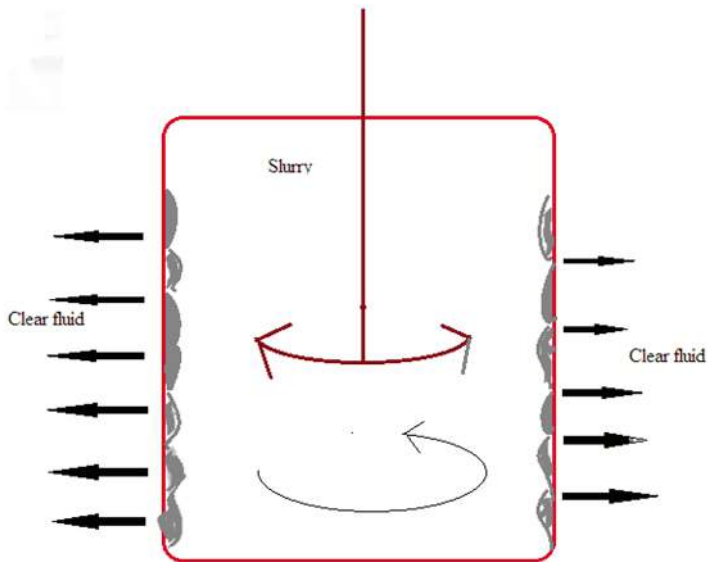


Fig. 6.2 Principle of filtration centrifuge

- **Membrane Pore Size:** The filter membrane used in cross flow filtration has selective pore sizes that allow the passage of liquid while retaining particles, microorganisms, and contaminants based on their size and molecular weight (Fig. 6.2).

Components of Cross Flow Filtration Systems

Crossflow filtration systems include filter membrane, pressure gauges, and controls for regulating flow rates and pressures

1. **Filter Membrane:** The filter membrane is a crucial component of cross flow filtration systems. It is made of materials such as polymeric membranes (e.g., polyethersulfone, polyvinylidene fluoride) or ceramic membranes. The membrane's pore size and material composition determine its filtration properties and compatibility with different liquid mixtures.
2. **Pressure Source:** Cross flow filtration systems require a pressure source to drive the liquid through the membrane. This pressure can be generated using a pump or other pressure-generating equipment.
3. **Flow Channels:** Flow channels are designed to direct the liquid across the membrane surface in a tangential direction. These channels help optimize the flow pattern and minimize fouling of the membrane.

4. **Recovery System:** In some cross flow filtration setups, a recovery system may be incorporated to recirculate the permeate (filtrate) back into the feed stream, increasing overall efficiency and reducing waste.

Mechanism of Cross Flow Filtration

- The liquid mixture is pumped into the filtration system under pressure.
- The liquid flows tangentially across the surface of the filter membrane.
- As the liquid passes through the membrane, particles, microorganisms, and contaminants bigger than its pore size are retained on the membrane surface.
- The purified liquid, known as permeate or filtrate, passes through the membrane and is collected for further processing or disposal.
- The retained particles and contaminants, known as the concentrate or retentate, are periodically removed from the membrane surface to prevent fouling and maintain filtration efficiency.

Applications of Cross Flow Filtration in Food and Dairy Processing

1. **Clarification of Fruit Juices and Beverages:** Cross flow filtration is used to remove suspended solids, pulp, and microorganisms from fruit juices and beverages, resulting in clear and visually appealing products.
2. **Concentration of Dairy Products:** Cross flow filtration is employed to concentrate dairy products such as milk, whey, and cheese brine by removing water content while retaining valuable components.
3. **Protein Separation:** Cross flow filtration is used to separate proteins from liquid mixtures in dairy processing, allowing for the production of protein isolates and concentrates.
4. **Wastewater Treatment:** Cross flow filtration is utilized in wastewater treatment processes to remove suspended solids, contaminants, and microorganisms from effluent streams, resulting in cleaner water for discharge or reuse.

4.5 Depth Filtration

Depth filtration is a widely used technique in food and dairy processing for the separation and clarification of liquids containing suspended solids or particulate matter. This method involves passing the liquid through a porous medium, where the particles are retained within the depth of the medium rather than just on the surface. It relies on the depth of the filter medium to capture particles throughout its structure. It traps particles on the surface and inside the filter media. (Sampath et al., 2014).

Principles of Depth Filtration

- **Porous Medium:** Depth filtration employs a porous medium such as filter aids, cellulose fibers, diatomaceous earth, or activated carbon. These materials have irregular pore structures that enable the entrapment and retention of particles throughout their depth.
- **Size Exclusion:** Particles are captured within the porous structure of the filter medium based on their size, shape, and surface characteristics. Larger particles are typically trapped near the surface, while smaller particles penetrate deeper into the filter medium before being retained.
- **Mechanical Filtration:** Depth filtration primarily operates through mechanical filtration mechanisms, where particles are physically trapped within the intricate network of the filter medium. The tortuous pathways and interstitial spaces within the medium create numerous opportunities for particle entrapment.

Components of Depth Filtration Systems

1. **Filter Medium:** The filter medium is the core component of depth filtration systems. It can be composed of various materials, including cellulose fibers, diatomaceous earth (DE), perlite, activated carbon, or synthetic materials. The filter medium used is determined by the individual application and filtration performance required.
2. **Filter Housing:** Depth filtration systems consist of a housing or vessel that holds the filter medium in place and directs the flow of liquid through the filter. The housing is designed to withstand the pressure differential across the filter and maintain the integrity of the filtration process.
3. **Support Structure:** Some depth filtration systems may include a support structure to reinforce the filter medium and prevent collapse or deformation during operation. This structure helps maintain the integrity of the filter bed and ensures consistent filtration performance.

Mechanism of Depth Filtration

- The liquid mixture containing suspended solids or particulate matter is introduced into the depth filtration system.
- The filter medium captures and retains particles as the liquid runs through its porous structure.
- Filter medium depth allows the accumulation of particles throughout its entire volume, resulting in efficient particle removal.
- The filter collects clean filtrate for processing or storage.

Applications of Depth Filtration in Food and Dairy Processing

1. **Clarification of Beverages:** Depth filtration is used to clarify beverages such as beer, wine, fruit juices, and soft drinks by removing suspended solids, yeast, and other particulate matter.
2. **Clarification of Dairy Products:** In dairy processing, depth filtration is employed to clarify milk, cream, whey, and cheese brine, resulting in products with improved clarity and shelf stability.
3. **Removal of Impurities:** Depth filtration is utilized to remove impurities, off-flavours, and odors from food and dairy products, enhancing their quality and sensory characteristics.
4. **Wastewater Treatment:** Depth filtration is applied in wastewater treatment processes within food and dairy processing facilities to remove suspended solids, organic matter, and contaminants from effluent streams, facilitating compliance with environmental regulations

4.6 Activated Carbon Filtration

Activated carbon filtration is a widely used technique in food and dairy processing for the removal of impurities, off-flavours, odours, and contaminants from liquids and gases. This approach uses activated carbon, a highly porous material with a huge surface area, to absorb and trap undesirable chemicals. Impurities and pollutants are absorbed onto the surface of activated carbon particles during the filtration process. The porous nature of activated carbon offers a wide surface area for adsorption (Tadda et al., 2016).

Principles of Activated Carbon Filtration

- **Activated Carbon:** Activated carbon, or activated charcoal, is a type of carbon that has been treated into a highly porous structure with a large surface area (Ioannis & Leivadara, 2014). The activation process involves treating carbonaceous materials such as coal, wood, or coconut shells with steam or chemicals at high temperatures, which creates a network of pores and increases the surface area available for adsorption (Miltz & Pikaev, 2006).
- **Adsorption:** The mechanism of activated carbon filtration is adsorption, where molecules of impurities and pollutants cling to the surface of the activated carbon particles through physical and chemical interactions (Inamuddin et al., 2020). The porous structure of activated carbon provides numerous binding sites for molecules to attach, effectively removing them from the liquid or gas stream.

Components of Activated Carbon Filtration Systems

Activated carbon filtration systems consist of activated carbon beds or cartridges contained in filter housings.

1. **Activated Carbon Medium:** The activated carbon medium is the central component of the filtration system. It is typically housed in a container or filter vessel and can be in the form of granules, pellets, powder, or a packed bed. The choice of activated carbon type and particle size depends on the specific application and targeted contaminants (Amin, [2019](#)).
2. **Filter Housing:** The filter housing holds the activated carbon medium in place and directs the flow of liquid or gas through the filtration system. It is designed to withstand the pressure and flow rate of the process stream and may include inlet and outlet connections for easy installation and operation.

Mechanism of Activated Carbon Filtration

- The liquid or gas containing impurities, off-flavours, or contaminants is passed through the activated carbon medium.
- As the stream flows through the porous structure of the activated carbon, molecules of impurities and contaminants are adsorbed onto the surface of the carbon particles.
- The activated carbon effectively traps and immobilizes the impurities, preventing them from passing through the filtration system.
- The purified liquid or gas, free from unwanted substances, exits the filtration system for further processing or use (Tadda et al., [2016](#)).

Applications of Activated Carbon Filtration in Food and Dairy Processing

1. **Removal of Off-Flavours and Odors:** Activated carbon filtration is used to remove off-flavours and odors from food and beverage products, including water, fruit juices, beer, and wine, enhancing their taste and aroma.
2. **De-chlorination and Decolorization:** Activated carbon is effective in removing chlorine, chloramines, and colorants from water and liquid food products, improving their quality and appearance.
3. **Purification of Syrups and Sugars:** Activated carbon filtration is employed in the purification of syrups, sugars, and sweeteners by removing impurities, pigments, and organic contaminants, ensuring product clarity and purity.
4. **Decontamination of Dairy Products:** In dairy processing, activated carbon filtration is utilized to remove unwanted compounds, such as antibiotics, pesticides, and mycotoxins, from milk, cheese, and yogurt, ensuring product safety and compliance with regulatory standards.

4.7 *Candle Filtration*

Candle filtration is a type of depth filtration method used in food and dairy processing industries to separate suspended solids and impurities from liquid streams. It employs cylindrical filter elements known as candle filters to effectively remove particles and contaminants from liquids such as juices, syrups, oils, and dairy products. Candle filtration utilizes cylindrical filter elements, often made of porous ceramics, through which the liquid passes from the outside to the inside. Particles remain on the outside surface of the candles (Sutherland & Chase, 2011).

Principle of Candle Filtration

- **Depth Filtration:** Candle filtration operates on the principle of depth filtration, where the liquid passes through a porous filter medium consisting of multiple layers. As the liquid flows through the depth of the filter, suspended solids, particles, and impurities are trapped within the filter media, allowing only the clarified liquid to pass through.
- **Physical Sieving and Adsorption:** The filter media in candle filtration acts as a sieve, physically capturing particles larger than the pore size of the media. Additionally, the filter media may have adsorptive properties, where certain contaminants are adsorbed onto the surface of the filter material, further enhancing the filtration efficiency.

Components of Candle Filtration Systems

Candle filtration systems include filter housings containing multiple candle filters, a feed pump, and valves for operation and maintenance

1. **Candle Filters:** Candle filters are the primary components of the filtration system. These cylindrical filter elements consist of porous filter media, typically made of materials such as cellulose, diatomaceous earth, or synthetic fibers. The filter candles are arranged vertically within a filter housing or vessel.
2. **Filter Housing:** The filter housing or vessel provides support and containment for the candle filters. It is designed to withstand the pressure and flow rate of the liquid stream during filtration. The housing may feature inlet and outlet connections, pressure gauges, and valves for efficient operation and maintenance.

Mechanism of Candle Filtration

- The liquid containing suspended solids and impurities is introduced into the filtration system.
- The liquid passes through the candle filters, where suspended solids and particles are captured within the porous filter media.

- As the liquid flows through the depth of the filter media, the particles become trapped, forming a filter cake on the candle surface.
- The clarified liquid, free from contaminants, emerges from the outlet of the filtration system.
- Periodically, the filter cake is removed from the surface of the candle filters through backwashing or cleaning procedures to maintain filtration efficiency.

Applications of Candle Filtration in Food and Dairy Processing

1. **Clarification of Fruit Juices and Syrups:** Candle filtration is used to clarify fruit juices, syrups, and concentrates by removing pulp, sediment, and suspended solids, resulting in clear and visually appealing products (Anderson & Strutt, 2000).
2. **Filtration of Edible Oils and Fats:** In the edible oil industry, candle filtration is employed to remove impurities, debris, and particulate matter from vegetable oils and fats, ensuring product quality and purity (Anderson & Strutt, 2000).
3. **Dairy Product Filtration:** Candle filtration is utilized in dairy processing for the clarification of milk, whey, and cheese brine, removing bacteria, proteins, and other contaminants to improve product shelf life and stability (Anderson & Strutt, 2000).
4. **Wastewater Treatment:** Candle filtration systems are also used for wastewater treatment and effluent clarification in food processing plants, helping to reduce environmental impact and comply with regulatory standards (Anderson & Strutt, 2000).

Centrifugation in Food and Dairy Processing

Application of Centrifugation in Food and Dairy Processing

1. Milk Products

In the sector of dairy processing, the centrifugation technique is frequently used to separate milk into cream and/or skim milk, and one of the most common equipment used for the separation of cream is disc bowl centrifuge. Milk is heated to **40–50 °C** before separation to reduce viscosity and increase the density difference between the fat containing and hydrophilic phases. The fat percentage of skim milk is decreased to less than **0.06–0.04%** using this procedure. Despite being a continuous operation, insoluble materials such as particulates of dirt, micelles of casein, and microbes/and microorganisms accumulate as filth in the centrifuge bowl and need to be cleaned frequently. As a substitute, self-opening or nozzle centrifuges with outputs for effluent, cream, and skimmed milk can be utilized. Centrifugation is another method that can be used to extract fat from whey and buttermilk (Leung, 2020).

2. Edible Oil Refining

Degumming is the process of treating crude oil with water, diluted acid, or alkali in the early stages of oil refining in order to eliminate phosphatides and mucilaginous particles. Through nozzle or self-opening centrifuges, the gums are separated after all of these procedures. If acid degumming occurs, centrifugation can be used to remove the gummed oil after washing it with hot water. After degumming, sodium hydroxide is used to neutralize the free fatty acids, phosphates, and particular pigments. This creates soap stock, which is further centrifuged to separate it from oil. This process is used for extracting the oil once it has been neutralized and cleaned with boiling water.

3. Beer Production

In various stages of the brewing process, centrifugation can be employed as a form of filtration. Self-opening centrifuges can be used to separate wort and beer, whereas nozzle discharge centrifuges are most effective in removing coarse beer from racking tanks and fermented containers. Hermetically closed centrifuges are often used in beer production to keep beer from decreasing its ability to absorb CO₂ and oxygen. Decanting centrifuges have the ability of clearing worts and beers with high yeast or trub content, while self-opening centrifuges are also utilized for recovering beer from fermentation vessels and tank bottoms.

4. Wine Making

Centrifugation is a versatile method, either alone or in conjunction with filtration, used in wine production. Typically, nozzle or self-opening centrifuges are employed for tasks such as clarifying must after pressing, stabilizing fermentation by gradual yeast elimination, clarifying new wines before filtration, and facilitating tartrate precipitation for tartrate crystal removal.

5. Fruit Juice Processing

Centrifugation serves a variety of functions in the production of fruit juice. Self-opening centrifuges may remove and manage pulp levels in pineapple and citrus juices, whereas centrifugation produces clear, pulp-free apple juice. To extract oils from citrus fruits, centrifugation is used in two phases, with the concentrated emulsion separated in a nozzle or self-opening centrifuge to generate citrus oil. Using hermetically sealed centrifuges excessive aeration of juice can be prevented

5 Conclusion

In conclusion, filtration and centrifugation play pivotal roles in food and dairy processing, ensuring product quality, safety, and shelf-life extension. Both technologies offer distinct advantages and are often used in conjunction to achieve desired outcomes. Filtration excels in removing particulates and microorganisms, while

centrifugation is effective in separating immiscible phases and concentrating solids. Together, they contribute to the production of high-quality food and dairy products that meet industry standards and consumer expectations. Ongoing advancements in technology and process optimization continue to enhance their efficiency and reliability in the food and dairy industry. Employing the separation and filtration principles may result in marks transformation how milk and its product will be treated throughout the world. Ongoing advancements in filtration and centrifugation technology continue to improve efficiency, reliability, and sustainability in food and dairy processing, driving innovation and meeting the emerging demands of the industry.

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Chapter 7

Food and Dairy Fermentation Processes



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1 Introduction

Presently human civilization is facing three enormous challenges: the rapid increase in disease burden, food security, and nutritional security. The world's population has already surpassed 7.71 billion and it is going to reach 9.8 billion by 2050. This growth of population will not only significantly challenge the provision of adequate food and nutrition, but also exacerbate the global disease burden. This is particularly relevant for countries like India. The interconnected crisis of food security, nutritional security, and the increasing non-communicable diseases require multifaceted solutions rather than a single measure. A critical step towards improving the nutritional parameters of food for various target groups is probably the promotion and identification of nutritionally rich foods and nutraceuticals. This eventually leads to the fulfilment of nutritional stability and sustainability on a global footing.

Fermentation is an age-old processing technology to convert various animal and plant materials into excellent foods by a diverse microbial population of yeasts, fungi and bacteria. Apart from enhancing sensory attributes and extending shelf life, certain microorganisms can transform the native constituents of animal or plant-based raw materials through food fermentation. This process results in various benefits such as improving the bioavailability of nutrients and imparting bio-preservative and safety effects. The toxic and anti-nutritive components are degraded, and several antimicrobial and antioxidant compounds are formed. This helps in enhancing the probiotic functions and forming some bioactive compounds that have health-promoting effects (Bourdichon et al., 2012; Farhad et al., 2010; Tamang et al., 2009,

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2015; Tamang et al., 2016a). Some of the major health benefits from fermented foods include inhibiting cardiovascular diseases, hepatic disease, cancer, inflammatory bowel disease and gastrointestinal disorders and alleviation of the symptoms of osteoporosis, allergic reactions, hypertension, diabetes, and thrombosis. In the present time, traditional fermented foods are gaining importance for ensuring food security as well as for supplying functional foods to a growing population susceptible to metabolic diseases.

However, to harvest the benefits of fermented foods their traditional route of production has to be revisited and often an engineered process is required to produce safe and functional fermented food. To produce fermented foods in a commercial setting, not only their structural & functional properties are to be known but also all the stages of fermented food production and supply chain need to be controlled. This chapter aims to discuss both the aspects of fermented products in two sections; the first part deals with the nutritional profile, bioactive composition, *in vitro* digestibility and functional properties and the second part deals with starter culture development, fermentation process design and optimization, post-fermentation processing, and packaging plus shelf life assessment of fermented products. In both sections, to represent the scientific and engineering principles a generic discussion will lead to the case studies of two traditional fermented food products: a dairy product (Chhurpi) and a plant product (Soybean).

2 Nutritional & Bioactive Potential of Fermented Food Products

A complex mix of nutrients and bioactive molecules can be delivered when a great variety of seeds, leaves, fruits, flour or animal tissues are fermented with a wide range of microbiota and often post-processed by drying, heating, frying, dry/wet milling, baking etc. The increased digestibility of the carbohydrate or protein matrix, synthesis of microbial metabolites like vitamin B complex and antimicrobials, and degradation of anti-nutritional components during fermentation are the most common reasons for the high nutritional and bioactive content of fermented foods. For instance, there is a possibility of delivering high protein via diverse fermented products to take care of different types of nutritional needs (Tables 7.1 and 7.2). One non-dairy and one dairy-fermented food i.e., alkali-fermented soy and acid-fermented chhurpi are two products that are used as specific examples in this chapter.

Soybean is considered as an excellent source of protein from plants (Table 7.2), though its nutritive values are suppressed by anti-nutritive factors. The fermentation of soybean aids in diminishing the toxins and also promotes the production of some specific bioactive peptides. These bioactive peptides exhibit properties such as ACE inhibitory, antioxidant, antidiabetic, antimicrobial and antitumor. Such peptides and isoflavones are health-beneficial components generally found in fermented soybean products (Sabat et al., 2024). The exceptional longevity among the residents of

Table 7.1 Protein content of some high-protein fermented foods

Sl. No.	Product	Raw material	Area of usage	Protein (%)	References
1	Ngari	Fish	Manipur	34.1	Tamang et al. (2012); Nath et al. (2024)
2	Hentak	Fish	Manipur	32.7	
3	Tungtap	Fish	Meghalaya	32.0	
4	SukakoMoacha	Buffalo/Chevon	Eastern India	35.0	
5	Sidra	Fish	Eastern India	25.5	
6	KaratiBordiaLashim	Fish	Assam	24.–35.0	
7	Kargyong	Yak/beef/pork	Arunachal Pradesh, Sikkim	16.0	
8	Maseura	Black gram	North East Himalaya	8–10	
9	Chhurpi	Milk	Sikkim, Arunachal Pradesh	53.4–68.5	
10	Kinema	Soybean	North East India	48	Sarkar et al. (1994)

Table 7.2 Proximate composition of some fermented foods (Owusu-Kwarteng et al., 2022)

Fermented foods	Proximate (unit/100 g)					
	Moisture (g)	Crude Protein (g)	Crude Fat (g)	Total Ash (g)	CHO (g)	Fiber (g)
Natto	60.8–64	40.7–49.6	18.0–24.7	4.7–5.6	23.3–29.9	3.49–3.55
Kinema	57.3–64.8	43.4–48.7	16.1–22.7	5.6–7.4	27.4–29.6	NA
Doenjang	54.7	13.8–23.4	8	21	45.4	3.1
Chongkukjang	57.7–62.8	14.8–20.9	5.4–8.5	1.4–2.3	8.6–16.3	NA
Thuo nao	56.4–64.9	38.9–42.8	3.2–25.2	4.7–7.9	33.6–40.3	NA
Meitauza	74.5	30.6–39.4	8.5–11.6	4.07–5.06	15.9–32.4	NA
Dawadawa	10.2	49.7	26.9	4.32	7.43	6.5
Okpehe	65–65.3	38.7–40.06	11.96–12.3	2.2–2.3	0.15–0.17	0.38–0.51
Oso	40.3	16.9	16.9	1.03	10.02	6.45
Ogin	27–31	21.4–22.9	20.8–22.3	3.07–3.47	15.2–21.4	5.2–6.4
Furundu	28.7–39	21.8–24.6	5.5–7.7	16.9–22.8	14.4–14.7	NA
Maari	10.3–13.4	13.4–14.7	15.1–18.1	0.68–0.88	4.65–5.11	NA
Owoh	46.6	13.6–28.6	15.3–42.8	1.25–6.1	13.7–15.7	NA

Okinawa administrative district in Japan is greatly attributed to their eating habits of regional and cultural foods such as natto, miso, shoyu, tofu, fermented vegetables and other high-bioactive, cholesterol-free and low-fat foods. The hypothesis that consuming soy foods lowers the risk of breast cancer has been sparked by the low rates of breast cancer mortality in Asian nations as well as the possible anti-estrogenic properties of isoflavones. Soy or isoflavones can lower the incidence of osteoporosis because of their structural similarities and their modest estrogenic effects, which has been demonstrated to enhance bone mineral density in postmenopausal women (Chao, 2008). In addition, soy isoflavones are also capable of

lowering the risk of hazardous diseases such as heart attack and kidney stone formation (Messina, 1997). These findings highlight the potential applications of soybeans in functional diets to prevent non-communicable illnesses and medications with additional health advantages. Furthermore, it provides affordable nutrition and a high protein source to both economically underprivileged individuals and the general population.

Ethnic fermented soybeans are regarded as one of the main sources of food in the Eastern Himalayas; they offer a low-cost, highly digestible, low-fat/low-cholesterol plant protein that is also rich in nutrients, antioxidants, and other health-promoting qualities in a local diet. Natto is a traditional Japanese food, an alkaline sticky paste-like product derived from the natural fermentation of whole soybean grains. In the north-eastern region of India, there are at least six variants of popular Natto-like fermented soybean products (NLFSP). They are typically consumed as an exotic and nutritious food by Indigenous communities. They have different nomenclature in different regions (Kinema - Darjeeling hills, Eastern Nepal, Sikkim, and south Bhutan), aakhone (Nagaland), hawaijar (Manipur), bekang (Mizoram), tungrymbai (Meghalaya), and peruyaana (Arunachal Pradesh) and shows variation in microbial diversity, functional property, taste and flavour (Tamang et al., 2015). During their fermentation they undergo many desirable changes like reduction of anti-nutritional factors, increasing digestibility, and synthesis of bioactive compounds (vitamins, enzymes etc) (Yang et al., 2011). Recent studies have established that these food products have functional activities and possess considerable therapeutic value. However, the production of these Natto-like fermented soy products in India is typically done on a household/domestic level with traditionally acquired expertise under natural fermentation. Natural fermentation and lack of sterility often cause mixed microbial populations in these products (Nout et al., 1998; Nout & Sarkar, 1999; Kaavya et al., 2024). Microbes such as *Candida sp.*, *Bacillus sp.*, *Saccharomyces cerevisiae*, and *Lactic acid bacteria (LAB)* have been plentiful in these products. Fermentation proves to be an important processing step in soybean product development because of its immense utility— the most economical method of food preservation, enhancement of taste, flavour and aroma, providing beneficial enzymes and various strains of probiotics, B-vitamins, Omega-3 fatty acids, enhanced digestibility that exerts health promoting benefits (Jeyaram et al., 2008; Sathe & Mandal, 2016).

Similar to soybean, milk is another protein-rich perishable food that offers many health benefits due to its unique immunoglobulins, phospholipids etc. The high nutritional value and water activity of milk make it easily susceptible to pathogenic microorganisms. This spoilage can be prevented and the shelf-life can be improved by fermenting the milk. The fermentation of milk, usually by LAB aids in the conversion of lactose (milk sugar) into lactic acid and the production of bacteriocin (antibacterial component). During fermentation, certain bacteria may also convert milk nutritive constituents into more bioactive forms, for example, hydrolysing casein proteins into bioactive peptides like immunopeptides, phosphopeptides and so on. Hence many of the indigenous fermented products from milk like dahi, buttermilk, yoghurt and kefir are good examples of functional dairy products.

Table 7.3 Nutritional composition of soft and hard chhurpi (Panda et al., 2016)

Parameters	Soft <i>chhurpi</i>	Hard <i>chhurpi</i>
pH	4.89	4.32
Titrateable acidity (%)	0.32	0.51
Total solid (%)	29.8	89.77
Moisture (% wt)	72.62	10.22
Protein (% DM)	60.78	63.33
Fat (% DM)	8.8	7.2
Ash (% DM)	5.9	6.3
Carbohydrate (% DM)	24.52	23.17
Lactic acid (mg/g)	0.12	0.23
Acetic acid (mg/g)	0.06	0.16
Riboflavin (μg/g)	162.71	102.22
Thiamine (μg/g)	64.48	35.60
Vitamin C (μg/g)	23.53	9.86

Chhurpi cheese is an indigenous casein-rich fermented milk product made from cow's milk or yak's milk. This cheese is available in certain areas of Ladakh, Darjeeling hills, Sikkim, Arunachal Pradesh, Bhutan, Nepal and Tibet. The primary step in this exotic fresh cheese production is homolactic fermentation, resulting in milk curdling. Followed by fermentation, the chhurpi cheese production process involves the separation of fat and boiling of the buttermilk. There are commonly two types of chhurpi cheese; soft chhurpi with high moisture content and soft texture whereas the other one is called hard chhurpi a dried version of the soft chhurpi that is suitable for longer storage. Additional slow drying causes major changes in the nutritional characteristics of the chhurpi types (Table 7.3). The amount of n-3 polyunsaturated fatty acids (PUFA) as well as the ratio of n-3 to n-6 PUFA were found to be significantly high in cheese prepared from yak milk compared to cheddar cheese made from cow milk (Or-Rashid et al., 2008). The fatty acid composition of yak cheese was found to be superior in terms of three conjugated linoleic acids i.e., cis-9, trans-11 CLA and trans-11-C18:1 for maintaining human health (Or-Rashid et al., 2008). However, this dairy product remains largely untapped, with immense potential to uncover its structural and functional properties.

3 Effect of Fermentation on Protein Quality of Traditional Fermented Soybean and Fermented Cheese

Many of the protein-rich fermented foods are health-beneficial not only because of their muscle-building ability but also due to their unique physiologically active peptides. Such bioactive peptides in many ethnic fermented foods may come from raw material like soy or milk as a native constituent or may occur due to microbial enzyme-mediated and/or non-enzymatic hydrolysis or may form during enzymatic proteolysis in the gastrointestinal tract. That is why the type/structure of protein in the raw material is important and not just the total protein.

Fermentation of soybeans is a traditional practice in Asian cuisine that improves nutritional quality and protein digestibility through enzymatic activities and microbial transformations. This process can increase the availability of essential amino acids as well as generate bioactive peptides that are capable of exhibiting biological activities and contribute to disease prevention and health management. This enhances the overall nutritional profile of fermented soybeans. The effects of fermentation on the protein quality of soybeans have been studied by many researchers, with the mechanisms behind these changes and their impact on the health of an individual. *Bacillus subtilis* can significantly increase the amount of soluble proteins and bioactive peptides during fermentation, which enhances both the nutritional and functional qualities of fermented soybeans. (Kumar et al., 2010) reviewed numerous fermentation processes that include traditional methods like miso and tempeh fermentation with their effects on protein quality. It is highlighted that enzymes during the fermentation process break down complex protein structures, and reduce the occurrence of anti-nutritional factors like trypsin inhibitors and phytic acid, which are responsible for hindrance in protein digestion. This enzymatic action also enhances the bio-availability of amino acids and peptides, thereby it improves protein absorption and utilization in the human digestive tract. This makes soybean proteins nearly equivalent to animal proteins in terms of nutritional profile. Lamsal (2017) discussed how proteolytic enzymes during the fermentation process break down larger proteins into bioactive peptides, that serve various health-promoting properties, such as antihypertensive, antibacterial, antioxidant and immune-suppressive properties. These biochemical transformations not only make the formal proteins more accessible and beneficial for human nutrition but also contribute to the development of unique flavors and textures in fermented soybean products across various culinary traditions.

Microbial proteolytic enzymes in the fermentation perform hydrolytic breakdown of proteins into peptides. The biological activity of these peptides is interfered by their chain length, amino acid sequence and composition. Moreover, solubility is increased by the bioconversion of large molecular weight proteins into smaller ones (Kwon et al., 2011; Meinschmidt et al., 2016; Vong & Liu, 2016). These proteolytic enzymes, which are generated by microbial communities during fermentation, hydrolyze proteins to produce peptides and free amino acids, which enhance the digestibility of soybean protein and have antioxidant properties (Dajanta et al., 2011; Sanjukta et al., 2015). Experimental studies have shown that the concentration of extractable protein in liquid fermented products is three times lower than in raw seeds, indicating a decrease in soluble protein content during legume fermentation. This decrease is likely due to the involvement of microbes and enzymes in fermentation that readily hydrolyzes soluble proteins, forming new peptides that the extraction conditions for original proteins do not adequately capture (Frias et al., 2008). According to Hong et al., fermenting soybean meal with the *A. oryzae* strain does not affect essential amino acid concentrations but increases the levels of Gly, Glu, and Asp. (Hong et al., 2004).

Milk proteins are an essential source of bioactive peptides, which are released through an enzymatic breakdown of proteins during milk fermentation. In the case

of Chhurpi, the major diversity of peptides probably comes from the milk source since the cheese can be produced from cow, yak or goat milk. Gao et al. (2023) reported 632 proteins in the whey fraction of yak milk. Many of these proteins were involved in cellular redox reactions and immune modulatory. The authors also found the protein expression levels varied significantly among three breeds of yak (Gao et al., 2023). Apart from the milk source, different specificity of starter proteinases to hydrolyze milk proteins results in the production of varied peptide profiles of fermented dairy products. Numerous studies measured the hydrolyzed milk protein content using the TCA soluble protein method. Abedin et al. (2022) suggested the bioactivity of protein from yak and cow milk-derived was more during *in vitro* digestion. The digesta of such cheese had higher antioxidant and anti-hypertensive traits due to the formation of bioactive peptides from α -S1-casein, α -S2-casein, β -casein, κ -casein, α -lactalbumin, and β -lactoglobulin. The highest protein hydrolysis was observed in chhurpi cheese produced using *Lb. delbrueckii* WS4 followed by *Lb. delbrueckii* WS15. This study (Rai et al., 2016a, b) showed that some of the proteolytic yeast strains can hydrolyse milk protein and release antioxidant peptides. In the future, specific proteolytic microorganisms can be utilized to produce novel bioactive peptides, leading to the creation of fermented cheese with improved functional properties.

4 Stater Design for Fermented Soybean and Fermented Cheese

The microorganisms employed in the fermentation process are the primary cause of differences between samples of a given traditionally fermented product. Due to this the sensory profile, nutritional, therapeutic, and nutraceutical values of spontaneously fermented products may vary widely. Some food fermentations exclusively occur with bacteria, while others involve only filamentous fungi and certain products utilize both types of microorganisms. For instance, traditional foods like kinema, natto, and chungkookjang are fermented only with *Bacillus* species; products such as douchi, tempeh, miso, and tofu rely on fungi like *Aspergillus oryzae*, *Rhizopus spp.*, *Mucor spp.*, and sometimes a combination of these. In the case of doenjang, a fermented soybean paste, the process involves bacteria such as *B. subtilis* along with fungi such as *Rhizopus spp.*, *Mucor spp.*, *Aspergillus spp.* and *Geotrichum spp.* This diversity in microbial involvement contributes to the distinctive characteristics and nutritional benefits of each fermented product (Cao et al., 2009; Jung et al., 2014; Steinkraus et al., 1960; Yasuda & Yasuda, 2011).

Fermented soybean products, such as kinema, miso, doenjang have deep roots in Asian culinary traditions, that offer not only unique flavours but also enhanced nutritional benefits. Traditionally fermentation methods of soybeans rely on indigenous microorganisms present in the environment. However, the fermentation process has revolutionized with the introduction of defined starters—carefully selected mixtures of specific microorganisms— that improve consistency, safety, and

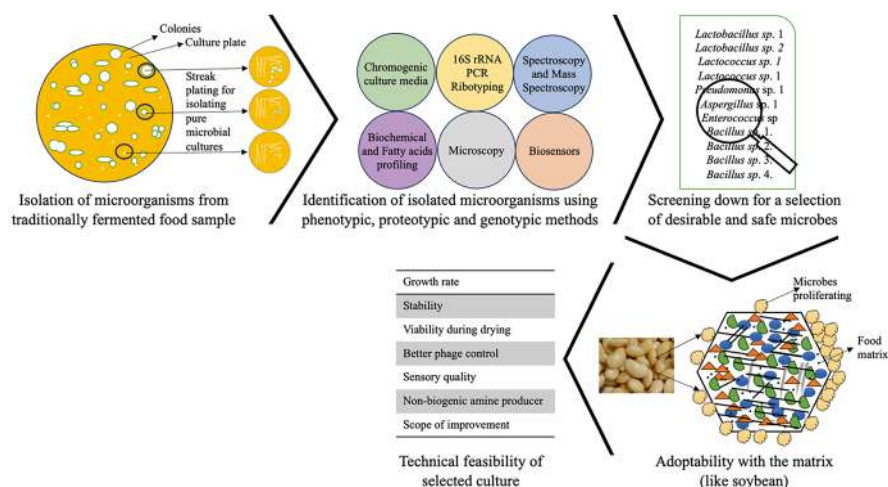


Fig. 7.1 Starter design for fermented foods

nutritional quality. The steps in the development of starter cultures are isolation and taxonomic characterization of the microbial strains isolated from the traditional fermented products. Followed by *in vitro* assessment of the safety of the microorganism, desired physiological properties and technical properties (Fig. 7.1) are used to zero down to the best strain for a given fermentation. Sometimes, certain *in silico* analysis and molecular docking techniques are required to come down to one or two most promising strain from a lot of strains which can then be further analyzed through whole genome sequencing. However, a critical and foundational step in developing starter cultures is documenting all the isolated strains from indigenous fermented foods.

Many studies as shown in Table 7.4 have isolated variant bacterial strains from different processing steps of chhurpi cheese, raw milk, curd, buttermilk, whey and end product chhurpi cheese (Kohli et al., 2023). Most of them have found LAB and yeast strains as the most prominent group of microflora in different steps of chhurpi cheese production. Their numbers are usually less in the mild flavoured cheese compared to their strong varieties (Tamang et al., 2000). Many traditional fermented foods are enriched with an enormous amount of LAB of various species. These bacteria are Gram-positive which lack catalase and oxidase enzymes. They are facultative anaerobic cocci or rods, non-spore formers, and under microaerophilic conditions, they produce lactic acid from carbohydrate metabolism. There has been increasing public awareness of the benefits of LAB found in traditional foods as a part of healthy dietary choices. These widely used LAB strains synthesise a broad range of enzymes with comparatively low lipase and esterase activity and significant leucine arylamidase, β -galactosidase, glucosidase, and phosphatase activities, along with peptidases and no proteinase activity detected with the techniques applied (Dewan & Tamang, 2006, 2007; Rai & Tamang, 2022; Tamang et al., 2000). Absence of proteinases such as trypsin and chymotrypsin, with high levels of

Table 7.4 Identified microorganisms in fermented soybean and cheese

Fermented soybean (Meju, Tempe, Natto, Bekang and Tungrymbai, Douchi, Kinema, Thua nao, Chungkokjang, Doenjang)	Fermented milk and cheese (Chhurpi, Soft chhurpi, Chhu, Dahi and Datshi)
Identified microorganisms	
<i>Bacillus</i> sp.	
<i>B. subtilis</i> , <i>B. citreus</i> , <i>B. mesentericus</i> , <i>B. circulans</i> , <i>B. licheniformis</i> , <i>B. amyloliquefaciens</i> , <i>B. pumilus</i> , <i>B. pumilis</i> , <i>B. megaterium</i> , <i>B. cereus</i> , <i>B. thuringiensis</i> , <i>B. sphaericus</i>	
<i>Lactobacillus</i> sp.	
<i>Lb. plantarum</i> , <i>Lb. lactis</i> , <i>Lb. fermentum</i> , <i>Lb. reuteri</i>	<i>Lb. alimentarius</i> , <i>Lb. kefir</i> , <i>Lb. delbrueckii</i> , <i>Lb. hilgardii</i> , <i>Lb. farciminis</i> , <i>Lb. plantarum</i> , <i>Lb. helveticus</i> , <i>Lb. gallinarum</i> , <i>Lb. bif fermentans</i> , <i>Lb. salivarius</i> , <i>Lb. brevis</i> , <i>Lb. curvatus</i> , <i>Lb. fermentum</i> , <i>Lb. paracasei</i> , <i>Lb. pentosus</i> , <i>Lb. paraplantarum</i> , <i>Lb. coryniformis</i> , <i>Lb. parabuchneri</i> ,
<i>Lactococcus</i> sp.	
	<i>Lc. lactis</i> , <i>Lc. lactis</i> subsp. <i>lactis</i> , <i>Lc. lactis</i> subsp. <i>cremoris</i> , <i>Lc. lactis</i> subsp. <i>tractae</i> , <i>Lc. lactis</i> subsp. <i>hordniae</i>
<i>Leuconostoc</i> sp	
<i>Leuc. mesenteroides</i>	<i>Leuc. mesenteroides</i> , <i>Leuc. pseudomesenteroides</i> , <i>Leuc. mesenteroides</i> subsp. <i>mesenteroides</i> , <i>Leuc. mesenteroides</i> subsp. <i>jonggajibkimchii</i>
<i>Aspergillus</i> sp.	
<i>A. niger</i> , <i>A. retricus</i> , <i>A. oryzae</i> , <i>A. wentii</i> , <i>A. flavus</i> , <i>A. fumigatus</i> , <i>A. terreus</i> , <i>A. spinosa</i>	
<i>Rhizopus</i> sp.	
<i>R. oryzae</i> , <i>R. oligosporus</i> , <i>R. nigricans</i> , <i>R. chinencis</i> , <i>R. sotronifer</i> , <i>R. arrhizus</i> ,	
<i>Enterococcus</i> sp.	
<i>E. faecium</i>	<i>E. durans</i> , <i>E. faecium</i> , <i>E. lactis</i> , <i>E. faecalis</i> , <i>E. pseudoavium</i> , <i>E. italicus</i>
<i>Mucor</i> sp	
<i>M. griseocyanus</i> , <i>M. circinelloides</i> , <i>M. adundans</i> , <i>M. hiemalis</i> , <i>M. jasseni</i> , <i>M. racemosus</i>	
<i>Penicillium</i> sp.	
<i>P. griesotula</i> , <i>P. citrinum</i> , <i>P. kaupscinskii</i> , <i>P. thomii</i> , <i>P. Griseopurpureum</i> , <i>P. lanosum</i> , <i>P. turalense</i>	

(continued)

Table 7.4 (continued)

Fermented soybean (Meju, Tempe, Natto, Bekang and Tungrymbai, Douchi, Kinema, Thua nao, Chungkokjang, Doenjang)	Fermented milk and cheese (Chhurpi, Soft chhurpi, Chhu, Dahi and Datshi)
<i>Other species</i>	
<i>Pedicoccus acidilactici</i> , <i>Botrytis cinerea</i> , <i>Rhodotorula flaca</i> , <i>Rhodococcus sp.</i> , <i>R. glutinis</i> , <i>Zygosaccharomyces japoninus</i> , <i>Z. saccharomyces rouxii</i> , <i>Citrobacter freundii</i> , <i>Enterobacter cloacae</i> , <i>Klebsiella pneumoniae subsp. Ozaenae</i> , <i>K. pneumoniae subsp. ozaenae</i> , <i>Pseudomonas sp.</i> , <i>Pseudomas fluorescens</i> , <i>Geotrichum candidum</i> , <i>Pantoeaga agglomerans</i> , <i>P. ananatis</i> , <i>Mu. plumbeus</i> , <i>Deb. hansenii</i> , <i>Tor. Halophilus</i> , <i>S. cerevisiae</i> , <i>S. exiguus</i> , <i>S. kluyveri</i> , <i>C. utilis</i> , <i>C. incommenis</i> , <i>C. edax</i> , <i>C. parapsilosis</i> , <i>H. senula holstii</i> , <i>H. anomala</i> , <i>H. senula capsulata</i>	<i>Kluyveromyces marxianus</i> , <i>Issatchenkia orientalis</i> , <i>Trichosporon asahii</i> , <i>Exophiala dermatitidis</i> , <i>Gluconobacter oxydans</i> , <i>Acetobacter lovaniensis</i> , <i>A. syzygii</i> , <i>A. pasteurianus</i> , <i>Enterobacteriaceae</i> , <i>S. cerevisiae</i> , <i>S. crataegensis</i> , <i>C. castellii</i>
References	
Astuti and Soesatyo dan (2013); Chettri and Tamang (2014); Dajanta (2013); Indigenous Fermented Foods of Southeast Asia - Google Books (n.d.); King et al. (2012); Moktan et al. (2008); Tamang et al. (2015); Wang et al. (2008)	Chourasia et al. (2022); Dewan and Tamang (2006); Dewan and Tamang (2007); Nakibapher Jones Shangpliang and Tamang (2021); Rai et al. (2016b); Rai and Tamang (2022); Shangpliang et al. (2018); Shangpliang et al. (2017); Tamang et al. (2000); Ghatani and Tamang (2017a)

peptidases (leucine-, valine-, and cystine-arylamidase) and esterases/lipases (C4 and C8) activities produced by the isolated LAB help in accelerated maturation and flavour development of chhurpi cheese (Dewan & Tamang, 2006, 2007; Tamang et al., 2000). LAB species showing high β -galactosidase activity suggest that dairy products prepared from them may be suitable for consumption by individuals with lactose intolerance. LAB strains exhibiting high phosphatase activity potentially play an important role in the degradation of phytic acid within fermented milk products (Dewan & Tamang, 2007). Some studies have also tested the ability of isolated LAB strains to reduce the pH and coagulate the milk at 30 °C and/or 37 °C (Dewan & Tamang, 2006, 2007; Rai & Tamang, 2022; Shangpliang et al., 2017). Some isolated *Lactobacillus* and *Lactococcus* species have shown antimicrobial properties which can help to reduce the number of unwanted microorganisms in milk products while also playing vital roles in preserving them for human consumption. The isolated LAB strains were also not shown to produce any bacteriocin and biogenic amines as evaluated by (Dewan & Tamang, 2006, 2007). All these technological properties and enzymatic profiles (using API-zym technique) were evaluated to reveal the acceptability of isolated LAB strains as possible starter cultures in the manufacture of fermented chhurpi cheese.

The common features of starter design involve safety concerns, the use of organisms in indigenous food fermentations, and the connection between phylogeny to

metabolic capabilities to provide criteria for selecting the culture. Such methods can also be chosen for microbial strains that offer health benefits. A scientific approach to developing new fermented foods can greatly enhance their value by creating more secure food systems, producing food products rich in health-promoting microbes, and offering foods that improve human health.

5 Effect of Defined Starter on Traditional Fermented Soybean and Fermented Cheese

Defined starters are also known as starter cultures that consist of specifically selected strains of microorganisms added to the food matrix during fermentation to standardize and enhance the fermentation process (Fig. 7.2). These starters have several advantages over traditional fermentation methods.

1. **Controlled Fermentation:** The use of defined starters allows precise control over fermentation parameters such as fermentation time, pH and temperature, ensuring good product quality and safety (Lee et al., 2019).
2. **Nutritional Quality:** Several specific strains in defined starters can contribute to increased levels of bioactive compounds, amino acids and vitamins during fermentation that increase the nutritional profile of the fermented product (Jung et al., 2014).
3. **Safety and Shelf Life:** Specific starter cultures can prevent the growth of undesirable microorganisms because of the production of organic acids and antimicrobial compounds, which also improves product safety and shelf-life (Tamang et al., 2016b).

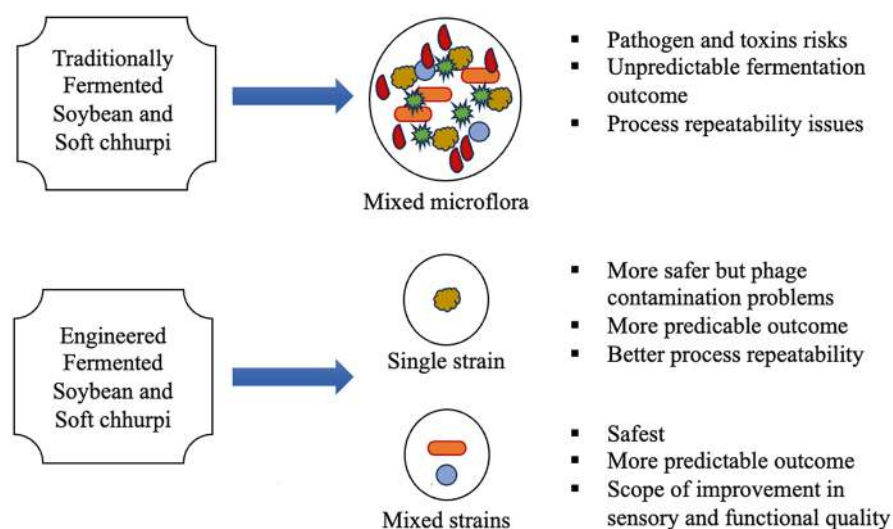


Fig. 7.2 A paradigm shift in the traditional fermentation process

Controlled and curated bacterial starter cultures can significantly alter the sensory profiles, pH, and soluble protein profiles of fermented soybean foods. These cultures are also effective in reducing antinutritional components such as phytic acid, tannins, saponins, and the residual antigenicity of proteins. Utilizing these curated cultures enables the development of customized fermented soybean products tailored to specific nutritional and sensory preferences and increases its market acceptance among consumers. Nowadays research on fermentation has provided notable insights into the effects of defined starters on traditionally fermented soybeans. For instance, studies by Jung et al. (2014) demonstrated the influence of different starter cultures on the fermentation dynamics and sensory characteristics of products like miso, highlighting significant changes in metabolite profiles and microbial diversity. Similarly, Lee et al. (2019) also researched the impact of specifically defined cultures on the bioavailability of nutrients in fermented soybeans, demonstrating increased levels of essential amino acids and bioactive peptides. In fermentations with LABs, it was found that there is a decrease in galactose while an increase in GABA content with the increase of *Lactobacillus* (Jeong et al., 2013; Komatsuzaki et al., 2008; Makarova et al., 2006; Siragusa et al., 2007). As the fermentation progresses there is a decrease in moisture content, increase in pH value and free amino acid content. It was found that the starter strain influenced biogenic amine content, there was the highest amount of biogenic content with *B. licheniformis* at 72 and 96 h (Shi & Moon, 2024). The production of unique volatile compounds by *B. licheniformis* and *S. succinus* contributes significantly to the distinct flavour profiles of fermented soybean products, unlike *S. saprophyticus*, which is less capable in this regard. The use of *E. faecium* and *T. halophilus* also alters flavor profiles during soybean fermentation, but not as profoundly as *B. licheniformis* and *S. succinus* (Jeong et al., 2017). Controlled starter cultures in fermentation can reduce soy immunoreactivity, offering the potential for developing hypoallergenic, nutritious soy products. Fermentation with *B. subtilis* results in low-range proteins below 20 kDa and shows no visible specific immunoreactivity, whereas fermentation with molds like *A. oryzae* and *R. oryzae* produces middle-range proteins (<50 kDa). Fermentation enhances the nutritional value of legumes by reducing non-nutritive compounds like trypsin inhibitors, phytic acid and galactosides, and, while preserving acceptable levels of protein, fibre, sugars, starch, vitamins, and minerals (Doblado et al., 2003; Torres et al., 2006). Doenjang samples that have been inoculated with *B. licheniformis* show strong concentrations of typical doenjang-like aromatics, such as notes of ammonia, balsamic, meju, and soy sauce. Samples made with *E. faecium* also display traditional doenjang-like aromatics along with strong solvent-like aromas, which may be specific to *E. faecium*. However, these traditional aromatics decrease when *S. succinus* is added (Lee et al., 2019).

This study (Chourasia et al., 2022) has produced chhurpi cheese by controlled fermentation of milk using various *Lb. delbrueckii* and *E. durans* starter strains and has reported that *Lb. delbrueckii* WS4 resulted in greater yield in comparison to other starting strains, as well as increased protein hydrolysis and antioxidant activity. Its antioxidant activity was further enhanced after gastrointestinal digestion. Another study (Rai et al., 2016a) reported the improvement of DPPH radical

scavenging activity when individual yeast isolates were used to ferment the skimmed milk and among the non-pathogenic yeasts, the higher antioxidant activity or DPPH radical scavenging activity was obtained with *S. cerevisiae* YAM14 and *K. marxianus* YMP45. The selection of appropriate LAB strains is important as they play an essential role during the fermentation process for the production of chhurpi cheese. They should possess such functional and protective properties to be selected as starter cultures for the manufacture of desirable fermented chhurpi cheese.

An urge to use the defined starter strains for the development of fermented foods including chhurpi cheese rise due to issues such as the dominance of antibiotic-resistant microbial strains like vancomycin-resistant *E. durans* strains in traditionally and commercially available fermented chhurpi cheese (Chourasia et al., 2022); presence of pathogenic yeasts like *Exophiala dermatitidis* and *Trichosporon asahii* in intermediate samples (improving antioxidant activity) but not in final chhurpi cheese due to their inactivation during buttermilk heating process (Rai et al., 2016a); pathogenic *Staphylococcaceae*, *Enterobacteriaceae*, *Clostridiaceae*, *Pseudomonadaceae* and *Bacillaceae* were found in relatively low levels by this (Shangpliang et al., 2018) study probably as contaminants; a notable number of *E. coli* and *Vibrio* sp. found in all samples probably coming from utensils or water used in indigenous chhurpi preparation (Panda et al., 2016), presence of shiga toxin-producing *E. coli* (STEC) and enteropathogenic *E. coli* (EPEC) that can cause serious illness in human beings (Bandyopadhyay et al., 2012). These undesirable microbes might be the result of an uncontrolled natural fermentation process (Shangpliang et al., 2018). Hence, apart from safety, the need for starter culture is rising to make the fermentation process more controllable, predictable and optimal compared to spontaneous and traditional back-slopping fermentation.

6 Optimization of Fermented Foods

The fermentation process is often optimized to maximize the desirable qualities such as taste, texture, yield, soluble protein, digestible protein and so on. Many techniques have also been used for the optimisation of the fermentation food process such as response surface methodology, one-factor-at-a-time, central composite design, fuzzy logic etc. However, it is equally important to characterize the raw materials and standardize the pre and post-fermentation steps too (Fig. 7.3). An attempt was made by (Kohli et al., 2023) to provide an integrated approach for standardising the preparation of fermented soft chhurpi. In a study (Bhat et al., 2022), response surface methodology (RSM) with a central composite rotatable design (CCRD) was used for the optimization of chhurpi processing conditions such as incubation temperature and time, inoculum concentration and drying time. The optimum yield and desirable sensory quality of fermented chhurpi cheese were obtained at an inoculum concentration of 35 g, incubation time of 9.85 h, incubation temperature of 29.76 °C and drying time of 26.05 h (Bhat et al., 2022).

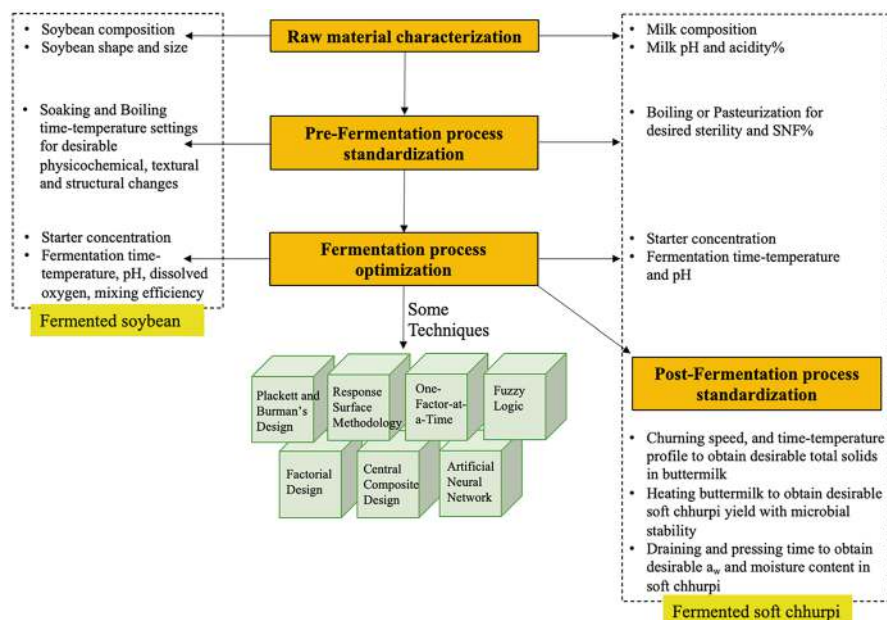


Fig. 7.3 Schematics demonstrating a process design and optimization required in different stages of fermented soybean and chhurpi production

CCRD was also employed to optimize the processing steps for the preparation of kinema by reducing ANF levels at each processing stage. The optimal soaking conditions were identified as a raw beans-to-water ratio of 1:10, with a soaking temperature of 10 °C, duration of 20 h, and pH of 8.0. For the cooking stage, the optimal conditions were soaked soybean to water ratio of 1:5, with a cooking pressure of 1.10 kg/cm² and a cooking time of 20 min. During fermentation, the optimal conditions were an inoculum load of 10³ total cells/g of grits, with a fermentation temperature of 37 °C and a duration of 48 h. In the final kinema product, TC, PAC, TIA, and HA decreased significantly by 100%, 61%, 71%, and 100%, respectively, compared to raw beans.

The optimization and standardization of fermentation processes are allowed by the integration of scientific knowledge and application of defined culture. This modernised version meets modern consumer expectations as well as preserves and enhances the nutritional and sensory attributes of these ancient culinary traditions. Researchers and producers are contributing to the innovation and improvement of traditional fermented products by leveraging scientific insights into microbial interactions and fermentation dynamics. This ensures their sustainability and relevance in contemporary food systems.

7 Probiotic Activity of Some Organisms Isolated from Traditional Fermented Soybean and Fermented Cheese

Fermented soybean products, such as natto, miso and tempeh, have significant roots in the Asian culinary system not only for their unique flavours but also for their health-promoting properties that are attributed to probiotic microorganisms. An effective probiotic strain is considered to be safe and viable, with an ability to survive in high acidity, bile acid, bile salts that are present in the stomach, upper intestine and small intestine respectively. They should also be capable to colonize and adhere to the gastric mucosa lining while providing at least one health advantage. High levels of hydrophobicity are linked to a greater capability of bacteria to attach to epithelial cells. A hydrophobicity percentage of more than 40% is considered as hydrophobic. A hydrophobic activity is considered significant when the hydrophobic index exceeds 70% for that strain.

Scientific studies related to soy fermentation have illuminated the potential of probiotic starters in fermented soybean products, particularly demonstrating the roles of LAB and yeast species. They are capable of exhibiting probiotic activities that contribute to various health benefits like improved gut health, immune modulation, and enhanced nutrient bioavailability. These probiotic microorganisms are essential in the fermentation process as they can produce beneficial metabolites like exopolysaccharides, antimicrobial peptides, and vitamins that enhance the functional properties of fermented soybeans. Research by Jung et al. (2014) suggested that LAB strains, that are isolated from Doenjang (Korean fermented soybean paste) can exhibit robust acid and bile salt tolerance, attachment to intestinal cells, and showed antimicrobial activity against pathogens. In addition, (Gaggia et al., 2010) highlighted the probiotic properties of various yeast strains, such as *Saccharomyces boulardii*, which can play a vital role in promoting gastrointestinal health and immune modulation. *Bacillus* species are generally known for their good probiotic potential that promotes gut health through the synthesis of antimicrobial agents and also the enhancement of bioavailability of nutrients (Hong et al., 2009).

The therapeutic potential of isolated (from different stages of chhurpi preparation) LAB cultures having in vitro probiotic attributes has been reported by many researchers. Some isolates were identified by (Ghatani & Tamang, 2017b) which showed good acid and bile salt tolerance and cell surface hydrophobic nature along with cholesterol-lowering properties (qualities of good probiotic microbes). Their cholesterol-lowering effects and probiotic qualities could be leveraged to reduce cardiovascular-related diseases. A study (Rai & Tamang, 2022) identified 53 LAB strains that demonstrated at least one in vivo probiotic trait along with gene detection. The same study also identified some LAB strains that have good abilities to tolerate low pH and bile salt and showed remarkable resistance to lysozyme (Rai & Tamang, 2022). Some strains of *Leuc. mesenteroides*, *Lc. lactis* subsp. *cremoris* and *Leuc. mesenteroides* subsp. *jonggajibkimchii* were provisionally chosen as potential probiotic species by this study. Some isolated LAB strains exhibited a significant

level of hydrophobicity (>70 – 75%), as tested by bacterial adherence to hydrocarbons and if consumed in a viable state, they might adhere to epithelial cells lining the human intestine, indicating a potential probiotic nature (Dewan & Tamang, 2006, 2007; Rai & Tamang, 2022). These studies collaboratively emphasize the importance of defined starters in enhancing the functional and nutritional profiles of fermented chhurpi and soybean products through their probiotic activities, supportive digestive health and immune function.

8 Some Engineering Challenges of Defined Starter

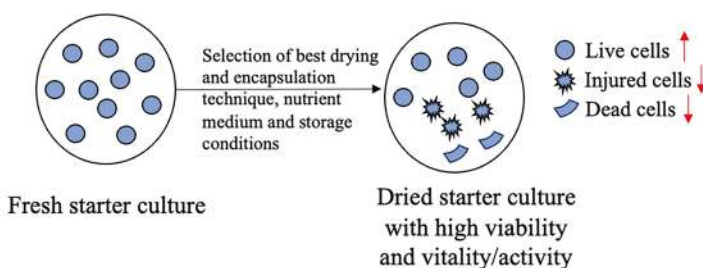
Engineering strategies commence with the meticulous selection of robust starter cultures noted for their resilience and efficiency in fermenting substrate. They are carefully chosen for their specialized fermentation capabilities and benefits, preserving the superior quality and consistency of fermented foods. These starter cultures are designed to optimize every aspect of the fermentation process, from the initial inoculation process to final product development. Engineering strategies can encompass several vital factors that are targeted to improve efficacy, functionality, and economic viability, including precise selection and optimization of microbial strains based on various criteria such as metabolic pathways, substrate preferences, flavour compounds and production of fermentation by-products like lactic acid. Stringent control over temperatures, pH and nutrient levels, and protection from moisture and oxygen is often required for producing good starter cultures. This can collectively sustain microbial survival and activity (Settanni & Moschetti, 2010). These conditions are also pivotal for successful fermentation and enhanced sensory attributes, functional properties and nutritional benefits of the final fermented soybean products. They can be achieved with the help of advanced monitoring and modernized automated systems. Figure 7.4 shows some technical approaches for preserving the well-defined starter cultures and producing the desirable fermented products.

8.1 Vitality and Viability Count

The vitality and viability of microorganisms in starter cultures are foundational to successful fermentation processes and fermented products. There lies an enormous challenge in packaging live microbes in such a state that viable microbes in adequate numbers are available at the time of fermentation. It should have more shelf life, accelerate the fermentation process and produce a product of consistent quality.

High initial cell counts are required to facilitate rapid and dominant fermentation and to contribute significantly to consistent product quality. Dried starter cultures are more manageable and stable at nonfreezing temperatures than frozen ones, which are greater in vitality and activity. Several factors can impact the viability and

Preparation of starter cultures



Addition of starter cultures to substrate

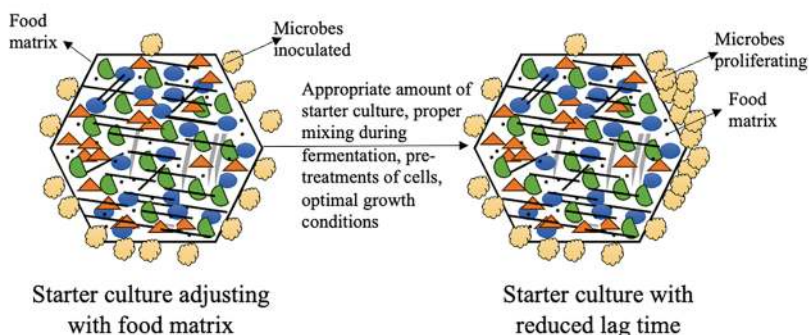


Fig. 7.4 Schematics depicting some technical solutions for attaining maximum efficiency of defined starter cultures

activity of the dried starter cultures throughout every stage of the process, from inoculating the starter cultures to storing them. This results in the creation of dried starter cultures with high viability and vitality. Optimized drying techniques, particularly freeze-drying or lyophilization are essential for the preservation of microbial viability in starter cultures and maintenance of fermented product quality. It is favourable for its gentle water removal process, which avoids heat and mechanical stresses that may compromise microbial integrity. Lyophilization involves freezing the starter culture at low temperatures and then subjecting it to vacuum conditions for the sublimation of the ice directly to vapour. Several parameters such as airflow rate, air temperature, and drying time are meticulously controlled to ensure rapid moisture removal while preserving cell viability (Liu et al., 2020). With its mild nature, freeze-drying produces a dried product with high survivability, metabolic activity, and excellent rehydratability among other benefits.

Many advanced technologies like freeze-drying have been developed to produce starter cultures. However, the usage of such high-cost sophisticated processing equipment ultimately results in a costly product and thus not in use so much. Since fermentation is an age-old process and carried out at household levels daily from the very beginning, if we need a starter culture to be accepted at the household level

then it should be less costly on the economic front and easy to use and store. So the challenge lies in cutting the cost of starter cultures. In a study (Bensch et al., 2014), fluidized bed drying is suggested as a cost-efficient and effective alternative to produce starter culture granulates with an average of 2.7×10^9 viable cells of *L. plantarum*/g. Another study reported 1.82×10^9 viable cells using a modified spray drying process for the development of *Lb. plantarum* MA2 starter culture to prepare yoghurt (Li et al., 2012). Indigenously designed vacuum tray dryers which have low power consumption can be used for drying products aseptically to a level where moisture content is less so that its shelf life increases but there are enough viable microorganisms to produce the fermented product and a low-cost packaging technology (Santivarangkna et al., 2007). This requires optimization of the drying process. Advanced monitoring systems can enable precise regulation of drying conditions that enhances starter stability and efficiency. The inclusion of protective agents and cryoprotectants further works as a safeguard for microbial cells. It facilitates the retention of metabolic activity and fermentation capacity upon rehydration and inoculation processes. These practices ensure consistent performance of defined cultures during fermentation processes. It also supports the production of high-quality fermented soybean products that fulfil consumer expectations for factors such as flavour, texture, and nutritional benefits while upholding industry standards (Peighambaroust et al., 2011). Microwave-vacuum drying also seems to be a promising alternative method for preserving starter and probiotic cultures (Ambros et al., 2016).

Apart from viability, vitality test is also an important parameter to assess starter cell physiological/metabolic activity and product quality. Assessment of microbial vitality requires several sophisticated techniques such as molecular methods, and flow cytometry that ensure precise measurement of live cell populations. The stressed or injured starter cells were identified in cheese starters using advanced flow cytometry studies (Wilkinson & LaPointe, 2020). These types of cells are not culturable or viable, yet they possess the capability to generate specific enzymes during fermentation. These enzymes contribute to the development of desirable characteristics in the final product, such as acidity, levels of reducing sugars, free amino N, amino acids, bioactive peptides, and so on. Therefore, it is imperative to evaluate both the viability and vitality of microbial cells when selecting and optimizing the drying and fermentation techniques for producing defined starter cultures.

8.2 Formulation of Starter Cultures

Other aspects that have to be considered while designing the starter culture technology include factors influencing the propagation or growth of starter cells. To achieve optimal final cell numbers and reduce lag time caused by injured cells, a suitable

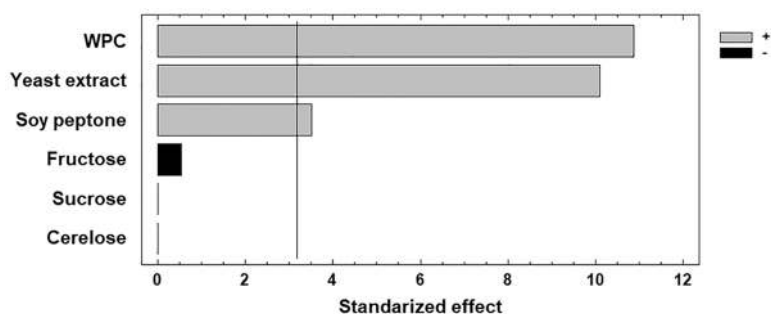


Fig. 7.5 Pareto chart illustrating how several nutrients impact the biomass yield of *Lb. sakei* ACU-2 (Galante et al., 2023)

and low-cost fermentation medium needs to be selected and optimized. Improving drying techniques and storage conditions can also help to minimize the recovery time of damaged microbial cells. The growth-promoting medium should be thoroughly sterilized to prevent any potential contamination. Figure 7.5 demonstrates how various components of the medium influence the biomass yield of *Lb. sakei* sp. *sakei* ACU-2 (Galante et al., 2023). This study showed that utilizing Plackett-Burman and mixture design techniques can optimize the nutrient medium, leading to a significant increase in biomass production (approximately 75.5%) compared to its native medium. Moreover, this optimization also resulted in a notable reduction in processing costs, ranging from 62% to 86% (Galante et al., 2023). Another study (Chen et al., 2010) optimised the nutrient medium (16.18 g, 17.53 g and 8.14 g per litre of corn steep liquor, soybean flour and yeast extract respectively) using Plackett–Burman and central composite design to increase the spore production of the *B. subtilis* (WHK-Z12) strain (Galante et al., 2023).

The formulation of starter cultures also involves developing carrier materials with protective agents that are responsible for protecting microbial viability during storage time and transportation. These techniques enhance their stability and ensure optimal functionality upon use. Engineering efforts are focused on encapsulation technologies such as spray drying and microencapsulation. These techniques can protect microbial cells from environmental stresses that include temperature fluctuations and oxidative damage, during storage and transportation time. Formulation strategies are also considered for the compatibility of carriers with fermentation substrates that ensure the controlled release of microorganisms upon the inoculation process. This is an optimized approach for starter activity and consistency across production batches for supporting efficient fermentation and product uniformity. Moreover, the use of prebiotic microorganisms and cryoprotectants in formulations is capable of improving microbial survival and metabolic activity, further enhancing fermentation efficiency and product quality (Frece et al., 2005; Leroy & De Vuyst, 2004).

8.3 *Storage Conditions*

Starting cultures must be stored under ideal conditions to ensure their vitality. Optimization in engineering solutions encompasses designing storage facilities with careful attention to controlled temperature and humidity levels, which are critical in mitigating moisture ingress and preventing microbial degradation. These optimized conditions uphold starter viability and activity and also ensure consistent performance over extended periods. Advanced packaging techniques, such as vacuum-sealing and inert gas flushing, further can fortify these efforts by minimizing oxidative stress that reduces the risk of microbial contamination. These vital measures are essential for extending shelf life and maintaining the integrity of starter cultures, thereby sustaining their efficiency and reliability during fermentation processes. Rigorous quality control protocols that include regular viability testing and microbial enumeration, serve as additional safeguards to verify starter potency and functionality before deployment. By adhering to these stringent practices, food producers uphold industry standards and meet consumer expectations for high-quality, reliable fermentation outcomes in end products.

8.4 *Decreasing Lag Time*

Lag time reduction- the period between initial inoculation and the onset of active fermentation, is essential for the optimization of production efficiency and product consistency. Modernized engineering strategies are focused on enhancing starter adaptation to fermentation substrates through various pre-conditioning techniques such as osmotic shock or heat shock. These methods are vital for prime microbial cells for rapid activation and metabolic acceleration during inoculation, minimization of lag time and acceleration of fermentation kinetics. Additionally, optimized inoculation techniques, containing starter culture concentration and nutrient supplementation, can promote rapid microbial growth and better substrate utilization. Continuous process monitoring and control facilitate real-time adjustments to fermentation parameters and are significantly crucial for further reduction of lag time that ensures consistent production outcomes. These integrated approaches result in improved fermentation efficiency, shortened production cycles, and enhanced sensory and nutritional properties of fermented soybean products.

8.5 *Mixing of Starter Culture with Substrate*

The blending of starter culture with the raw material or substrate is a crucial step but is often overlooked in fermentation processes. Depending on the physical state, the starters may exist as powder, liquid, or frozen cultures. It is frequently observed that

mixing liquids within a liquid system is much easier and controllable compared to mixing solid-liquid and solid-solid substances. Inadequate stirring could prolong fermentation or potentially endanger the safety of fermented foods. It can produce inconsistency in product quality in terms of taste, texture, colour, pH, acidity, formal protein content and more. Increased agitation during fermentation reduced system heterogeneity by significantly improving heat transfer. It also helps in the reduction of the lag phase. A study noted that the specific growth rate of *L. bulgaricus* was over twice as high in the agitated fermentations compared to the non-agitated ones (Aguirre-Ezkauriatza et al., 2008). A study investigated how the fermentation of mung beans by *B. subtilis subsp. natto* differed across different reactor designs, such as shaking flasks, static chambers, and soft elastic tubular reactors (SETR). The changes in soluble protein levels, reducing sugar content, and protease activity of mung beans following a 6-h fermentation process with *B. subtilis subsp. natto*, with or without SETR pre-treatment, were documented (Lyu et al., 2024). Their research findings indicated that the ratio of metabolites acetoin (AC) to butanediol (Bu) was roughly 7 times greater when using a Rushton/propeller combination and 1.5 times higher when using a combination of Lightnin A-310 and Rushton turbines compared to two Rushton turbines. Higher ratios of AC/Bu indicate improved oxygenation and mixing conditions within the fermenter. Such mixing concepts are well-studied in food processing and fermentation systems but as per our knowledge, their consequences are not evaluated in-depth in starter culture technology.

8.6 Amount of Starter Culture

The addition of the right amount of starter culture is essential to obtain desirable properties in the final product. It may include taste, texture, yield, moisture, acidity, microbial count and so on (Kumar et al., 2014). This study (Kumar et al., 2014) determined the effect of starter culture amount on the texture properties of buffalo milk-type cheese. The hardness of cheese was found to be maximum and minimum with 1% and 2% starter culture respectively. The chewiness, cohesiveness and springiness as well total solids of ripened cheeses decreased with an increase in the rate of culture concentration. However, the yield, moisture, fat, and protein of cheese increase with an increase in stater amount (Kumar et al., 2014).

8.7 Optimal Growth Conditions

Optimal growth conditions are required for defined starters, creating this condition requires precise control over environmental factors that can influence microbial performance. Factors such as pH, temperature, oxygen levels, and nutrient availability are functional parameters that dictate microbial growth and metabolic activity

during the fermentation process. Optimized engineering solutions involve the design of fermentation systems that are equipped with modern instruments, automated monitoring and control systems. These techniques can adjust environmental conditions continuously based on real-time data, which ensures ideal growth conditions for starter cultures. This approach can maximize the utilization of substrate and accelerate metabolic processes by enhancing the production of desired fermentation by-products, which contribute to the sensory, functional and nutritional characteristics of fermented products (Steinkraus, 1995).

8.8 Phage Infection and Mutation

The fermentation of protein-rich animal and plant-based raw materials creates an ideal environment for the proliferation of bacteriophages that infect starter cultures, especially strains of LAB and *Bacillus* species. Bacteriophages may play a significant role in controlling food-borne pathogenic bacteria (such as *E. coli*, *Salmonella* and *Staphylococcus* spp.) in fermented foods (Chukeatirote et al., 2018). This research identified two particular *B. cereus* bacteriophages (BaceFT01 and BaceCM02) with strong lytic action against *B. cereus* present within Thua Nao fermented product (Phongtang & Chukeatirote, 2021). Another study reported a huge number of phages infecting *B. subtilis* in Korean fermented soybean foods (*Gochujang*, *Doenjang* and *Cheonggukjang*) (Ghosh et al., 2018). They also found that false contamination with *B. subtilis* phage BSP18 at as little as 102 PFU/g greatly impeded the growth of *B. subtilis* during the fermentation of *Cheonggukjang* (Ghosh et al., 2018; Phongtang & Chukeatirote, 2021). This resulted in the production of inferior products due to the degradation of the viscous polymer, γ -PGA. At times, virulent phages are deliberately introduced to eradicate bacterial pathogens during the fermentation process. Two phage cocktails targeting *Staphylococcus aureus* were formulated to efficiently eliminate a population of 10^6 colony-forming units per gram of *S. aureus* and suppress enterotoxin production following a 14-day ripening period of Cheddar cheese curds at 4 °C (El Haddad et al., 2016). A combination of four carefully chosen coliphages was introduced into the milk to control the initial gas formation caused by the growth of saprophytic *E. coli* during the cheese ageing process (Tabla et al., 2022).

However, if these phages infect the culture characterized by a single strain, it could potentially cause complete fermentation failure, leading to the production of unsafe products. For instance, BasuTN3, a highly infectious bacteriophage of the Myoviridae family, was discovered in Thua Nao (Gewtaison et al., 2023). This phage demonstrated the ability to lyse *B. subtilis* strain TN3, which is a promising candidate for use as a starting culture for fermenters because of its proteolytic capabilities (Gewtaison et al., 2023). Therefore, this virulent phage infection,

associated with the usage of single-strain starter culture, remains a persistent problem in plant or dairy-based starter culture technology. An abortive infection is also one mechanism by which *Lactococcus lactis* develops defenses and prevents their extinction against lytic phage infections during the production of cheese or other milk products (Rodríguez-Román et al., 2024).

However, the rise of mutant phages that target host bacteria can bypass the bacterial Abi systems, potentially resulting in financial setbacks (Rodríguez-Román et al., 2024). Typically, to enhance fermentation performance regarding its physical, chemical, structural, functional, and sensory aspects, various strategies are employed. These may include utilizing modified processes, employing phage-resistant starter cultures or mutant systems, combining different strains, rotating strains, or using a specialized culture medium (Guérin et al., 2023; Sing & Klaenhammer, 1993; Deng et al., 2018; Durmaz & Klaenhammer, 1995; Lyu et al., 2024; Pitaksutheepong et al., 2015; Ma et al., 2015; Madera et al., 2003; Zhang et al., 2023).

9 Conclusion

Fermentation is a processing operation that promises to be used for the production of designer cheese and soy nutraceuticals. The understanding of solid-state fermentation involved in traditional fermented food production is still empirical in nature. This restriction of knowledge often makes it difficult to adopt such products on an Industrial scale. Similarly, well-designed clinical studies will help in establishing the true health benefits of the plethora of traditional fermented products. This chapter covers some of the important topics in engineering the processing steps of traditional fermented food products. Also, it addresses some engineering challenges related to the application of defined starters. The fermentation of soybean and chhurpi requires a holistic approach integrating advanced technologies and meticulous process control. Optimization of vitality and viability, establishment of ideal growth conditions, formulation of stable cultures through microencapsulation and related techniques, and precise storage and drying methods help producers enhance the efficiency, reliability, and economic feasibility of defined starters. Minimizing the lag time between initial inoculation and fermentation initiation can further improve production efficiency and product consistency. These efforts collectively ensure the consistent production of high-quality fermented products that meet consumer expectations for flavour, texture, and nutritional benefits, thereby upholding industry standards and also enhancing market competitiveness. Continuing advancements in microbial ecology, modernized systems and biotechnological innovations, will further refine these engineering practices, which also support sustainable and efficient fermentation processes in the food industry.

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Chapter 8

Food and Dairy Freezing and Cooling Techniques



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1 Introduction

Food represents a fundamental requirement for human survival, derived from both animals and plants. As food is highly perishable, it requires preservation through appropriate processing to ensure availability year-round and in various locations. Lowering the temperature to preserve food is a widely recognized method that has been utilized for an extended period. Nearly all types of food items, whether they're in their raw state, partially processed, or fully prepared, can be kept fresh by freezing. Within the processed foods industry, there's a notable preference among consumers for frozen food compared to dried or canned alternatives. This trend is particularly evident in the meat, dairy, fruit, and vegetable industries. Freezing and cooling not only enhances the value of the product but also imparts a sense of freshness to it (Muthukumarappan et al., 2019). Freezing and cooling are essential techniques in the dairy and food industry. These methods are important for preserving the standard and security of perishable products, prolonging shelf life, and preserving nutritional content (Prestes et al., 2022). Low-temperature processing has gained significant traction as a means to prolong the freshness of perishable food items (Bassey et al., 2021). Unlike conventional thermal methods, low-temperature processing minimizes thermal degradation of the quality of food supplies (Hu et al., 2022). Moreover, the reduced reliance on chemical preservatives has emerged as a key benefit of employing low-temperature methods in the food industry. Typically, food systems are unstable, with components like proteins, water, lipids and carbohydrates capable of undergoing phase transitions when exposed to variations in

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pressure or temperature. Pressure and temperature are two primary factors governing these phase transitions. They play crucial roles in determining the physical and chemical characteristics of food items, influencing its texture, flavor, and shelf life. Additionally, variations in pressure and temperature can affect the structural integrity of food matrices and alter the interactions between different components, leading to changes in food quality and stability over time (LeBail et al., 2003). Because of the significant latent heat of water evaporation, various rapid cooling methods have been devised, leveraging decreases in pressure. Among these techniques are VC (vacuum cooling), VFC (vacuum film cooling), and VSC (vacuum spray cooling). These methods exploit the principles of thermodynamics to swiftly lower the temperature of food products. By reducing the pressure, these cooling methods prompt water to evaporate more rapidly, drawing heat away from the food and resulting in efficient cooling. These innovative approaches are particularly useful in preserving the freshness and quality of perishable foods, such as vegetables and fruits and delicate produce. Additionally, they offer advantages in terms of energy efficiency and reduced processing time in contrast to traditional cooling techniques (Zhu et al., 2021). Conversely, owing to the distinct phase characteristics of water when subjected to pressure, techniques have been devised to regulate ice nucleation during the process of freezing. These methods comprise PSF (pressure shift freezing) and ICF (isochoric freezing). By manipulating pressure levels, these innovative freezing techniques provide precise control over the development of ice crystals within food products (Roos & Drusch, 2015). The aim of this chapter is to examine several processing methods by low temperature and their impact on the quality and durability of food materials.

2 Principle of Freezing and Cooling

The process of freezing involves lowering the temperature of food or dairy products below their freezing point, causing the water content within the products to solidify into ice (Sahagian & Goff, 2019). This transformation inhibits microbial growth, enzymatic activity, and chemical reactions, effectively ensuring the products' quality, safety, and shelf life (De Ancos et al., 2012).

On the other hand the principle of cooling involves the transfer of heat energy from a substance (such as food or dairy products) to its surroundings, resulting in a decrease in temperature (Ibrahim Dincer, 1997). This process aims to lower the temperature of the products to decelerate or inhibit enzymatic reactions, microbial growth and chemical reactions that lead to spoilage as shown in Table 8.1 (Amit et al., 2017).

Table 8.1 Studies reported on pressure based freezing techniques

Substance	Freezing technique	Conditions	Conclusion	References
Shrimp	Pressure shift freezing	PSF at pressures of 100 MPa achieves temperatures of -8.4°C , at 150 MPa reaches -14°C , and at 200 MPa achieves -20°C	Ice crystals are smaller, evenly spaced, and uniformly distributed.	Su et al. (2014)
Pork liver	Pressure shift freezing	PSF achieves temperatures of -8.4°C at 100 MPa, -14°C at 150 MPa, and -20°C at 200 MPa.	Ice crystals are smaller, evenly spaced, and uniformly distributed.	Su et al. (2014)
Carrot	Pressure shift freezing	High-pressure carbonation infusion (HPCI) up to 10 MPa	Damage in tissue is decreased, decreased drip loss, and improved nutrient retention.	Xu et al. (2014)
Shrimp and pork liver	Pressure shift freezing	PSF reaches temperatures of -8.4°C at 100 MPa, -14°C at 150 MPa, and -20°C at 200 MPa.	Reduced phase transition durations; smaller and uniform, ice crystals	Su et al., 2014
Spinach	Isochoric freezing	-4°C and 29.7 MPa	Enhanced preservation of quality attributes, maintained cellular integrity, and prevented dehydration of cells	Bilbao-Sainz et al. (2020a, b)
Potatoes	Isochoric freezing	Between -5°C and -3°C (at 30 MPa)	No browning and weight loss, and preserved cellular integrity	Lyu et al. (2017)
Pomegranates	Isochoric freezing	-2.5°C or 12 MPa	Maintained texture, color, and decreased microbial presence	Bilbao-Sainz et al. (2022)
Sweet cherries	Isochoric freezing	-4°C or -7°C , 29.5 MPa for 24 hours	Minimized cellular damage, retained nutritional value	Bilbao-Sainz et al. (2019)
Fish (tilapia)	Isochoric freezing	-5°C for 3 hours	Maintained texture, lowered microbial load	Bilbao-Sainz et al. (2020a, b)

3 Factors Affecting Freezing and Cooling

Several factors can affect the freezing and cooling of food products. These factors affect the process's efficiency and the final product's quality. Some of the key factors include:

3.1 Temperature

The temperature of the freezing or cooling agent (such as air or refrigerant) directly affects the speed at which heat is extracted from the food item. Lower temperatures generally lead to faster freezing or cooling but must be controlled to avoid freezing too rapidly or excessively (James & James, 2023).

3.2 Rate of Cooling/Freezing

The speed at which the food product is cooled or frozen can impact its quality (James et al., 2015).

3.3 Product Characteristics

The composition, size, shape, and starting temperature of the food item affect its freezing and cooling behavior (Parandi et al., 2022). Products with higher water content freeze more readily (Nowak & Jakubczyk, 2020), while those with higher fat content or thicker consistency may require longer cooling or freezing times (Yang et al., 2020).

3.4 Surface Area of the product

The speed at which heat transfers during cooling or freezing is dependent on the ratio of surface area to volume in the food product. The larger surface area foods cool or freeze more rapidly than the foods that have less surface area, as studied by Sian et al. (2023) and Oyinloye and Yoon (2020).

4 Cooling Techniques Based on Pressure

Considerable efforts have been made to innovate and develop emerging cooling methods. These new approaches aim to improve efficiency, minimize damage to food products, and enhance overall quality and safety. Some examples of emerging cooling methods are discussed below.

4.1 Vacuum Cooling (VC)

Vacuum cooling (VC) initially found success in rapidly cooling lettuce and mushrooms before its application expanded to various fruits and vegetables. Over time, its utility extended to efficiently cooling cooked meat products. Furthermore, VC techniques have been adapted for cooling other moisture-rich items, including cut flowers, bakery goods, fishery products, and steamed buns. This method has proven versatile in preserving freshness and extending shelf life across a diverse range of perishable products. The principle underlying vacuum cooling (VC) is rooted in the concept of evaporative heat transfer (Zhu et al., 2019). Vacuum cooling has emerged as a highly promising low-temperature method in the food industry, leveraging pressure differentials to achieve rapid and efficient cooling of food products (Li et al., 2017). This innovative technique works by creating a vacuum environment, resulting in a decrease in the boiling point of water, enabling it to vaporize rapidly from the surface of the food. As water evaporates, it carries away heat, effectively cooling the food (Zheng & Sun, 2004). One of the notable benefits of vacuum cooling lies in its capacity to reduce the risk of thermal damage to delicate food items (McDonald & Sun, 2000). Unlike conventional cooling methods, which may subject foods to prolonged exposure to high temperatures, vacuum cooling rapidly reduces the temperature without causing significant heat stress (Feng et al., 2012).

The vacuum cooling (VC) process unfolds in three stages. Initially, During the phase of constant temperature and pressure reduction, no cooling takes place. As the pressure decreases to the point where water vaporizes at the product's initial temperature (known as the flash point), the second stage commences, marked by the onset of cooling. Here, as moisture evaporates and vapor is discharged, the temperature swiftly descends to the desired level. Finally, in the third phase, referred to as pressure restoration, the air is allowed back in the chamber by vent valve, returning it to ambient pressure. In the case of liquid cooling, the process can be further categorized into phases occurring prior to boiling, during boiling, and following boiling, determined by the flash point (Song et al., 2015).

A typical vacuum cooling system consists of several key components designed to create the necessary conditions for rapid and efficient cooling of food products. These components may include vacuum chamber, vacuum pump, vapour condenser (Sun & Zheng, 2006). The vacuum chamber serves as a tightly sealed enclosure where the food samples are placed for cooling (Bao et al., 2023). It connects to a vacuum pump, which is responsible for creating and maintaining the necessary vacuum level within the chamber (Parikh, 2015). By removing air and other gases from the chamber, the vacuum pump creates a low-pressure environment, enabling quick vaporization of water from the food's surface samples. Additionally, the vacuum chamber may feature insulation to reduce the transfer of heat from the surroundings and ensure efficient cooling. It also provides a regulated environment where temperature, pressure, and airflow can be adjusted to maximize the cooling method and preserve the foods quality (Chambers, 1998). The implementation of vacuum cooling has proven effective in enhancing processing methods for various

food items, including liquid and baked goods. By significantly reducing cooling times, this technique boosts process efficiency and minimizes the time required for products to reach markets. As a result, vacuum cooling not only streamlines production processes but also facilitates quicker delivery of fresh goods to consumers, ultimately benefiting both producers and consumers alike (Wang & Sun, 2001).

4.2 Vacuum Film Cooling (VFC)

It is a modified version of the vacuum cooling technique, which leverages the principles of evaporative heat transfer to achieve cooling. VFC includes applying water as a thin film onto the surface of the food item before subjecting it to a vacuum environment (Tyuftin & Kerry, 2023). This water film improves heat transfer efficiency and enables faster cooling than traditional vacuum cooling methods. The Vacuum Film Cooling (VFC) process typically comprises three primary stages: The stages of mild evaporation, flashing, and boiling occur during VFC and are influenced by the pressure (vacuum) in the chamber relative to the saturation pressure at the food sample's temperature. At the beginning of the VFC process, the chamber's initial pressure exceeds the saturation pressure. During the mild evaporation phase, evaporation is mainly governed by free diffusion. Water molecules evaporate gradually from the exterior of the food product as the pressure decreases, absorbing heat and causing a gradual reduction in temperature.

As the pressure continues to decrease, a point is reached where it equals the saturation pressure. This marks the onset of the flashing stage. In this stage, the evaporation rate increases significantly as the surface water on the food product initiates to vaporize rapidly. This rapid evaporation results in a sudden drop in temperature, facilitating efficient cooling of the food product.

Finally, as the pressure continues to decrease further, it falls below the saturation pressure, leading to the boiling/mild evaporation stage. In this stage, the surface water of the food product reaches its boiling point and begins to boil vigorously. Despite the vigorous boiling, some evaporation may still occur due to mild evaporation, contributing to further cooling of the food product (Zheng & Sun, 2004).

4.3 Vacuum Spray Cooling (VSC)

Vacuum spray cooling introduces a novel application of spray cooling within a vacuum environment, offering a distinctive method for achieving rapid cooling. By operating within a vacuum, this technique capitalizes on the principles of flash evaporation to enhance cooling efficiency (Wang et al., 2017). The operational fluid and the heat transfer coefficient of the spray flash unit gives the efficiency of VSC cooling. The temperature of the liquid film on the surface is influenced by various factors such as nozzle atomization, vacuum level, and spray height, which impact

the droplet flash process. Notably, reducing the diameter of droplet to one fifth results in a twofold acceleration of the droplet temperature increase over time (Fu et al., 2022). VSC harnesses the principles of evaporative heat transfer and vacuum technology to achieve swift and uniform cooling, maintaining the quality, texture, and freshness of perishable foods. VSC involves spraying water as a fine mist onto the surface of the food product within a vacuum chamber, where the reduced pressure promotes rapid evaporation, leading to cooling (Zheng & Sun, 2004). The overall convective heat transfer coefficient undergoes several influences during the heat transfer process, particularly from factors like flow rate. Increasing the flow rate twofold significantly boosts the coefficient of heat transfer (a 266% increase). The flow rate of spray, which depends on factors such as nozzle discharge coefficients, quantity of nozzles, and spray pressure differentials, is managed through various methodologies detailed in multiple studies. Therefore, it is crucial to examine parameters such as nozzle discharge coefficients, multi-nozzle arrays, spray pressure differentials, and levels of vacuum in the flash chamber on VSC (Gao et al., 2019). VSC has demonstrated substantial reductions loss in quality during vacuum cooling and efficiently shortens cooling times. It also maintains the water-holding capacity and pH of food and dairy items post-treatment (Li et al., 2023).

5 Freezing Techniques Based on Pressure

5.1 Pressure Shift Freezing (PSF)

This technique has garnered attention for its ability to precisely manage ice crystals arrangement and the size in food items, thereby further enhancing their quality (Norton & Sun, 2008). PSF is notable because, after pressurization at low temperatures and subsequent pressure reduction to atmospheric levels, it induces rapid and uniform ice crystal distribution, promoting ice nucleation due to supercooling. In contrast, conventional freezing sees the phase transition starting from the surface and progressing toward the innermost part of the sample, encountering various temperature ranges that result in crystal growth (Préstamo et al., 2005). This phenomenon can be broken down into two main steps. First, there's the part where the temperature rises from super-cold (-20°C) to the freezing point (-0°C). This happens because heat is released during this process, which is called primary freezing. Then comes the second step, where the ice turns into water, marking the end of freezing. This step is known as secondary freezing (Fernández et al., 2006). Foods treated with PSF exhibited lower levels of tissue harm when compared to products frozen through conventional methods (Choi et al., 2016). PSF emerges as an invaluable technique for freezing large food items, particularly those characterized by poor thermal conductivity. The inherent challenge lies in the uneven distribution of temperature within such foods, resulting in significant thermal gradients. These gradients hinder the attainment of swift freezing rates, particularly in the core of the

food item. In this context, PSF offers a strategic solution to overcome these challenges and achieve more uniform and efficient freezing throughout the entire food item (James et al., 2015). One of the primary advantages of PSF is to reduce damage to the cell microstructure during processing. Products treated with PSF retain sensory attributes (texture, color, flavor, odor, overall appearance) and nutritional properties closer to those of the raw product (PrUstamo et al., 2004).

5.2 *Isochoric Freezing (ICF)*

Isochoric freezing is considered a unique method involving high pressure (Zhu et al., 2020). While conventional freezing methods rely on the isobaric (constant pressure) approach, ICF utilizes a constant volume process. This technique has been found to result in higher quality frozen foods with fewer irreversible changes compared to traditional freezing methods (Nida et al., 2021). In an isochoric procedure, there is an isotonic solution in which food is kept within a durable container built to endure high pressures. Tubes made of stainless steel, composites of carbon fiber, and sturdy phenolic thermosets are used, each equipped with pressure sensors and safety valves tailored to specific pressure and temperature requirements (Rubinsky et al., 2005). The thermodynamic conditions of freezing play a crucial role. Studies on tomatoes, cherries and potatoes have shown that ICF (isochoric freezing) enhances the nutritional quality of food kept at temperatures below freezing. From these findings it can be concluded that isochoric freezing significantly enhances the physical, chemical and nutritional quality of stored foods in contrast to conventional methods. This technique prevents the formation of ice crystals in samples processed at low pressures and temperatures, ensuring high quality. Additionally, isochoric processing can mitigate temperature fluctuations during transportation and storage, which might otherwise cause phase transitions unlike gradual temperature changes (Dhanya et al., 2023).

6 **Effects of Low Temperatures on Microorganisms**

Microorganisms are classified into four distinct categories based on their sensitivity to temperature: thermophiles, mesophiles, psychrotrophs, and psychrophiles. Each group exhibits specific temperature ranges conducive to their growth (Waites et al., 2009), as outlined in Table 8.2. Beyond just temperature requirements, these groups also vary significantly in their growth rates. Notably, psychrophilic bacteria tend to exhibit slower growth rates, even under optimal temperature conditions. This disparity in growth rates is particularly significant in refrigerated environments, where psychrotrophic and psychrophilic microorganisms pose primary concerns for food safety and preservation (Margesin, 2009). Understanding these

Table 8.2 Microorganism grouped by their growth temperature

Group	Optimum temperature (°C)
Thermophiles	55–75
Mesophiles	30–45
Psychrotropes	20–30
Psychrophiles	12–15

temperature-dependent microbial behaviors is crucial for effectively managing and controlling food spoilage and ensuring food safety standards are met.

Freezing and cooling play pivotal roles in inhibiting the growth of a broad range of foodborne microorganisms within the food and dairy industry (Amit et al., 2017). By lowering the temperature of food products, these processes effectively slow down or halt the proliferation of most microbial contaminants. This inhibition plays a critical role in maintaining quality of food products by preventing the growth of harmful bacteria, molds, and yeasts. These microorganisms can cause food spoilage and pose potential health risks to consumers. Consequently, proper freezing and cooling practices are integral components of food safety protocols in both the food and dairy sectors, ensuring that products meet regulatory standards and maintain their integrity from production to consumption (James & James, 2023).

7 Effect of Low Temperature on Enzymatic Spoilage

The impact of low-temperature freezing and cooling on enzymatic spoilage in food is substantial. Enzymatic processes are intricately linked to temperature, as lower temperatures typically impede or cease enzymatic reactions altogether (Zaritzky, 2000). Through freezing and cooling, the activity of enzymes involved in food degradation is restrained, efficiently extending shelf life and preserving the integrity of food products (De Ancos et al., 2012). This inhibition of enzymatic activity is important for safeguarding food safety and quality, particularly in items such as vegetables, fruits, and dairy products. Moreover, the controlled application of low temperatures helps mitigate enzymatic spoilage throughout the food supply chain, ensuring consumer satisfaction and reducing food waste.

In freezing, if the temperature is decreased below the freezing point of water, it significantly slows down enzymatic reactions. As the temperature drops, the mobility of water molecules decreases, limiting the movement of enzymes and their access to substrate molecules. This effectively slows down enzymatic activity, reducing the rate of spoilage reactions in frozen foods (Charoenrein & Harnkarnsujarit, 2017).

Likewise, during cooling processes, the gradual reduction of food product temperatures leads to a deceleration of enzymatic reactions. Though less pronounced compared to freezing, cooling remains effective in tempering enzymatic activity by diminishing the kinetic energy of enzymes (Ashie et al., 1996). This reduction in

energy levels curtails their catalytic potential, thereby slowing down the pace of spoilage reactions. Such controlled cooling methods are crucial in maintaining food quality and safety. By impeding enzymatic degradation, cooling methods contribute significantly in maintaining the nutritional value of food items. Additionally, the implementation of proper cooling techniques is integral to ensuring regulatory compliance and meeting consumer expectations for fresh, high-quality food items.

Overall, both low-temperature freezing and cooling effectively inhibit enzymatic spoilage in food by slowing down enzymatic reactions. This preservation method is very crucial in maintaining the quality, safety, and shelf life of food products, especially those prone to enzymatic degradation, such as fruits, vegetables, and dairy products. Temperature control is important to prevent enzymatic spoilage and ensure the longevity of food products throughout the supply chain.

8 Other Benefits

8.1 Preservation of Quality

Low-temperature methods reduce bacterial growth, enzymatic activity, and chemical reactions that can lead to food spoilage and deterioration of quality.

8.2 Extended Shelf-Life

Chilling and freezing can prolong shelf life of perishable products, reducing food waste and improving profitability.

8.3 Increased Food Safety

Low-temperature methods, by reducing bacterial growth, contribute to improved food safety and help prevent foodborne illnesses.

8.4 Cost Savings

Longer shelf-life and reduced food waste result in cost savings for food and dairy companies.

8.5 Retention of Nutritional Value

Freezing and cooling methods help preserve the nutritional value of food and dairy products by slowing down degradation processes.

9 Conclusion

Low-temperature methods, such as cooling and freezing, are widely addressed to improve the shelf-life of food and dairy products. These methods preserve product quality better than conventional thermal methods, as low temperatures do not cause thermal damage. The use of chemical preservatives in food has been reduced due to the adoption of low-temperature processing methods. Various cooling methods have been explored, but conventional cooling has limitations in terms of efficiency and potential damage to the food. To overcome these limitations, pressure-related techniques like vacuum cooling, Vacuum spray cooling, pressure shift freezing and Isochoric freezing have emerged as efficient solutions. These methods offer improved efficiency and effectiveness in preserving product quality. Overall, the continuous innovation and integration of advanced freezing and cooling techniques hold great promise for enhancing the characteristics of food items.

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Chapter 9

Mixing, Blending, and Emulsification in Processing



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1 Introduction: Mixing

Mixing, is a unit operation carrying a main objective of blending ingredients, bringing reduction in the non-uniformities in various properties of food such as concentration, color, texture and taste in various parts of the mixture. Mixing generally requires movement of all the ingredients for acquiring a desired homogeneity or the product must have uniform distribution of all the ingredients. It is achieved by blending of the various food particles in different parts of a particulate mass. Mixing can be a simple as well as a very complex process. Mixing can simply be carried out by placing all the ingredients in conjunction in a single vessel while in complex case of mixing requires high amount of planning, energy and expenditure. Food industries are highly dependent on this operation to ensure products having uniform properties. Optimum method of mixing produces a uniform product in minimum cost and time for power, labor and overhead (Barbosa-Cánovas et al., 2005). When every single part of the mixture contain equal amount of each component, it is referred to as a perfect mixture and no difference exist in the sample anywhere (Cullen et al., 2017).

Ingredients that are to be mixed greatly influence the type of equipment and it is dependent on various mixing scenario i.e. liquid—solid mixing (dough, butter and pastes), solid—liquid mixing (sugar and coffee), solid—solid mixing (powders or textural effects), liquid—liquid mixing (emulsions: spreads and margarines) and gas—liquid mixing (chlorination or fermentation). For obtaining maximum size of production, a balance is must to be made between the equipment's and the

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properties of the ingredients without consuming high amounts of energy and time that would give better and energy efficient process. Apart from it, equipment is also decided on the basis of rheology, hygienic design and the suitability of the equipment for cleaning. These are important parameters to be considered to prevent food products from microbial contamination leading to poor hygienic standards. Liquid—liquid mixing is carried out by a wide range of mixers i.e. paddle mixer, turbine mixers (variable impellers), anchor mixers, wide range of static mixers and propeller mixers.

1.1 Role of Mixing

‘Mixing’, is an elemental unit operations in many industries such as pharmaceuticals, chemical and food industries. Mixing is carried out for bringing an increase in the level of homogeneity and causing a reduction in non-uniformity in food in terms of composition, properties and temperature. Additionally, mixing also contributes in controlling the rates of heat and mass transfer along with changes in structure and reactions.

Mixing is combination of several raw materials together along with controlling the reactions and modification of food’s structure. Failure in the mixing quality might result in poor quality, functional properties, organoleptic attributes and safety concerns of the product. Challenges faced during mixing in the food processing industries are their sanitary design, limitations in continuous mixing, impact of the mixing on the final food products, sensory profile of the product and their complex rheology. The most common unit operations are the mixing of solid, liquid and gases in the food industries. Mixing can also be used for the development of the desired food characteristics i.e. texture apart from maintaining the homogeneity of the food product. If mixing fails at some point of processing than production costs are significantly increased for the required yield of the product, organoleptic properties, functional attributes and quality (Cullen, 2009).

1.2 Terminologies

Some terms must be discussed before discussing mixing:

Stir: to keep anything in motion

Agitate: to move; to disturb; to shake or to excite

Agitator: equipment that is used for mixing things together

Blend: to mingle things intimately to mix them together that they should be inseparable and indistinguishable leading to the production of a harmonium product

Mix: when two or more substances are put together with one another so all the ingredients are diffused with the other one

Knead: working up of dough into a paste or dough and these are weld and blend together

1.3 Factors Affecting the Extent of Mixing (Lindley, 1991)

- Mixing time
- Type of material used
- Temperature of the food product
- Mixer's design including shape, psize, rotational speed and paddle geometry
- Concentration of salt and polyphosphate

In food industries, mixing is generally carried out in batches due to the greater flexibility it gives along with lower installation costs when compared to continuous processes of mixing (Gijón-Arreortúa & Tecante, 2015).

1.4 Different Systems of Mixing for Different Operation of Mixing in Food Industry

Food products that are to be mixed exist in three different phases i.e. solid, liquid and gas that gives rise to a variety of mixing possibilities (Rielly, 1997).

1.4.1 Solid-Solid Mixing

All the solid ingredients are mixed in such a way that they fulfill the requirement in terms of consistent nutrition that is mentioned in the labelling and provide specified organoleptic properties in terms of specific taste and textural effects. Various factors influence mixing i.e. time, size, density, shape and types of powder and design of mixer that is used. Ingredients of solid mixing have variable densities, size, shape and texture (Berk, 2009). The ability of the raw ingredients to mix together can be assessed by porosity and bulk density (Barbosa-Cánovas et al., 2005). Successive mixing and demixing phases are responsible for mixing of different particles as variable particles of the mixture possess different behaviors. The tendency of the mixtures to separate either during or after mixing depends upon the dry ingredients physical properties density and particle size (Shenoy et al., 2015). Ingredients of similar sizes have the probability to possess equilibrium state in contrast to ingredients of different particles size that are highly prone to segregation; however, deviations in density or shape of the particles could be additional parameters that could be used for the determination of the segregation of the particles (Williams, 1976). Homogeneity of the mixture is determined by the distribution of the particle size of ingredients in the solid mixture. Particles smaller in size are more prone to fall

downwards due to their reduced density that leads to their segregation. Maintaining a balance between size and density of the particles can prevent occurrence of free surface segregation. Several other properties of dry mixtures i.e. compressibility, bulk density and flowability are affected by the particle size distribution. A uniform mixture having ingredients of smaller particle size have greater surface contact area which strengthens the intermolecular forces followed by bringing a reduction in the degree of their tendency to segregate (Landillon et al., 2008). Solids are mixed with greater difficulties when compared to liquids due to the variability in the size, density and shapes of the solid particles. Equipment's used for mixing of solids can be classified into two sections:

- Diffusive mixers—the particles are in random motion due to the effect of gravity or vibration. Examples—drum blender, V-shaped tumbler and double-cone tumbler
- Convective mixers—the particles are mixed by mechanical agitation. Example—paddle mixer and trough mixers. Rubber mixer, a kind of trough mixer is one of the most common type of mixer used.

1.4.2 Solid-Liquid Mixing

Solids added to the liquids for reconstitution purpose of fluid i.e. coffee, tea, sugar is mixed to hot water. Liquids added to the solids for the formation of food dough, pastes and batters. The major phenomenon's for gassed and ungassed suspensions are design of the machinery, hydrodynamics and mass transfer in floating and settling solids. Denser particles of solid when compared to liquid settles down when no agitation is applied while less dense particles floats in the suspension. These lighter and denser particles of solids have air entrapped within them are somewhat water resistant. Mixing can be done by means of gas bubbles ow without them thereby termed as gassed and ungasses suspensions respectively. Gas bubbles can enter a system directly or indirectly by variable means such as a product of gaseous reaction, hydrogenation process that is solid catalyzed and evaporative crystallization. They are entrained either purposefully or unintentionally from the headspace.

Usually, solid suspensions are prepared in vessels that are agitated or stirred manually or mechanically. Possibilities of suspending small amounts of solids are there with the help pumped liquid jets. For incorporation of small particles into polymers static mixers are employed. The basic goals of solid-liquid mixing are creation or maintenance of slurry and acceleration and improvement is carried out for mass transfer rate between the phases of solids and liquids. According to Atiemo-Obeng et al. (2003), the mixing process facilitates the following:

- Mass transfer across the solid–liquid interface;
- Solids suspensions;

- Settled solids resuspension;
- Floating solids incorporation;
- Solid aggregates dispersion, particle size control and abrasion from interaction between particles and particles-impeller and also from fluid shear.

1.4.3 Liquid-Liquid Mixing

In this creation of liquid-liquid emulsions takes place i.e. margarine and spreads. Liquid mixing is divided into two classes i.e. miscible and immiscible liquids. Mixing of two miscible liquids is expressed by the term “blending” while dispersion of two immiscible liquid or emulsion formation is referred to as “mixing”. Immiscible liquids used for mixing water, acidic/alkaline solution and hydrocarbons with various organic liquids leads to formation of various products of emulsions. Fluid dynamics is useful in the characterization of liquid mixing using several phenomena that include breakup of droplets, drop suspension, coalescence, interfacial area, inversion of phase, mean flow pattern, drop size distribution, turbulence, composition of system and small impurities in food products. These phenomena are responsible in making dispersion of liquid-liquid a difficult technique in many industries. However, blending two miscible liquid is easy in nature when two soluble solids are present and there is no resistance of dissolution at the interface of the two fluids. Molecular diffusion and natural convections are slow processes of blending. Therefore, agitation systems are used that apply forced convection bringing homogeneity in any sample rapidly. Mixing operations are complex as it requires understanding of both fluid flow aspects along with considering the power requirements and the mechanical equipment (Afshar Ghotli et al., 2013). Variable mixing equipment's are used for different application for prevention of scorching, mass transfer, for lowering or increasing viscosities, promote heat transfer i.e. in jacketed kettles, phase dispersion or the combination of two or more processes.

The input power (P) required for agitation is calculated by the following formulae:

$$P = f(\mu; g; \rho; N; D)$$

Where,

μ = viscosity of the liquid

g = acceleration due to gravity

ρ = density of the liquid

N = rotational speed of the impeller

D = diameter of the impeller

1.4.4 Gas-Liquid Mixing

Incorporation of gas into the fermentor liquid to enhance microbial growth. In food industries, this type of mixing holds similar importance as liquid-liquid mixing. This type of mixing is recently innovated to use in foods where air acts as their primary element. Gas inclusion is an important step in food sector in meals where bubbles are found that includes bread, champagne, some chocolates, beer and ice cream. “The inclusion of bubbles in foods permits creation of very novel structures.” Gas inclusion is important in food products like yogurt and cheese for the growth of bacteria. Several food products (ice cream, beer, etc.) also contain foams. Two main techniques that are carried out for incorporation of gases into liquid are mechanical agitation and mixing induced by steaming. Analysis of amount of gas introduced can be analysed along with the phase by phase mixing techniques when gas-liquid mixing is carried out. Amount of gas bubbles that are incorporated in liquid foods can also be analysed by the gas hold up by the food products. “The range of gas-hold up values in liquid foods that contain bubbles is from 15% to 20% in milkshakes to over 90% in extruded products like rice cakes and popcorn.” (Elia et al., 2011).

1.5 Mechanism of Mixing (Cullen, 2009)

Mechanism of mixing is of three types depending upon the scale of mixing:

Micromixing

Micromixing is small scale mixing that is carried out in molecular level.

Macromixing

Macromixing is carried out in large scale levels

Mesomixing

Mesomixing is said to be mixing that is carried out in immediate level.

In contrast to miscible liquid mixing, mixing of solid particles is a reversible operation. When there are 2 miscible liquids, the mixing is improved or retained over the transportation while in case of mixing up of two solid particles, separation takes place. On movement, particles of solid mixtures change their positions and rearrangement takes place randomly. Change of circulation path is the characteristic property of powder mixing. Exchange of position of two identical particles is useless so for a useful mixing, the particles must undergo a different circulation path. The three-basic mechanism of solid mixing are: shear, diffusion and convection. There can be other mechanism i.e. segregation.

1.5.1 Shear Mixing

Mixing has been induced by change in the momentum of the solid particles that have different velocities i.e. differential velocity distribution. Shear mixing causes the coherent group of particles to break along the plane as sliding planes and emerge in the bulk material. Around the agitation impeller and walls of the vessel, a change in velocity distribution takes place due to the extension and the compression of the bulk powders. Shear mixing can be carried out in powder vessels, rotary vessels and blowing ports of gas-flow mixers in both continuous and batch operations. These are also capable of mixing of particles that are semi-microscopic in size. In case of free-flowing powder, diffusive and shear mixing both takes place that are also useful in segregation according to sizes or de-mixing therefore convective mixing is the major mechanism for free-flowing powders. In shear mixing, particles are mixed by slipping them along the failure planes in the materials.

1.5.2 Diffusive Mixing

Random motion of the dry ingredients is also called as 'random walk phenomenon'. Diffusive mixing is generally used for mixing of the microscopic homogenization and the rate of mechanism is lower than then convective mixing. Axial mixing is the most suitable mechanism for diffusive mixing and it is almost similar to diffusion of gaseous molecules into the liquid phases. In close mixtures, pure diffusion is of major importance when individual particles are mixed and these are mixed in exceedingly slower rates. This mixing is obtained when particles are relatively similar to each other therefore giving a fine scale mixing.

1.5.3 Convective Mixing

Mixing of particles takes place in huge groups or masses from one location to another. Convective mixing is caused by some kind of rotational motion in a mixer vessel, gas flow or by an agitation impeller (ribbon or paddle). Mixtures of powders' macroscopic particles in bulk quantity generally uses it for the mixing. Larger segments of the populations travels at faster rate thereby no changes occur at the microscopic levels. Due to this, pure convection is less effective that finally leads to a mixture that still may have poor characteristics of mixing. Convective mixing is satisfactory for batch mixing operations; however, continuous mixing possess some unfavorable effects. In convective mixing, group of similar particles are displaced by each other that leads to partial mixing or larger scales (Rielly et al., 1994).

1.5.4 Segregation

Particles having variable physical properties in terms of size, density and shape when mixed together go with the tendency to un-mix afresh. Therefore, in segregation mixing and de-mixing occurs simultaneously; however, predominance of mixing over de-mixing results the intimacy of mixing. Other properties responsible for segregation are surface properties, friability, tendency to cluster or aggregate, flow characteristics and moisture content. The similarity in size, density and shape makes the process of mixing easier with great intimacy in the final product. Once, equilibrium is achieved on mixing and de-mixing, it briefs the final product's condition (Ortega-Rivas & Ortega-Rivas, 2012).

1.6 Mixing Process

Mixing process can either be batch wise or in continuous phase. In food and agricultural industries, batch wise mixing is used; however, continuous mixing is used in the production of products like ice cream and margarines. Batch processes are generally used as they have lower installation costs and possess greater flexibility in contrast to continuous process (Gijón-Arreortúa & Tecante, 2015). Attributes of batch and continuous mixers are summarized in Table 9.1 (Niranjan et al., 1994).

Table 9.1 Attributes of batch and continuous mixers

	Batch	Continuous
Advantages	Suitable for small-scale production Versatility Shut down cleaning Start-up is easy Interchangeable impellers that allow materials of wide variety to be mixed Changing of product is easy	Variation of batch to batch mixing is reduced Low requirement of labor Physically small for given throughput Integral part of continuous production processes
Disadvantages	Large batch to batch variation Upstream and downstream processes are also in batches leading to requirement of holding vessels. Labor intensive Cleaning, sterilization, loading and unloading takes time	Limited to mixing of solids and liquids that have suitable flow characteristics Start up and shut down of the machine leads to product wastage as a result of non-equilibrium conditions and cleaning
Examples	Horticultural compost Preparation of dough Dough preparation	Margarine Ice cream Carbonation of drinks

1.7 Types of Mixtures

Mixtures of two or more ingredients that have variable compositions (dry beverages, ice-cream or cake mixes) leads to the formation of food powders. Mixtures may contain either small (dried meat or vegetables) or large particles (soup mixes with noodle particle) (Barbosa-Cánovas et al., 2005). Different types of mixture are diagrammatically summarized in Fig. 9.1. Powder mixture can be further classified into three main categories:

- (a) Random mixtures (non-interactive)
- (b) Ordered mixtures (interactive)
- (c) Segregating mixtures

1.8 Forces and Mechanisms of Mixing (Lindley, 1991)

Mixing operation is accompanied by variable energy transfers or exchanges and these are usually by physico-chemical or physical means. Transport/transfer of energy occurs fundamentally by mass transfer, heat transfer or by momentum transfer in the moving media (fluid flow).

The mechanism of mixing can be summarized in the following ways:

- For low viscosity liquid food products—turbulence and diffusion
- For highly viscous liquid food products—breaking, deformation, recombining, laminar flow, streamline flow and shear flow.
- For dry and non-cohesive solids—convection, diffusion and shear.
 - Degree of mixing
- Degree of mixing can be affected by various factor: (Fellows, 2022)

The relative particle size, density and shape of each component

The tendency of the particles to aggregate

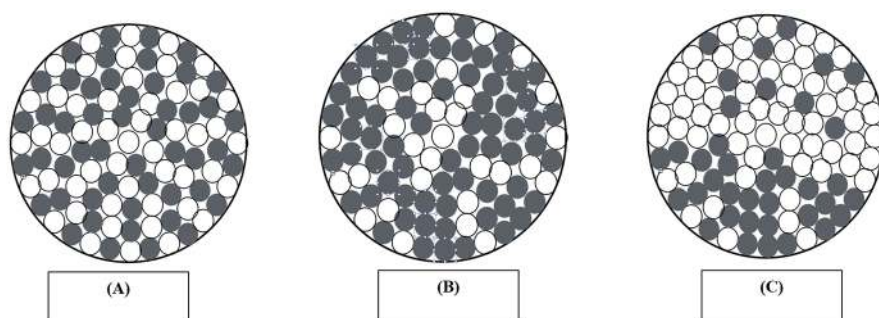


Fig. 9.1 Types of mixture; (a) Ordered mixture; (b) Random mixture; and (c) Segregated mixture

Each component's moisture content, surface characteristics and flow properties

Efficiency of a particular matrix for mixing those components

- Indices of mixing
- Factors affecting equipment design
- Applications

1.9 Mixing Quality

Quality of mixing is a persistent requirement of industries that ensures accuracy of control over the mixing process. Mixing is affected by many factors that includes the type of mixing, the time of mixing, types of the powder that needs to be mixed and design of the mixer (that includes the shape, rotational speed, size and paddle geometry). For mixing, a relative motion is required that makes the mixture of desired uniformity and of homogenous distribution (Cuq et al., 2013).

Mixing quality of the ingredients also depends upon the input energy given by unit fluid volume and unit mass of the dry ingredients. In mixing, power number, Froude number and Reynolds number are correlated. These numbers are used for understanding the forces that are required in different mixing procedures that relates to its dimension, operating conditions and the type. Reynolds number is the combination of all the inertial and the viscous forces. Froude and power number are related to gravitational forces and power/torque respectively with respect to the speed of shaft, liquid's density and impeller's diameter. Reynolds number is useful in understanding the flow regime and also helps in assessing whether the power number is constant or not. The importance of the Froude number is their when Reynolds number is more than 300 and the vessel should not be baffled.

1.10 Overmixing

Overmixing means excessive mixing in one way or another leads to wasting of energy along with getting counter proactive i.e. opposite of the desired effects. On mixing biological materials, excessive power inputs or high speeds of impeller leads to damaging the mammalian cells or the mycelia in the fermenters. Characteristics rheological properties of certain polymer solution is due to their molecular structure which are either destroyed or not reformed due to overmixing. In the process of crystallization, high speed of mixers would lead to enhanced mass transfer that facilitates secondary nucleation and inhibits the formation of large crystals. In solid mixing, adequate mixing might be attained during short duration and further mixing might lead domination of segregation that further causes degradation in the mixture quality. Therefore, over mixing i.e. either mixing for more time or with more energy

might harm the product in one way or another and leads to product development of a poorer quality (Nienow et al., 1997).

1.11 Challenges in Mixing

Food mixing is the mixing of various ingredients from dry powders, highly viscous liquids to nanoemulsions and particulate suspensions. In food particles, particulates are in wide variety with different shape, density, strength and size that results in major issues of segregation. These challenges of segregation problems can be reduced by production of particles of similar sizes, reduction of turbulence during transport and prevention of particles from agglomeration. Food safety is a major element of the food industries, therefore mixing process must be designed in such a way that it must not lead to any kind of microbial infestation. Therefore, it is essential to use standard protocols of cleaning in addition to it equipment's must have appropriate hygiene design (Cullen & O'Donnell, 2009).

2 Blending

Blending is classified into three phases before further processing:

- Dry blending (blending of dry ingredients)
- Liquid blending (blending of liquid ingredients) and
- Blending of aqueous and dry ingredients

2.1 Dry Blending

Blending of dry substances such as grain, grain pieces, powders, flours, starches, etc. is most frequently carried out via ribbon blenders that is sometimes known as horizontal batch mixers. The agitator's two ribbon faces are in opposite direction. This design is useful for carrying out high-capacity blending in an uniform manner and this mixing is held in any constant suspension. Stainless steel blenders are constructed where clean in place (CIP) type of cleaning is preferred.

These blenders are covered by gasketed hinged covers that reduces any kind of leakage. The blender should not consist of any type of bolts, pockets, ledges or screws on the inner side. All the bearing should be in the outer side of the blender for reduction in the contamination. It is a batch type of operation where the size of ingredients to be processed at a single time should not exceed the height of the ribbon as it may lead to non-uniform blending. The common cause of blending is overloading of mixer by ingredients expecting higher output.

2.2 Loading and Unloading of Ingredients

The most common way to load ingredients in mixers is to open the head of the tank or the instrument followed by dumping all the ingredient in the instrument by hand. However, this method leads to high amount of dust in the surrounding making it a worst method. This disadvantage leads to the use of an improved method in which in the dump station, a hood is present that is used for the purpose of dust suction finally leading it to the dust collector. Further, a still better method in which the mixer is directly loaded with a receiver (present over the mixer in which all the ingredients are loaded). It is one of the fastest methods hence improves the efficiency of blending. The total cycle time comprises of three parameters i.e. (a) loading; (b) blending; and (c) discharge. Compounds once uniformly mixed are discharged out with the help of a discharge hole gate that is usually present towards the bottom of the mixer. From here, mixed items can be conveyed anywhere where they are to be used.

2.3 Continuous Blending and Mixing

When dry ingredients are uniformly mixed using blending is followed by mixing with liquids, a continuous blender is used. Continuous blender has a horizontal housing in which one or two shafts are mounted. Dry ingredients that are to be blended are added to one end where they undergo blending followed by releasing them from another end are further mixed by liquid that is injected through the ports. These continuous blenders are generally constructed from carbon or stainless steel and are commonly used for blending the syrups, flavors and oils to the dry ingredients. Designs of paddle mounted on the shaft can vary accordingly. Usually, paddles are mounted in shaft in a way in which they can pitch forward or backward thus ensuring uniformity of mix and proper retention time. For gentle mixing, loop paddles can be employed. These mixers have clean-out doors that ease out the access to the inner surfaces for clean up.

2.4 Liquid Blending

Commonly used flavour materials in breakfast cereals are malt extract of barley, dry or liquid sugar. Apart from them, few other flavour materials can also be used such as water soluble heat stable vitamins, salt, etc. Ingredients of the solutions before mixing with solids are blended uniformly. Malted barley extract mixes well with toasted grains and these foods are generally bland in taste and can be consumed as a breakfast food. This mix of toasted grains and barley malt extract is very difficult to weight and move as it is composed of solids (80%) therefore making it a very

viscous, unpumpable and sticky mix. For its uniform dispersion over the grains, it is diluted with water and it is mostly carried out in batch kettles or tanks that have in built agitators. Components to be blended are kept in kettles with measured amount of water and the equipment's used for these measurements must be carefully engineered so any kind of inconsistency is avoided in delivering the amounts of liquid from batch to batch. In continuous systems, either volumetric gravimetric measurement system or loss in weight is observed. Agitator in another type of mixture is mounted on the top of the open tank. Propeller blades acts in mixing and agitation and further leads to blending of malt, sugar, water, salt and other ingredients too. Whenever liquid flavour mixing is done, a special care must be taken for selecting the materials for constructing the vessels and the pipings. Few mixtures can be corrosive in nature therefore, always stainless steel must be used and grade 316 of stainless steel is better than normal grade 304.

2.5 Blending Dry and Liquid Mixes

This blending is generally used in blending of flavors in liquid forms with the dry ingredients. It is generally completed by the use of continuous mixers having either one or two shaft and also in screw conveyors having simple cut-flight (Caldwell et al., 2000).

3 Emulsion

Emulsion is a fundamental example of liquid-liquid mixing that is amongst the major systems of mixing and it is well known due to its nature of complexity. A major group of products in the food industries are either emulsion or are produced with the help of those emulsions. Emulsions is highly complex in their structure along with its composition and dynamic. Emulsion consists of two liquids that are immiscible in nature in which one is dispersed in another in the form of small and spherical droplets. Few examples of emulsions in food industries are milk, desserts, salad creams, sauces, mayonnaise, butter and soups. The major objective of any food industry is to acquire homogeneity in fluid to keep the price low (Elia et al., 2011).

Emulsion droplets reflect every conventional feature of metastable colloids: Brownian motion, irreversible transitions that typically entail their destruction, and reversible phase changes due to droplet interactions that may be significantly altered. Emulsions are produced by shearing of two immiscible liquids that causes fragmentation of one phase into another phase. Emulsions that are dense in nature are known as bilyquid foams due to the structural similarity they have from foams cell structure of air-water and their ratio is low in the continuous phase. A great variation is found in the internal and mechanical dynamics of the emulsions from

extremely concentrated to the diluted. It is expected that droplets those are highly diluted in nature exhibited the characteristics of the Newtonian fluid behaviour due to the Brownian motion. The internal dynamic of emulsions is highly constrained and they behave like viscoelastic solids when they are more concentrated, which means it is above the volume fraction of random close packing that is around 63% for monodisperse droplets (Israelachvili & Tabor, 1972; Israelachvili & Adams, 1978).

Emulsion consists of two liquids that are immiscible in nature in which one of the liquid droplets are smaller and tends to disperse in other liquid. Basically, emulsion consists of continuous phase (external phase in which the droplets are dispersed) and other is a discontinuous phase (dispersed phase/ internal phase) (Nour, 2018). Some examples of food emulsions in the food applications are milk, desserts, mayonnaise, sauces, butter, soups and salad creams. High quality of the emulsions can be obtained by choosing the right quality and amount of the emulsifier and also the effective procedure for the formation of emulsion and its packaging and storage. Emulsion's physico-chemical and sensorial characteristics are determined by the structure, concentration and type along with the interactions occurring in between the components. Emulsions are generally polydisperse in nature which means the diameter of each droplet varies from another droplet; however, it is possible to produce monodisperse emulsion (Elia et al., 2011).

Emulsion, is an unstable system that are a unfavourable contact between 2 phases i.e. oil and water. Few emulsions possess stability due to the smaller sizes of the droplets and also due to the interfacial films that are present around the droplets. Emulsion can be formed using mechanical force that causes dispersion of one phase into another phase. When the emulsions are formed without any active surface material, they turn out to be unstable as the phases of emulsion will separate out with time into variable layers that depends upon the density of individual layer. Therefore, there is a requirement of surfactants which are necessary for the development of stable emulsions for longer periods of time (Akbari & Nour, 2018).

Food industries have wide applications of emulsions in production of several products as in case of homogenized milk, sauces, creams, desserts, dips, toppings and desserts (Bai et al., 2021). The physico-chemical properties and the sensory profile of any product based on emulsion is influenced by the characteristics of droplets that includes charge, size, concentration and interaction.

3.1 Types of Emulsion (Friberg et al., 2003)

Emulsions are generally classified as simple direct and inverse emulsions. Simple emulsions have oil droplets that are dispersed in continuous phase of water and in inverse emulsion there are water droplets that are dispersed in continuous phase of oil. Generally, emulsions consist of two phases that are immiscible in nature and have a nonzero surface tension. Multiple components are present in these phases on presence of appropriate surface active agents and in principle, they may also involve other fluids that are lipophilic or hydrophilic in nature. In simple emulsions,

Table 9.2 Types of emulsion

Types of emulsion	Properties	References
Water-in-oil emulsions (w/o)	Continuous phase—hydrophobic material (oil); dispersed phase—water Three ingredients—solvent, water and surfactant Four states—stable (Brown in appearance; water content—60 to 80% water), Mesostable (Brown and black appearance; in between stable and unstable), unstable (rapidly separate into two phases in short time) and entrained water (black in appearance; initially 30 to 40% water and after one week around 10% remains)	Ali and Alqam (2000) and Nour (2018)
Oil-in-water emulsions (o/w)	Continuous phase: Water; dispersed phase: Oil Often known as reverse emulsions	Abdel-Raouf (2012) and Nour (2018)
Multiple emulsions Water-in-oil-in-water (w/o/w) Oil-in-water-in-oil (o/w/o)	Generally stabilized by mixture of hydrophilic and hydrophobic surfactants At least two emulsifiers are required in the system in which one should have a low HLB while other has high HLB.	Yaqoob Khan et al. (2006) and Nour (2018)

continuous phases consists of smaller droplets that are sometimes scattered within each droplets of the dispersed phases. These types of emulsions are either referred to as multiple emulsions or double emulsions (Parker, 1992). Types of emulsion are summarized in Table 9.2.

Emulsions could be classified widely into 3 types:

(a) **Water-in-oil (W/O);**

Butter, margarines and fat-based spread.

Stability of these emulsions is due to the fat and surfactants used in the formulation therefore, fewer parameters are considered while determining their stability.

(b) **Oil-in-water (o/w)**

Oil droplets' are suspended in the waters' continuous phase. These types of emulsions are most multifaceted and includes creamers, toppings that can be whipped, mayonnaise, cream liqueurs and mixes of ice creams. Variation in the levels of surfactants can control the level of stability.

(c) **Water-in-oil-in-water (w/o/w)**

These are a type of o/w emulsions and the droplets in them further contains droplets of water (w/o). These emulsions are difficult to stabilize as the water droplets must be stable in the oil phase and further the oil droplets must also be stable in the continuous phase.

3.2 *Emulsifiers*

3.2.1 Principle of Emulsifier

Emulsifiers reduces the interfacial tension between two liquid that are immiscible in nature and wants to be emulsified to form a stable emulsion and prevents the formed emulsion by inhibiting the droplets to coalescence from the internal phase (Ortega-Rivas & Ortega-Rivas, 2012).

3.2.2 Mechanism of Emulsifiers

Emulsifier molecules are aligned at the interface of the two phases in an emulsion in which polar phase faces the aqueous phase while the non-polar phase is towards the oil phase that causes formation of a film at interface. The formed thin layer of emulsifying agent at the interface of two liquids behaves as a coating on the droplet that behave as an internal phase thereby preventing the droplets from further coalescing when any kind of interfacial tension is suffered by them.

Emulsions can be stabilized with the help of emulsifiers. Emulsifiers are “surface-active agents” that are absorbed on the droplet’s surface rapidly after their formation and inhibits their reunification (McClements, 2004). Emulsifiers can be both natural and synthetic in nature. There are only a few emulsifiers; however, synthetic emulsifiers are developed via treating natural emulsifiers with some form of chemicals. Most of the emulsifiers are amphiphilic in nature that means they consist of both polar and non-polar parts facilitating them to form a uniform emulsion of two immiscible liquids. If it carries only lipophilic part then there is no chance of dispersion (Hui, 2006). Water in oil emulsion is produced when the parts of hydrophilic groups are increased while the particles lipophilic in nature are reduced. Emulsion transition takes place from water-in-oil to oil-in water on rise of amount of hydrophilic groups in the emulsion that causes colloidal solution’s development. The reduction in interfacial tension is majorly ascribed to the use of emulsifiers between both the liquids; however, it still does not lead to any improvement in the disruption that is accomplished by providing a mechanical agitation (Hasenhuettl & Hartel, 2008). Therefore, in the food industries a combination of multiple emulsifiers is used so that a wide range of functions are covered. An example where combination of emulsifier is used is cake that makes the cake soft, fluffy and moist simultaneously. Basic emulsifiers that are used by the food industries i.e. small surfactants, phospholipids, proteins, polysaccharides, etc. Most of the emulsions are based on the monoglycerols or their derivatives (Barbosa-Canovas et al., 2009). Effects of emulsifiers on various food products is given in Table 9.3.

Emulsions along with water, oily phases and emulsifiers also contains several other materials such as vitamins, fatty acids, proteins and sugar. An emulsion needs to be stable which means that their properties do not change over time. Droplets must have constant diameters for formations of stable emulsions. Without the use of emulsifiers, the mixture of immiscible will separate out immediately once the

Table 9.3 Effects of emulsifiers in food products

Food product	Emulsifier	Effect	References
Butter	Sodium caseinate	Reduction in the size of fat globules increased Reduction in hardness, elastic modulus and friction coefficient Enhance globule-matrix de-bonding and fracture propagation	Panchal et al. (2021)
Mayonnaise	Soy milk	No effect on viscosity up to 75% replacement No effect on stability up to 50% of replacement No effect on sensory properties up to 50% replacement	Rahmati et al. (2014)
Salad dressings	Sodium caseinate, pea protein blends, tween 20 and sucrose distearate	Blends prepared from higher weight ratios of pea protein/egg yolk has improved or similar rheological characteristics Better physical stability that emulsion formed from egg yolk-stabilized emulsions	Riscardo et al. (2003)
Mayonnaise	MG, DG and TG blends	MG of 98% sin mayonnaise had highest stability Reduction in the levels of MG lead to reduction in the emulsion stability Increment in the MG caused small differences in the rheological properties	Kantekin-Erdogan et al. (2019)
Mayonnaise	Egg yolk and milk protein-based emulsifier	No increase in the oxidative stability was observed on substituting egg yolk with milk protein-based emulsifier	Sørensen et al. (2010)
Walnut butter	Mono-diglyceride and lecithin	Emulsifier leads to reduction in size of the droplets Structural modification of butter on high incorporation of lecithin Increase in stability	Shahidi-Noghabi et al. (2019)

process of mixing is stop. Emulsifier stabilizes the mixture kinetically for a certain time period known as “kinetically trapped” emulsion. Chemical reactions (oxidations) might be responsible for negatively affecting the stability of emulsions and these reactions can be inhibited by making and antioxidants could be brought in use for inhibition of these reactions. Certain external factors (light) might also be responsible for destabilization of emulsions. Continuous phase has enhanced viscosity that results in increasing the stability of emulsion. Addition of thickeners and gelling agents in a mixture results in increment of the mixture’s viscosity. Various examples of food stabilizers are cellulose derivatives, gelatin, pectin, starch, alginates and other jelly forming compounds (Cullen, 2009). Few examples of synthetic emulsifiers are esters of glycerol, sorbital esters of fatty acids,

carboxymethylcellulose, propylene glycol and cellulose esters. Most of the emulsifying agents have chemical compounds that contains both polar and non-polar groups ex. Soap (sodium palmitate) (Ortega-Rivas & Ortega-Rivas, 2012; Bangar et al., 2023).

Mixture of immiscible liquids can be stabilized with appropriate emulsifier along with mechanical methods i.e. agitation using high pressure valve homogenizers or high speed blenders. Formation of the emulsion could be carried out via forcing liquid out of the dispersed phase using membrane, ultrasonication or micro structured system. One other such equipment is homogenizers that leads to homogenization. Droplets diameters are reduced in homogenization as high pressure and shear forces are exerted on the droplets. Prevention of cream separation from milk in dairy industry is an example of high-pressure homogenization (Kutz, 2007). For mixing immiscible liquids of high viscosity, mixers are used that have the ability to provide high rotational moment at a low speed. Examples of agitators used in mixing are planetary and sigma-blade mixers. These agitators exhibit intensely high shear force thereby drastically altering the structure of emulsion (Berk, 2009).

3.3 Destruction of Emulsions

Emulsions are broken down using two different mechanisms. First, Ostwald ripening is caused when dispersed phase is diffused through the continuous phase. During this method of destruction, rupture of film does not occur as the material is continuously exchanged through the continuous phase leading to an increased droplet size but the quantity of them is decreased. As a result, the dispersed system is ultimately destroyed as recovery of two macroscopic phases that are immiscible in nature takes place.

In the second mechanism, the thin film formed between the two neighboring droplets is ruptured and it is referred to as coalescence. For this mechanism to take place, a hole is formed in the thin film that will further grow leading to fusion of two neighbouring droplets. Coalescence and Ostwald ripening is delayed with the use of surface active species that causes the covering up of the interfaces, hence the life-time of emulsions is widened. In real terms, there is a considerable correlation between the existence of molecules of surface-active agents at the interfaces of emulsion and their metastability.

3.4 Weak Forces of Attractive Interactions and Equilibrium Phase Transitions

Reversible phase transitions or flocculation may be induced by attractive interactions between droplets; sedimentation or creaming may also occur, and it depends upon the relative densities of the droplets and the solvents. The aggregation of

emulsion droplets without the disruption of the stabilising film in between is known as flocculation. When several separated droplets shows a notable total pair interaction, flocculation occurs. If the attractive well's depth of the droplets is of order k_bT , droplets aggregates and coexists together as a single Brownian droplets.

When the aggregated and free droplets undergoes continuous exchange between them which owns to a thermal energy leads to achieving a condition of equilibrium. When it is kept for settling for some hours, the formed emulsion separated out into two phases in a macroscopic level; (a) a dilute phase; and (b) a concentrated cream/sediment. When the attractive well's depth is greater than $10 k_bT$, or a significant number in relation to k_bT , the droplets are firmly bonded to the aggregates and are not readily dispersed again by thermal motion. All of the droplets are eventually trapped inside massive, fragile clusters that encompass the entire area. This gel-like network may contract over an extended period of time, particularly in concentrated emulsions (Bibette et al., 1999).

3.5 *Production Methods of Emulsions*

Food emulsions are produced via several methods that are classified as:

- low-energy and
- high-energy processes.

Production method to be used is selected on the basis of volume that is to be processed, physicochemical properties of the emulsion, process cost, characteristics of the initial mixture and droplet size. Low-energy methods of production comprises of spontaneous emulsions and the emulsion phase inversion that might occur due to environmental and compositional changes i.e. pH, formulation's ionic strength and temperature. Low-energy methods of production are cost effective when compared to high-energy methods (McClements & Rao, 2011). Low-energy methods are restricted to few definite oils and emulsifiers which are in requirement of huge numbers of surfactants that are generally not desirable majorly in many types of food products. This method produces droplet of larger size i.e. greater than $10\text{ }\mu\text{m}$ when compared to high-energy methods (Grumezescu, 2016).

High-energy method of emulsion production is responsible for generation of the intensive forces that promotes phases of oil and water to disrupt and thus leading to formation of a subsequent mixture (Dickinson, 2011). They consist of a stator device or a rotor—stator device that are able to mix the components with high speeds (Silva-Avellaneda et al., 2021). In this method of production, droplet size of emulsions is $1\text{--}10\text{ }\mu\text{m}$. High-pressure homogenizers have a pressure pump ($3\text{--}500\text{ MPa}$) and when coarser emulsion is passed through a homogenizing valve, intensive disruptive forces i.e. cavitation and shear are generated that leads to size reduction of droplets (Santamaria-Echart et al., 2021).

- **Low-energy methods:** Spontaneous emulsification (O/W), phase inversion temperature (O/W) and emulsion phase inversion (W/O)
- **High-energy methods:** High pressure homogenization (O/W), microfluidization (O/W), Colloid mills (W/O), Ultrasonic homogenizer (O/W), Membrane emulsification (W/O/W), Microchannel homogenizer (O/W) and High-speed homogenization (O/W)

3.6 *Factors Affecting the Properties of Layers (Guzey & McClements, 2006)*

- pH
- Salt
- Solvent quality
- Emulsifier characteristics
- Polyelectrolyte characteristics

3.7 *Adhesion Emulsions*

Strong attachment of emulsion droplets with one another leads to their distortion. For stabilisation of the droplets against coalescence, an intense and sharp repulsion at shorter range is required. When droplets adhere to each other they give rise to wide contact angles. Coating is carried out by adhesion at a specific interface at the surface of the substrate however adhesion between the droplets cause gels to be harder and rigid as the droplets are stuck. Adhesion bring significant alteration on the rheology, stability effects of emulsions with diverse substrates, both of these phenomena may be quite significant in a variety of applications.

The contact angle imposed by adhesion's energy are similar to that in process of classical wetting. In adhesion emulsion, continuous phase thin layer exists in the middle of the surfaces in contrast to classical wetting. Surfactants that are adsorbed at the surface are responsible for film stabilisation and one of crucial aspect of adhesive emulsion is the surfactant film's structure (De Feijter et al., 1978). The adhesion emulsion is not determined by the phases that are in contact rather by the characteristics of the film possessed by the surfactant (Gennis & Gennis, 1989; Ivanov, 2023). Foams and emulsions that are stabilised with the same surfactant have similar adhesive behaviour while the Hamaker constants differ for the air and oil systems (Poulin et al., 1996). This suggests that the van der waal interactions are not very significant between oil and air media (Derjaguin et al., 1987).

3.8 Double Emulsions

- O/W/O (oil-in-water-in-oil)
 - Aqueous globules that are dispersed further contain smaller oil droplets that are dispersed
- W/O/W (water-in-oil-in-water)
 - Aqueous globules that on dispersing themselves gives small aqueous droplets.

These emulsions are gaining more and more importance due to the benefits it possesses from their double/multiple compartment system. Double emulsion provides us with a wide range of opportunities for regulated release of those compounds that were primarily imprisoned on the interior droplets. Industrial sectors including cosmetics and food industries are highly interested in formulation of these complex systems.

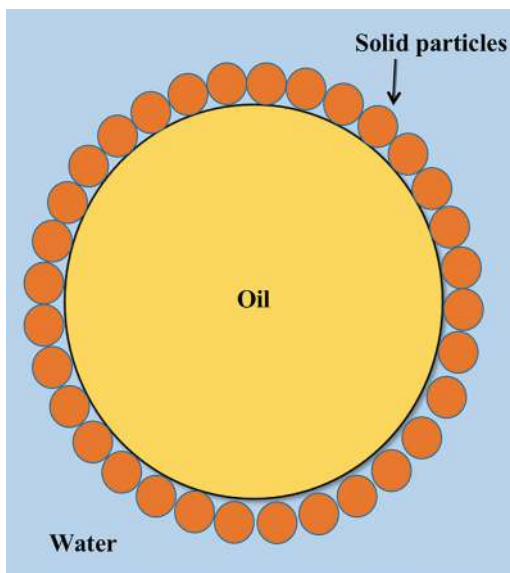
Water-in-oil-in-water (W/O/W) emulsions are considered as potential delivery agents for several pharmaceuticals that are hydrophilic in nature (vaccinations, vitamins, hormones and enzymes that are release gradually on consumption. Apart from it, the active ingredients are capable of mobility from outer phase of the emulsion to the inner phase. This is well suited for overdose therapy or detoxification or in other terms helpful in removing of toxic compounds from waste water. Double emulsions formulated for drug delivery remains considerable in the meadow of controlled release unless other release or stability processes are better understood (Florence & Whitehill, 1982; Garti, 1997). The two surfactants used to prepare double emulsions typically have opposing solubility. A low hydrophilic-lipophilic balance (HLB – 10) is required to create an O/W/O emulsion and a W/O/W emulsion. The binary surfactant mixture's composition determines how long the films last because both the surfactants present in the mixtures generally mix at the interfaces.

Multiple emulsions display intrinsic instability at three different levels:

- (i) between big globules,
- (ii) between small core droplets,
- (iii) between the globule and its scattered small droplets.

However, major mechanisms that are main cause for film ruptures are still unknown. Diffusion is thoroughly studied and accepted as a mechanism that is useful in transportation of active ingredients but in the case of multiple emulsion, reverse micellar transport is suggested because the concentration gradient is exerted by different molecules such as electrolytes, surfactant and actives. When the emulsions are broken down due to any of the above mechanisms or their combinations, the active ingredients that is encapsulated in the inner phase is released in an uncontrolled way to the outer phase at varying rates. This could be a possible reason why multiple emulsions are not too suitable for commercial purposes however they have gained a lot of attention in the recent times (Garti et al., 1983).

Fig. 9.2 Pickering emulsion



3.9 Pickering Emulsions

Emulsions that are stabilized using solid particles instead of surfactants are known as pickering emulsions. Pickering emulsion is shown in Fig. 9.2. The properties of these emulsions are similar to conventional emulsions that use surfactants thereby these can be used as a substitute. Stabilization of emulsions with solids in place of surfactants provides emulsions some specific properties. The major benefit of using solid particles for emulsion stabilization is their benefit to coalescence. They can be beneficial where surfactant might show some adverse effects. Size of solid particles required in development of pickering emulsions are smaller than those of droplet size in emulsion. Diameter of solid particles ranges from nanometric size to sub-micron region that stabilize the droplets of larger size that are of few millimeters (Chevalier & Bolzinger, 2013).

Solid particles with the help of surfactants absorb at the surface of the droplets in the emulsion leading to stabilization. In surfactants, their amphiphilic nature is very necessary for stabilization; however, no such mechanism is required in stabilization of emulsion by solid particles. In pickering emulsions, the slight wetting of water and oil surface causes to strong anchoring of solid particles on the interfacial layers of oil and water emulsion (Aveyard et al., 2003). In pickering emulsion systems, increment of the concentration of the particles results in decrement of the size of the formed droplets that facilitates coverage of the surface that leads to network like structure around the droplets that are present in the emulsion which further increase emulsion stability (Wu & Ma, 2016).

3.9.1 Preparation of Pickering Emulsions

Generally, for preparation of stable pickering emulsions, it requires external forces that are needed to overcome the high energy barriers or selection of appropriate conditions is done for their preparation. In pickering emulsions, the formed particle bridges between droplets are destroyed and formed by either shear forces or by wettability of the particles. Pickering emulsions are developed using particle bridging that lead to the development of emulsions having high internal phase (Wu & Ma, 2016). Depending upon their relative affinity, certain particles position themselves at the interface of 2 phases and it was further characterized as contact angle. A bend in the interface is formed by the particles which have comparatively lower relative affinity. Particles having higher affinity for water will form o/w type of emulsion and those having higher affinity for oil will form w/o type of emulsion. Particles that are absorbed at the interface requires higher energy for their removal and it depends upon two factors i.e. contact angle they form with interface and their size (Berton-Carabin & Schroën, 2015).

3.10 Advantages of Emulsions in Dairy Products

In present scenario, low fat food products and foods that give some kind of positive impact on the human health are most popular. In developing countries, obesity and the problems associated to it affects a large number of people hence the civilization. W/o/w emulsions bid supplementary advantages and suggest a potential method for producing low-fat products. Fat has an enhanced sensory profile as when the external coating of oil comes in touch with the taste buds, one cannot distinguish the presence of emulsified droplets of internal water. Although they have been explored for fat replacers i.e. sucrose, fatty acid esters, fibre, etc. but still they are not fully capable of replacing the sensory profile that is acquired in any food product by its fat content. (Silva et al., 2018). Components loss during digestion is minimised as the chemicals are encapsulated inside the water phase in w/o/w emulsions. Various models are used for preparing a wide variety of dairy products that includes fresh white cheese, calcium fortified soybean milk, inulin/caffeine fortified yogurt, milk-based desserts that are ferrous sulfate fortified, low fat stirred yogurt, etc. (Klojdová et al., 2019). Other advancements of mixing in dairy products include encapsulation of pigments such as anthocyanins or various microorganisms (*Lactobacillus salivarius*, *Lactobacillus acidophilus*, *Lactobacillus delbrueckii*). Lactoferrin (glycoprotein that occurs in milk of mammals) can be guarded by water-in-oil-in-water emulsion from the substances thus compromise its antimicrobial activity. Lactoferrin inhibits a range of microbes such as a variety of pathogenic bacteria, fungi, and parasites while fostering the growth of probiotic bacteria (Al-Nabulsi et al., 2006). Bioactive peptides with opioid, immunomodulatory, antithrombotic, and antihypertensive properties are found in milk proteins including caseins (Silva & Malcata, 2005). But during digestion, they have to endure the conditions in the

gastrointestinal tract (Chen & Li, 2012). Consequently, w/o/w emulsions can prevent heat-induced labile chemical degradation, improving the quality of products in terms of value addition (Kheynoor et al., 2018).

3.11 Efficiency and Emulsions Stability

Evaluation methods of w/o/w were expensive, specialised and challenging to do as assessed by a large number of researchers making it a barrier for their use in industries. Therefore, manufacturers and researchers must work together to solve this problem.

3.11.1 Encapsulation

3.11.1.1 Indirect Methods

Encasing a marker inside the internal phase and measuring it in the exterior phase after preparation or storage is possible for determination of the amount of internal water phase entrapment. Centrifugation of w/o/w emulsions typically yields exterior water phases. Glucose is a suitable marker for dairy systems. Glucometer is useful in the determination of glucose in the phase. Although, this technique is easy to carry out but sometime hydrocolloids such as galactomannans causes misleading results and give enhanced glucose concentration (Benichou et al., 2007). Glucose can interact with few compounds; however, dyes are generally used as markers and identification is carried out by spectrophotometers (O'Regan & Mulvihill, 2009).

Other markers that can be used are vitamins, electrolytes and minerals. The basic idea of these markers is, the quantity of internal water that escapes out is directly proportional to the quantity of the marker that is found in the external water phase. Few markers also have the ability to pass through the oil membrane that might lead to erroneous readings for water escape. Therefore, newer and more trustworthy techniques are required.

3.11.1.2 Direct Methods

Differential scanning calorimetry (DSC) is a direct measurement technique for the internal water phase. Encapsulation efficiency is calculated using latent heat of freezing which is theoretically required by the internal water droplets and the percentage of water present in the water-in-oil emulsion (Schuch et al., 2014). Nuclear magnetic resonance (NMR) tracks down the path in which the water molecule transports into the oil phase and it is a non-destructive technique (Vermeir et al., 2016). NMR of high fields have the capability to give descriptions at the molecular levels

of the emulsion and NMR T2-relaxometry and the Carr-Purcell-Meiboom-Gill (CPMG) sequence demonstrate the gelling of water phase in emulsions of w/o and w/o/w types (Bernewitz et al., 2011; Balcaen et al., 2016).

3.11.2 Droplet Size

Diameters of droplet are particularly crucial factors for stability of emulsion. Changes in the droplet size (dispersion width) leads to ostwald ripening. Tiny droplets keep on getting smaller while the larger droplets keep on increasing (Bernewitz et al., 2011). A guaranteed mono dispersion emulsion is challenging during high pressure homogenization and mixing at high intensity. However, polydispersity may lay lead to inaccurate measurement of droplet size. Generally, droplet sizes are affected by viscosity, makeup of oil and water phases and interfacial characteristics. Droplets sizes are also regulated by thickening agents and the type of emulsifiers used (Oppermann et al., 2018). Mono disperse emulsions having bigger droplet sizes are generated by either microchannel devices or by membrane emulsification. Apart from these, rigorous conditions of laboratories are also capable of generating larger size droplets of monodisperse emulsions. Further, a specific number of similar interior water droplets were added in a outer droplet of mono dispersion (Chu et al., 2007). Widely used technique for the measurement of size of the droplets are dynamic light scattering (optical technique) hat uses correlation function for the measurement of Brownian motion and laser diffraction techniques which works on the phenomenon of Mie theory (Bernewitz et al., 2011). For internal emulsion of w/o type of dilution is carried out of oil (Tepsonkroh et al., 2015). Another useful technique for the measurement is automated image analysis (Scherze et al., 2005). 3D pictures were produced using Raman scattering perspective of coherent anti-stokes (Meyer et al., 2008). Pulsed field gradients (PFG-NMR), a technique that does not require any dilution are frequently used in water-in-oil types of emulsions. Sauter's diameter is the mean size of the collective droplets and is a function of energy which is equal to the pressure difference between the valves of the homogenizers and a relationship exists between Sauter's diameter and of maximum droplet size (Schubert & Engel, 2004). Therefore, Sauter diameter I continuous emulsification with disruption of droplet is expressed as following:

$$x = a_i \cdot E_v^{-b}$$

where,

$x_{3,2}$ = Sauter diameter

E_v = energy density

a_i and b = constants that are dependent on emulsification agents, emulsification equipment and continuous and dispersed phase properties

$$\text{Energy density}(E_v) = \frac{P}{V} = \Delta p$$

Where,

P = power input into the machine

V = volume flow rate

Δp = pressure difference

When the emulsions are produced in a high pressure homogenizer having a orifice wave where $\Delta p = E_v$.

$$X_{3,2} = 1.7 \times 10^{-4} \Delta p^{-0.34}$$

Now the bioavailability (B) of the added compounds can be calculated as:

$$B = \frac{B_{\max} + B_{\min} \cdot k \cdot x_{3,2}}{1 + k \cdot x_{3,2}}$$

k is assumed to be 10^6 m^{-1}

4 Conclusion

The current chapter deals with unit operations that are mixing, blending and emulsification. Along with stating what is mixing it also states different types of mixing i.e. solid-solid, liquid-liquid, liquid-solid and gas-liquid mixing. Although researches are being carried out in the field of mixing from many years, expertise and understanding of actual mixing in terms of solid-solid/powder mixing is still limited and the future holds a great potential for the development of various techniques to address this problem. Solid ingredients are complex food items whose properties varies during or after the mixing. Apart from mixing, this chapter also incorporates the phenomenon of blending and emulsification. Blending can be described as the mixing of two miscible liquids while emulsion is the mixing of two immiscible liquids that can be stabilised with the help of emulsifiers. Emulsions can be destroyed either by optical ripening or coalescence. The only solution to stop destruction of emulsions is using a very high concentration of pickering particles that allow full interfacial coverage otherwise phase inversion will occur. All these unit operations are used in most of the industries at one step or another therefore, a in depth knowledge of these techniques is very necessary.

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Chapter 10

Zero Hunger: Food and Dairy Packaging Preservation



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1 Introduction

1.1 Conceptualization of Sustainable Development (SD)

The concept of sustainable development (SD) was emerged as an environmental concern for the first time in the World Charter for Nature (UN, 1982). Furthermore, the issues were discussed in Our Common Future and significantly highlighted in 40 Chapters of Agenda 21, Earth Summit in 1992 (WCED, 1987; UN, 1992). The adoption of 17 broadly recognised Sustainable Development Goals (SDGs) in 2015 is a component of the better conversation to promote governance unification (Vijge et al., 2020). The notion is that global sustainability governance will be unified by a clearly defined set of broad goals (Young et al., 2017; Kanie et al., 2019; Biermann et al., 2017; Vijge et al., 2020). Global goals of the Sustainable Development Goals (SDGs) has generic approach and incentive to improve combine effort among international organizations and institutions and consequently, coherence of policy (Haas & Stevens, 2017).

Franklin D. Roosevelt, US President convened the meeting as the first in a planned series of meetings addressing the post-war architecture of the envisaged United Nations. There were attendees from about 44 nations, which is quite an accomplishment considering how difficult it is to travel during a world war. It was historic because of presence of ‘less advanced nations’ consisting of 27 countries which includes representation from China, Latin America Egypt, Ethiopia, Iraq, Iran, and Liberia, Philippines and India who were fighting for their independence

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then. The Sustainable Development Goals (SDGs) were agreed upon by nations during a September 2015 meeting held at the UN in New York were 17 global goals with 169 targets were made to achieve by 2030 (UN, 2015).

1.2 Sustainable Development goals (SDGs): Zero Hunger

Out of 17 goals of Sustainable Development Goals (SDGs), the aim of second goals is to end hunger crisis, attain food security, improve the nutrition status of developing countries, and encourage agriculture practise in a sustainable manner by 2030. Even more concerning, within the past year, there has been a noticeable rise in the severity of acute food insecurity in a number of low- and middle-income nations (Blesh et al., 2019; The World Bank, 2021). Approximately, two billion people worldwide facing the moderate to severe food insecurity out of which 135 million populations, there is extreme food insecurity in Africa, Asia and Latin America (FAO et al., 2019; FSIN, 2020). Globally, millions of population under developed countries are facing hunger and malnutrition which is increasing in very terrifying speed. The challenges for developing and developed countries are such that the former faces lack of guarantee production stability and latter needs healthy eating and reducing food waste. Also, the shoot up population growth and dietary pattern changes one of a prominent factor which demand the food and feed demand worldwide (Pradhan et al., 2014).

As we are progressing post COVID Era, still one-third of the food production get lost or wasted globally (Quinton, 2019) and the bitter fact is that the underdeveloped countries are still suffering from hunger because of scarcity of food. There are various factors which influenced the conditions and the most prominent one is the post SARS-CoV-2 pandemic period. Wastage of food occurs during the supply chain process such as unskilled labour in the farm site, transportation injuries and raw material loses, improper storage condition leading to product loses, low level retail stocking etc. Therefore, these various steps involve in supply chain of agricultural products has to be taken care critically. Consequently, Food Packaging play a very critical role in scaling down the global issue of the food spoilage/security during various supply chain process and preserving the shelf life of agricultural products (Fig. 10.1). The market for fresh food packaging was expected to be worth \$150 billion USD in 2022 and is anticipate to grow to \$245 billion USD by 2032 (Fresh food packaging market, 2023).

Food packaging is very crucial during the farm to fork process. Various petroleum based plastic and bioplastic products are design to hold and protect the agricultural products and contributes to the sustainable lifestyles which the demand of the modern world. Bioplastics are quite popular and recognized as one of the potential replacement for petroleum based resource which is a one of the non-renewable resources and threat to the environment.

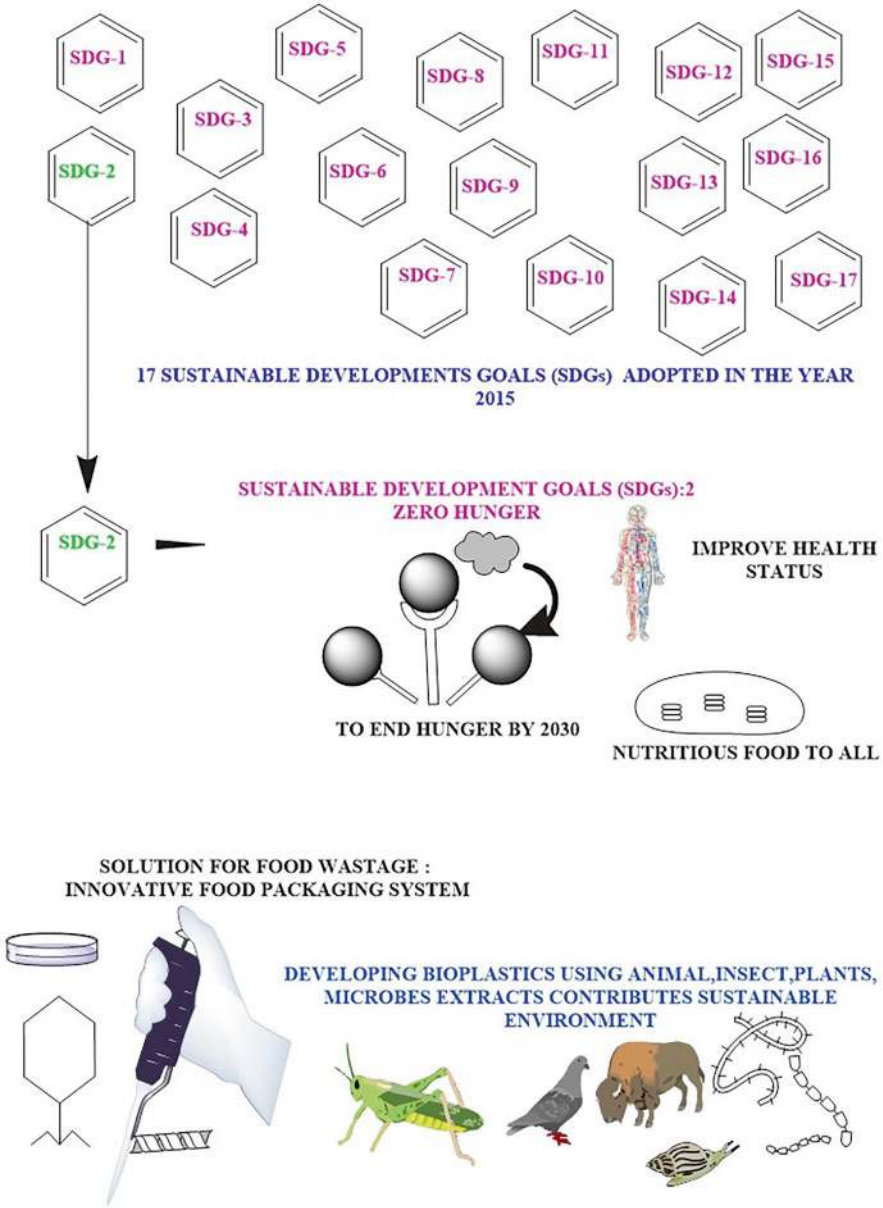


Fig. 10.1 Achieving SDGs by decreasing food wastage using food packaging innovations

2 Overview of Food Packaging: Innovations, Challenges and Sustainability

From starting point of manufacturing to the final point of consumption, food packaging plays a crucial role in maintaining the quality, safety, and freshness of food products. The changing customer demands and technology improvements has led to major advancements in food packaging in recent years. Using smart technologies into food packaging is one popular trend. Sensors and indicators are being used by manufacturers more often in packaging to track and convey the safety and freshness of the food inside (Salgado et al., 2021). Customers are able to make better decisions because of this real-time knowledge, which also helps to decrease food waste. The growth of environmentally friendly packaging options is another noteworthy trend. The packaging industry is actively looking into eco-friendly substitutes for conventional packaging materials as environmental concerns gain attention. Materials that are recyclable, compostable, and biodegradable are becoming increasingly widely used in an effort to reduce the negative environmental effects of packaging waste. Achieving a balance between maintaining food quality and reducing environmental effect is one of the challenges in food packaging. For the industry, finding a balance between affordability, environmental responsibility, and usefulness is still a difficult issue (Marsh & Bugusu, 2007). Packaging innovations are just one aspect of food packaging that incorporates sustainable behaviors beyond materials. It is possible that the food packaging sector will witness additional developments in the future that tackle the environmental and technical aspects of food packaging (Marangoni Júnior et al., 2022).

2.1 *Evolution of Food Packaging*

Food packaging has traditionally evolved through a journey from basic, natural materials to progressively more complex polymeric materials. Food in ancient time were preserved by people using easily accessible materials like leaves, straws, and animal skins. Food preservation and packaging techniques evolved along with civilization, giving rise to new materials and procedures (Teixeira-Costa & Andrade, 2022).

The widespread use of plastics in the middle of the twentieth century marked a crucial turning point. Packaging underwent a revolution when synthetic polymers were introduced, providing a number of advantages that were unmatched at the time. Plastics offered a lightweight substitute for conventional packing materials, saving money on shipping and improving consumer convenience. Additionally, they were adaptable, allowing for a range of sizes and forms, and they provided a strong barrier against air, moisture, and pollutants, increasing the shelf life of food items (Majid et al., 2018). Plastic packaging has also shown to be economical, which has led to its extensive application in a variety of industries. But, in recent years,

packaging materials have been reevaluated due to the influence of plastics on the environment. Because of their resilience, which made them useful for packaging, plastics stay in the environment and cause pollution and endanger ecosystems. Global efforts to find more environmentally friendly packaging options are the thrust areas of areas. Eco-friendly packaging materials have been developed and widely used as a result of the growing emphasis on sustainability. Biodegradable alternatives such as Plant-based materials and compostable plastics that could be decomposed organically could solve the problem of plastic pollution (Teixeira-Costa & Andrade, 2022). In addition, there’s a rising interest in investigating substitute materials made from renewable resources including sugarcane, bamboo, and other plant-based sources. A growing number of firms, consumers, and governments are realizing the benefits of circular economy models, which reduce total environmental impact by reusing, recycling, or composting goods (Awulachew, 2022).

3 Recent Innovations in Food Packaging

3.1 Active Packaging

In order to increase the shelf life of food products and to preserve the ideal conditions during storage and transportation, active packaging involves incorporating additives or components into the packaging materials (Fig. 10.2). These additives are made to regulate particular elements like moisture, oxygen, and microbiological

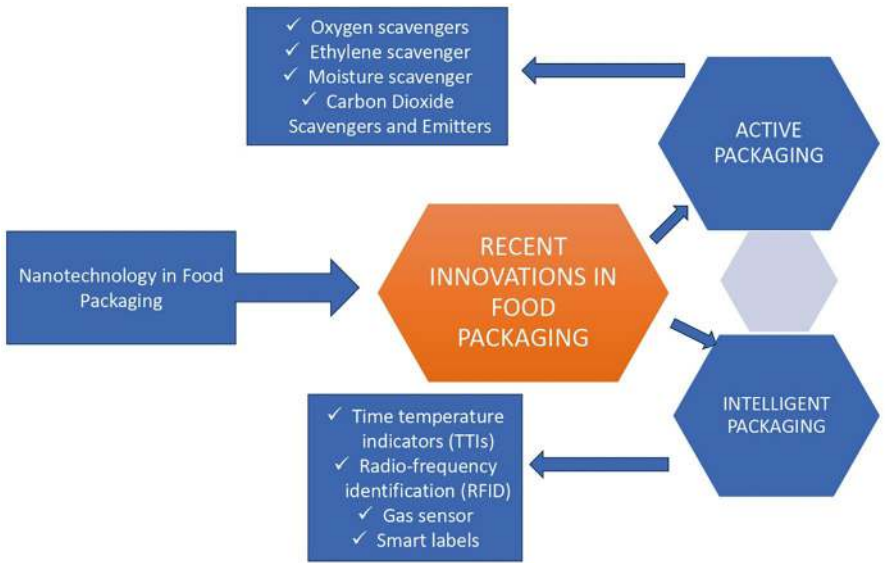


Fig. 10.2 Innovation in food packaging

growth that can keep safe the packed items' quality and safety (Kalpana et al., 2019; Pal et al., 2019).

The following are some instances of active packaging:

Oxygen Scavengers These are compounds added to packing materials with the purpose of absorbing or lowering the amount of oxygen inside the box. Food degradation and spoiling can be avoided with the use of oxygen scavengers, which work to stop oxidation. This is especially important for goods like nuts, snacks, and some drinks (Awulachew, 2022; Yan et al., 2022).

Ethylene Absorbers Fruits and vegetables mature and decompose quickly due to ethylene, a naturally occurring plant hormone. Horticultural produce that is perishable can have its freshness and shelf life prolonged by using packaging that includes ethylene absorbers to regulate the gas's level (Majid et al., 2018; Yan et al., 2022).

Desiccants These substances absorb moisture to stop the formation of bacteria and mold. They are frequently utilized in the packing of spices, dried fruits, and other goods that need moisture free environment (Awulachew, 2022).

Antimicrobial Films Food products' surfaces can be made less conducive to the growth of bacteria and other microbes by using packaging films that contain antimicrobial chemicals. This is advantageous for goods where microbial contamination is a major concern, such as meat and poultry (Pal et al., 2019; Salgado et al., 2021).

3.2 Intelligent Packaging

In order to offer real-time information about the state of the food inside, intelligent packaging integrates sensors, indicators, or labels with the outer container (Fig. 10.2). By providing useful information regarding freshness and safety of the item to customers and retailers, these technologies help to improve quality control and decrease food waste. Here are some examples of intelligent packaging:

Time-Temperature Indicators (TTIs) These indicators provide a visual signal or change in color in response to the packaged product's cumulative exposure to a given temperature over time. TTIs are frequently used to determine the perishability of the commodities, such as seafood and dairy products. They assist retailers and customers in making their decision before its purchase or use ((Han, 2021; Pal et al., 2019).

Radio-Frequency Identification, or RFID, Tags These are employed to track and keep an eye on the flow of goods along the supply chain. Better inventory management and quality control are made possible by the information they may offer regarding the product's origin, storage requirements, and expiry date (Han, 2021).

Gas Sensors By identifying variations in the gas composition inside the packing container, these sensors can provide details regarding the food's freshness. They can be used, for instance, to track the ethylene levels in horticultural produce packing and evaluate the various phases of ripening (Han, 2021).

Smart Labels By scanning the label, customers can obtain information about the product, such as its origin, nutritional value, and expiry date, by scanning the QR code or NFC (Near Field Communication) technology on the label (Han, 2021).

4 Nanotechnology in Packaging

The use and application of materials at the nanoscale typically, 1–100 nanometers are the focus of nanotechnology. Nanotechnology has been used in the packaging industry to improve the qualities of various packaging materials, resulting in creative, sustainable, and effective solutions (Pal et al., 2019). The application of nanoparticles in packaging has resulted in notable advancements in barrier characteristics, mechanical strength, and antibacterial effects.

Enhanced Barrier Properties By adding nanomaterials to packaging materials, such as nanoparticles and nanocomposites, barriers that successfully stop the permeability of gases, moisture, and other outside components can be developed. This improved barrier function is especially helpful in prolonging the shelf life of perishable goods by shielding them from elements that can cause deterioration and spoilage, such as moisture and oxygen. For example, the barrier qualities of polymer films can be enhanced by the addition of nanoclay particles that lessens gas permeability thus, nanoclay improves the effectiveness of packaging in maintaining the freshness of food items (Pal et al., 2019).

Antimicrobial Effects Packaging materials may now be made with antimicrobial compounds integrated at the nanoscale, which also makes it possible to stop the growth of germs and fungi. Lowering microbial contamination is important for preventing foodborne illnesses and increasing the shelf life of food. For example, packaging materials can incorporate silver nanoparticles, which are well-known for having antibacterial qualities. This gives the packaging the capacity to release silver ions, which prevents bacteria from growing on the food's surface when it is packaged (Majid et al., 2018).

Increased Mechanical Strength By reinforcing packing materials, nanomaterials increase their mechanical strength and longevity. As a result, the packaging is stronger and less likely to break when being handled, moved, and stored. Enhanced mechanical strength can also result in the development of lighter, thinner packing materials, which will use less material for development (Pal et al., 2019). For example, paper and cardboard packaging can be strengthened and made more resilient by adding nanoparticles, like nanocellulose. Packaging that are both robust and lightweight can be made possible by this strengthening.

Active Release Systems The use of nanotechnology allows packaging to be designed with active release systems that release encapsulated active chemicals in response to certain parameters like pH, temperature, or microbial activity. Antioxidants, flavorings, or preservatives can be delivered in a targeted way with this controlled release, improving the packaging's overall performance (Salgado et al., 2021). For example, antioxidant-containing nanocapsules can be incorporated into packaging materials. The nanocapsules release antioxidants in response to oxidation-promoting environments, assisting in preserving the food's quality that has been packaged.

4.1 Nano Sensors in Food Packaging: Real-Time Monitoring for Quality Assurance

Advanced device known as nanosensors use nanotechnology to measure and identify changes in the products chemical or physical properties at the nanoscale. When it comes to food packaging, nanosensors have the potential to monitor food quality in real time, allowing for the early and easy identification of spoilage, infection, or other unwanted changes. Gas nanosensors and biosensors are two prominent kinds of nanosensors found in food packaging (Salgado et al., 2021).

Gas nanosensors are a useful tool for determining the freshness and quality of packaged goods since they are made to identify particular gases linked to food decomposition. Gas nanosensors are capable of detecting the gases emitted when food products deteriorate. For example, ammonia, which is created as proteins degrade, is a typical spoiling gas. Meat and fish items can begin to degrade when even minute levels of ammonia are detected by gas nanosensors. Fruits and vegetables ripen more quickly when exposed to ethylene, a naturally occurring plant hormone. Produce packaging can incorporate gas nanosensors that are sensitive to ethylene levels, enabling real-time ripening stage monitoring and extending shelf life. The integrity of the packaging itself can also be kept an eye on using gas nanosensors. The sensors can identify changes in the composition of gases as a leak compromise in the packaging, thereby warning consumers and manufacturers of possible contamination or spoilage (Majid et al., 2018). Biological components are used in food packaging to identify particular compounds, including pollutants or pathogens, that may jeopardize food safety (Tripathi et al., 2023). These biological elements combine with the nanomaterials to produce a detectable signal, offering a quick and accurate way to spot any threats. Biosensors can be made to detect the existence of harmful microorganisms in the packing environment, such as viruses or bacteria. For example, a biosensor can identify *Salmonella* or *E. Coli*, allowing for early intervention to stop infection. By customizing biosensors to identify allergens, food products that are packed are guaranteed to be free of particular chemicals that could cause allergic reactions in customers. Biosensors can also be used as general

food quality indicators (Salgado et al., 2021). For example, variations in freshness, acidity, or the presence of particular compounds linked to spoiling can be found, offering information about the state of the food that has been packaged. Nanosensors allow for real-time monitoring, which enables prompt action in the process of food safety or quality. These sensors' nanoscale sensitivity makes it possible to identify even the smallest changes, leading to a more precise and trustworthy evaluation of food conditions. By utilizing nanosensors for early detection, proactive actions can be implemented to lower the risk of foodborne diseases, spoilage, and contamination (Pal et al., 2019).

To guarantee requirements are met and safety is maintained, the use of nanosensors in food packaging may be closely examined by regulations. A key component of a successful adoption of nanosensor technology is consumer acceptance and understanding. Before being widely used in the food packaging sector, the cost of integrating nanosensors and the scalability of production processes need to be taken into account. The use of nanomaterials in packaging also gives rise to questions about environmental effect, safety, and possible nanoparticle migration. The proper and safe implementation of nanotechnology in packaging necessitates giving these aspects significant thought.

Packaging materials made with nanotechnology are more effective in maintaining product quality, cutting down on waste, and improving sustainability all around. Nanotechnology can help reduce material usage and environmental impact by facilitating the creation of lighter and thinner packaging materials.

Modern technology such as nanosensors has enormous potential to transform food quality assurance and monitoring in the packaging sector. All along the food supply chain, improved food safety and quality are facilitated by the capacity to determine pollutants, detect spoiling gasses, and offer real-time information on food conditions. Future food safety procedures will probably be greatly influenced by the incorporation of nanosensors into food packaging as nanotechnology develops. New avenues for developing more sophisticated, effective, and environmentally friendly packaging solutions have been made possible by the use of nanotechnology into packaging materials. Enhancing barrier qualities, producing antimicrobial effects, and boosting mechanical strength are just a few examples of how nanotechnology may be used to address important issues facing the food packaging sector and could bring environmentally friendly packaging solutions (Khwaldia et al., 2010).

5 Biodegradable and Edible Packaging

A growing interest in creating sustainable substitutes for conventional packaging materials has resulted from growing awareness of environmental challenges, particularly the pervasive issue of plastic pollution. Edible and biodegradable

packaging materials have surfaced as viable choices with the ability to lessen the adverse environmental effect of traditional plastic. These materials offer a number of advantages in terms of environmental friendliness, waste reduction, and consumer safety. They are generated from natural sources such as proteins, cellulose, and starch (Majid et al., 2018).

5.1 *Biodegradable Packaging*

Biodegradable packing materials are made to naturally decompose into substances like water, carbon dioxide, and biomass through biological processes, usually triggered by microorganisms (Fig. 10.3). Enzymes produced by bacteria, fungi, or other living things frequently aid in this breakdown (Majid et al., 2018). Among the essential elements of biodegradable packaging are:

Starch-Based Polymers Biodegradable polymers can be produced by processing starch, which can be obtained from sources such as corn, potatoes, or tapioca. Packaging materials based on starch have a reputation for being biodegradable and dissolving into natural elements (Teixeira-Costa & Andrade, 2022).

Polylactic Acid (PLA) Made from renewable materials like sugarcane or maize starch, PLA is a biodegradable and compostable polymer. Disposable cutlery and food containers are among the packaging applications that frequently employ it (Teixeira-Costa & Andrade, 2022).

Cellulose Biodegradable films and coatings can be made using cellulose, which is generated from plant fibers. Packaging materials made of cellulose are renewable and have a minimal environmental impact due to their biodegradability (Bangar et al., 2023; Teixeira-Costa & Andrade, 2022).

5.2 *Advantages*

Compared to conventional plastics, biodegradable materials decompose more quickly in the environment, which lessens the persistence of packaging trash. As an alternative to finite fossil-based resources, a large number of biodegradable packaging materials are created from renewable resources. A portion of the biodegradable components can be composted in industries, which helps to produce important compost for use in farming (Siracusa et al., 2008).

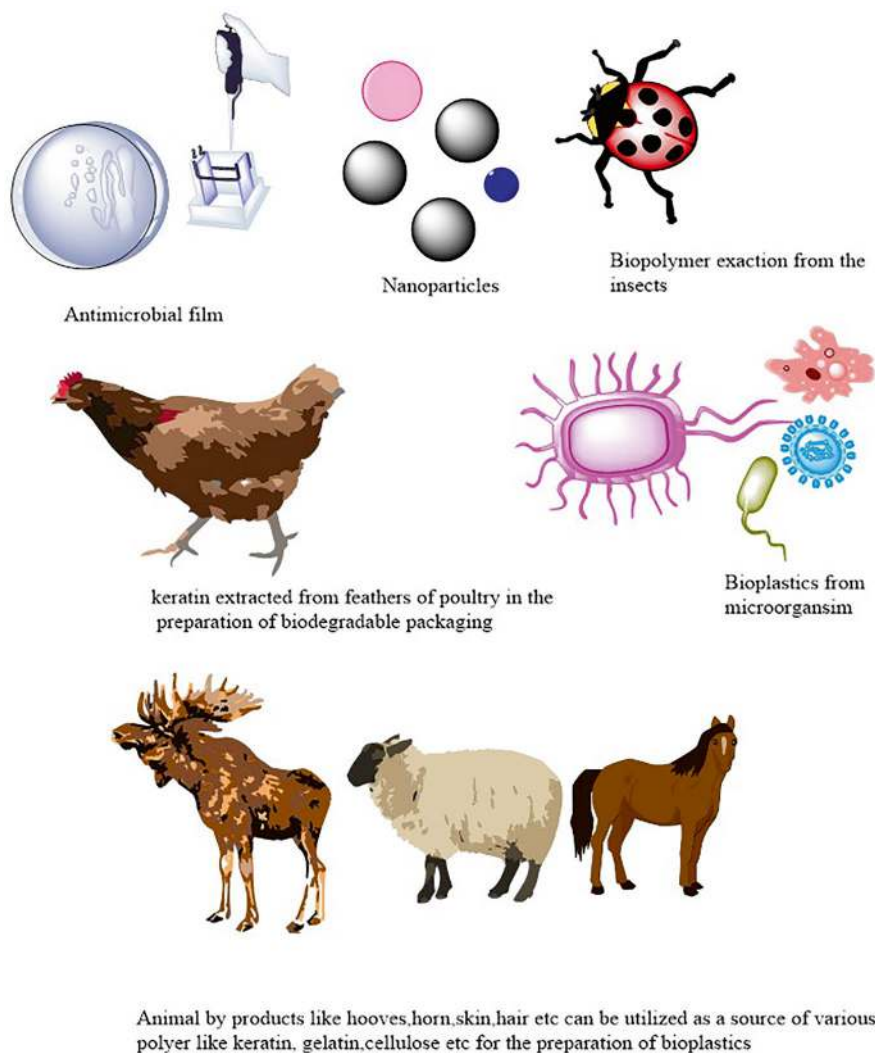


Fig. 10.3 Depicting various types and source of bioplastic/biodegradable film

5.3 Challenges

Compared to conventional plastics, biodegradable materials might have a shorter shelf life. This could cause problems for applications that need to preserve products for a longer period of time. For efficient breakdown, many biodegradable materials need particular environmental conditions, such as industrial composting facilities. Their biodegradability may be hampered by improper disposal (Marangoni Júnior et al., 2022).

5.4 Edible Packaging

Edible packaging goes beyond sustainability by using materials that are safe for ingestion by humans in addition to those that decompose naturally. These materials, which are intended to be ingested either alone or in conjunction with packaged food, are frequently composed of edible components. According to Majid et al. (2018), essential elements of edible packaging consist of:

Proteins Plant-based or gelatin-based proteins can be used to make edible films and coatings. These substances offer food a barrier of protection in addition to being biodegradable (Marangoni Júnior et al., 2022).

Alginate Made from seaweed, alginate is a material that can be utilized to make edible capsules and films. It has been used to package small food products and beverages (Marangoni Júnior et al., 2022).

Pectin Edible coatings for fruits and vegetables are made from pectin, a naturally occurring carbohydrate present in fruits. It contributes to fresh produce's longer shelf life (Teixeira-Costa & Andrade, 2022).

5.5 Benefits

Since edible packaging may be eaten along with the meal, there is no need for disposal, resulting in zero waste. Food may be presented in a unique and inventive way thanks to edible packaging. Edible packaging encourages sustainable consumption habits and helps to cut down on packaging waste.

5.6 Challenges

Food-grade packaging materials ought to be appetizing and shouldn't adversely affect the flavor or texture of the food they contain. It might be difficult to find the ideal balance between functionality and sensory aspects. The stability and shelf life of edible packaging may be impacted by moisture sensitivity. To solve this problem, packaging design must be done properly.

6 Packaging with Smart Labels and QR Codes

In the advancement of packaging, smart labels and Quick Response (QR) codes are becoming more and more common. These technologies give customers quick and easy access to comprehensive product information (Rotsios et al., 2022). These

technologies are essential for increasing transparency since they give consumers access to data about the product's ingredients, sustainability practices, and place of origin, enabling them to make better decisions.

6.1 Smart Labels

A development on standard product labels, smart labels use technologies like Bluetooth, RFID, and Near Field Communication (NFC) to allow for communication between the label and a smartphone or other suitable device. Beyond what is normally printed on conventional labels, these labels have the capacity to provide and store additional data (Rotsios et al., 2022).

Smart labels have the ability to offer comprehensive details regarding a product's origin, processing, and distribution along with its path through the supply chain. This improves traceability and enables customers to confirm the product's origin and quality. A few smart labels have sensors built in to keep an eye on things like humidity and temperature. Customers are guaranteed to be informed of the product's storage conditions, this is possible due to real-time monitoring, which is especially crucial for perishable things that need special care. By enabling customers to interact with the goods via their cellphones, smart labels promote interactivity. This communication may take the form of getting information, taking part in sales, or exploring more about the company. By offering distinct IDs or tamper-evident characteristics that customers can confirm via their devices, smart labels can include capabilities to assist resist counterfeiting (Rotsios et al., 2022).

6.2 QR Codes

Two-dimensional barcodes known as Quick Response (QR) codes have a large amount of data stored in them. Smartphones can quickly scan these codes to access the information that points to webpages, videos, documents, and other digital stuff (Rotsios et al., 2022).

Product information can be accessed directly using QR codes included on packaging. Customers can obtain details about components, nutritional information, allergies, and usage guidelines by scanning the code. Customers can obtain special content, loyalty points, and promotional savings by scanning QR codes (Rotsios et al., 2022). Customers can be engaged in this way, and brand loyalty can be developed. QR codes can direct users to websites with reviews and feedback that they can

read or leave. Customers are more likely to trust the company and its products as a result of this transparency and social proof (Ahmed & Shivhare, 2020).

6.2.1 Benefits of QR Codes and Smart Labels

By giving customers easy access to comprehensive product information, smart labels and QR codes both promote transparency. By providing interactive experiences like promotions, recipes, and user reviews, these technologies improve consumer engagement. By allowing customers to follow the product's provenance and path, they can feel more assured about its genuineness and excellence. In response to the growing customer demand for environmentally friendly products, industries should utilize these tools to convey their sustainability programs and practices. Smart labels and QR codes provide quick and easy access to information, enabling customers to make knowledgeable selections at the point of sale (Ahmed & Shivhare, 2020; Rotsios et al., 2022).

6.2.2 Challenges

The efficacy of QR codes and smart labels is contingent upon users possessing smartphones and a dependable internet connection. Customer knowledge and comprehension of these technologies' efficient use are necessary for their widespread acceptance. Using these technologies for data collection and transmission presents privacy and data security problems that producers and industries must carefully manage (Ahmed & Shivhare, 2020).

6.3 Challenges in Food Packaging

6.3.1 Environmental Impact

The sector faces a great deal of challenges when it comes to the environmental impact of food packaging, especially since single-use plastics and non-recyclable materials are so common. The increasing demand for packaged goods makes it necessary to discover sustainable alternatives in order to lessen the negative environmental effects (Majid et al., 2018).

6.3.1.1 Non-recyclable Materials and Single-Use Plastics

Because single-use plastics persist in the environment, there has been worry over the extensive usage of these materials, including plastic bags, containers, and packaging films. One of the main causes of contamination in the environment is single-use plastics. These materials can release toxic substances into the environment for hundreds of years if they are not disposed of appropriately (Teixeira-Costa & Andrade, 2022). The general health of the environment, marine life, and ecosystems are all negatively impacted by plastic waste. These materials frequently hurt wildlife and causing pollution in landfills, the ocean, and other habitats (Majid et al., 2018). Packaging that isn't recyclable makes things worse by making waste management systems more difficult to operate.

The manufacture of single-use plastics uses limited fossil fuel resources, which raises carbon emissions and depletes resources. Moving toward materials with less impact on the environment and those obtained from renewable resources is one way to address this problem. A lot of single-use plastics can't be recycled easily or can only be recycled into lower-quality goods. As a result, recycling programs are less successful and a large quantity of plastic garbage is either burned, dumped in a landfill, or handled incorrectly, worsening environmental problems (Khan et al., 2020).

Single-use plastics and non-recyclable materials can be used less frequently by creating and implementing packaging alternatives made of renewable resources, such as plant-based plastics, biodegradable polymers, and compostable materials. Recycling rates can be raised and the environmental effect of packaging waste can be decreased by investing in and upgrading recycling infrastructure to accept a greater variety of materials, including more types of plastics (Teixeira-Costa & Andrade, 2022). Adopting circular economy models in which materials are recycled, composted, or reused supports packaging that is more environmentally friendly. Educating consumers about how packaging materials affect the environment and promoting appropriate disposal techniques will help cut down on pollution and promote a sustainable lifestyle. The food packaging sector has the potential to promote a more ecologically conscious future and a healthier planet by working together and adhering to sustainable practices (Khan et al., 2020).

6.3.2 Chemical Migration

For the food business, ensuring the safety of food packaging is of top priority, with the main goal being to stop harmful chemical compounds from leaching from the packaging materials to the food that is packed. This problem entails managing possible risks related to the transfer of chemicals, additives, and residues that could jeopardize the packed items' quality and safety (González-López et al., 2023). The process by which ingredients from the packing materials seep into the food is referred to as migration. Numerous factors, including temperature, contact time, and the type of packaging material, may contribute to this. Chemical migration is a

serious issue since some of the materials used in packaging may be harmful to humans if they come into contact with food (Alamri et al., 2021).

Plasticizers, antioxidants, and colorants are among the chemicals used in packing materials that may seep into food. Prolonged exposure to these compounds can have detrimental consequences on health, such as carcinogenicity and endocrine disruption. Chemicals from packaging can migrate into food more quickly in high temperatures. This is especially important for materials like plastic, since heat can release plasticizers and other additives into food, especially when it's being transported, stored, or heated in a microwave. Interactions between specific food varieties and packaging materials may promote migration (González-López et al., 2023). Foods that are fatty or acidic, for instance, may accelerate the process of chemical migration, particularly when they come into touch with incompatible components (Alamri et al., 2021).

It can be difficult to follow strict regulations on materials that come into touch with food. In order to prioritize customer safety, the sector must make sure that regulations dictating permissible amounts of particular compounds in food packaging are followed. We can reduce the risk of chemical migration by selecting packing materials that are rigorously safety tested and especially made for food grade. Using materials that are thought to be inert and have a low chance for leaking hazardous compounds is one way to do this (Alamri et al., 2021).

By establishing a barrier between the food and the packing material, barrier coatings or layers can stop or lessen chemical migration. This is especially crucial for materials that migrate easily, like certain plastics. To detect and measure possible chemical migration, rigorous testing procedures, such as migration studies and analytical testing, are necessary. It is critical to keep up with and abide by the national and international laws governing items that come into contact with food. Packaging materials are guaranteed to meet the relevant safety requirements through regular updates and adherence to regulations (Castle & Gilbert, 2018).

Mitigating migration problems may be possible by investigating innovative technologies like active and intelligent packaging. One preventive strategy might be including scavengers, which absorb or neutralize chemicals that are moving. Preventing the migration of dangerous compounds from food packaging materials is a challenging task that requires a multifaceted approach that includes technical breakthroughs, stringent testing, material selection, and regulatory compliance (Castle & Gilbert, 2018; González-López et al., 2023).

7 Sustainability on Food Packaging

7.1 Circular Economy Method

Sustainable food packaging can be achieved by applying the circular economy method. Through techniques like reducing, reusing, and recycling, it entails building a closed-loop system where resources are saved, waste is reduced, and commodities are used effectively. This strategy places an emphasis on a more sustainable and conscientious use of resources while addressing environmental issues and reducing the negative effects of packaging on ecosystems (Majid et al., 2018).

A key component of the circular economy is waste reduction. This pertains to food packaging and entails reducing the quantity of packaging used, especially single-use packaging that has a major negative impact on the environment. Industries are urged to create packaging that uses materials as sparingly as possible while taking dimensions, weight, and functionality into account (González-López et al., 2023). This may result in less packaging waste. Packaging can be made more environmentally friendly by removing extra layers, coatings, or other parts that don't improve the product or the user experience (Marangoni Júnior et al., 2022). Reusing materials entails prolonging the life of packaging by promoting customers to repurpose packaging for different purposes or by implementing returnable packaging systems or refillable containers (Liu et al., 2021).

7.2 Benefits and Challenges

By reducing waste and reusing materials, the circular economy strategy helps to conserve important resources and promotes a more sustainable use of natural resources. The manufacture and disposal of packaging materials have a negligible negative impact on the environment thanks to reduction, reuse, and recycling. By reducing material consumption, streamlining operations, and boosting supply chain efficiency, adopting circular economy principles can result in cost savings (Liu et al., 2021).

But it can be difficult to get customers to accept and actively engage in circular economy practices, such as refilling and returning packaging. Industry, government, and communities must work together to invest heavily in and enhance recycling infrastructure. Changing intricate supply chains may be necessary to implement circular economy principles, which can be difficult to organize and integrate (Marangoni Júnior et al., 2022).

The circular economy strategy offers a comprehensive and long-term way to solve the environmental issues raised by food packaging. Adopting this strategy calls for creative design, cooperation between stakeholders, and a dedication to reducing the environmental impact of packaging. Future food packaging strategies

will be greatly influenced by the circular economy concept, as long as the sector maintains its focus on sustainability (Liu et al., 2021).

7.3 Bioplastics and Plant-Based Materials

A class of plastics known as “bioplastics” is made from biomass that is renewable, like plants, animal byproducts (Fig. 10.3) and is frequently intended to decompose or biodegrade. As its main feedstock, bioplastics use resources like maize starch, sugarcane, or other plant-based materials, in contrast to standard plastics, which are usually generated from fossil fuels like petroleum (González-López et al., 2023).

One of the most popular bioplastics is PLA (polylactic acid). It comes from fermented plant sugars, which are often generated from sugarcane or maize crops. PLA is well-known for being compostable and biodegradable in some situations. PHA (Polyhydroxyalkanoates) is a group of bioplastics made by different microbes. It is compostable and biodegradable, and it comes from renewable resources. Corn or potato starch are frequently used to make starch-based bioplastics (Teixeira-Costa & Andrade, 2022). They can replace conventional plastics in some applications and are biodegradable. Bio-PET, or bio-based polyethylene terephthalate, is a type of PET plastic that is frequently used in beverage bottles. It is made from sustainable resources, such as sugarcane (Abdul Khalil et al., 2016).

7.4 Characteristics and Advantages

Compared to the manufacture of standard plastics, the production of bioplastics frequently results in lower greenhouse gas emissions. Under certain circumstances, a lot of bioplastics can compost or biodegrade, which lessens the amount of plastic trash that ends up in the environment and helps create a more sustainable and circular waste management system. Bioplastics have a wide range of uses, such as food containers, packaging, disposable cutlery, and agricultural films. Like conventional polymers, they are practical and versatile (Teixeira-Costa & Andrade, 2022).

7.5 Challenges and Consideration

There are issues with the infrastructure for recycling bioplastics. Despite coming from renewable resources, not all bioplastics are recognized in recycling programs, and it's possible that appropriate disposal methods, including industrial composting facilities, aren't readily accessible. Using agricultural operations to produce feedstocks for bioplastics may cause issues with land usage, deforestation, and competition with food crops. Because conventional and bioplastics have different

characteristics, combining them in recycling processes can present difficulties. To optimize the environmental advantages of bioplastics, segregation and specialized recycling facilities are required (Abdul Khalil et al., 2016).

8 Packaging and Preservation of Dairy and Dairy Products: Innovations and Difficulties

Proteins, vitamins, and minerals are among the vital components found in dairy products, making them an essential part of the human diet. Dairy products' freshness, safety, and general quality are all impacted by how they are packaged and preserved.

8.1 *Preservation Techniques in the Dairy Industry*

8.1.1 Heat Treatment

8.1.1.1 Pasteurization

It entails heating milk to a predetermined temperature for a predetermined amount of time in order to successfully lower the microbial load without noticeably changing its flavor. Generally, milk is heated to between 63 °C and 72 °C (145 °F and 161 °F). The particular pasteurization technique employed determines the precise temperature and length of time. After heating the milk, it is kept at the desired temperature for a set amount of time, usually 15–30 min. To avoid any possible recontamination, the milk is quickly cooled to below 10 °C (50 °F) following the holding time (Myer et al., 2016).

To make milk safe for consumption, pasteurization aims to eradicate or drastically reduce harmful bacteria like *Salmonella*, *Listeria*, and *E. coli*. Pasteurization prolongs the shelf life of milk relative to raw milk, however not as much as certain other preservation techniques.

8.1.1.2 Ultra-High Temperature Processing

Ultra-high temperature (UHT) processing is a cutting-edge heat treatment technique that includes heating milk to extremely high temperatures for a brief period of time, usually 2–5 s over 135 °C (275 °F). Milk is quickly brought to an extremely high temperature, which effectively kills or inactivates any microorganisms that may be present. In order to avoid recontamination, the UHT-processed milk is subsequently aseptically packaged in sterile containers. Milk's shelf life is greatly increased by UHT processing, which enables it to be kept at room temperature for several months without refrigeration (Vaghela et al., 2024).

Compared to conventionally pasteurized milk, UHT-processed milk tastes more like raw milk because of the brief exposure to high temperatures that minimizes flavor alterations. Because UHT processing allows milk to be stored without a cold chain, it is beneficial for milk distribution in areas where refrigeration is scarce.

The dairy industry relies heavily on heat treatment techniques like pasteurization and UHT processing to extend the shelf life and safety of milk products. These preservation methods enable dairy products to be distributed worldwide while satisfying consumer needs for convenience and safety. Several variables, including the intended shelf life, flavor retention, and supply chain logistics, influence the decision between pasteurization and UHT processing (Vaghela et al., 2024).

8.1.2 Fermentation

Lactic acid fermentation is a naturally occurring process in which lactic acid bacteria transform lactose, the sugar found in milk, into lactic acid. For ages, different types of fermented dairy products have been produced using lactic acid fermentation. Fermentation is started by adding or introducing lactic acid bacteria, such as *Lactococcus* and *Streptococcus*, which are naturally occurring. Lactose is broken down into lactic acid by the lactic acid bacteria. Lactic acid bacteria turn lactose, the sugar found in milk, into lactic acid through metabolization. The milk's transformation and preservation are aided by this acidity process (Ahansaz et al., 2023).

Probiotic fermentation is the process of adding probiotics beneficial bacteria to dairy products. Probiotics are live microorganisms that, when taken in sufficient quantities, have positive effects on health. Specific strains of probiotic bacteria, like *Bifidobacterium bifidum* or *Lactobacillus acidophilus*, are introduced to the milk. The deliberate addition of live beneficial bacteria to milk products is known as probiotic fermentation, and it has several advantageous effects. The positive effects of these bacteria on gut health are well established. Probiotics improve flavor and texture and may have positive health effects (Granato et al., 2019). They might have a favorable effect on immune system and gastrointestinal health. Probiotics have been connected to immune system support, better gut health, and the preservation of a healthy gut flora. Additionally, for those who are lactose intolerant, they might aid in the synthesis of specific vitamins and the breakdown of lactose.

Research has linked probiotics to a number of health advantages, such as better nutritional absorption, better digestion, and the preservation of a balanced gut microbiota. The milk product gains distinct flavors from the fermenting process, which enhances its sensory profile. Yogurt, kefir, and other cultured dairy products are frequently made via probiotic fermentation. These products are valued for their taste as well as the additional components that support good health (Granato et al., 2019).

Because of lactic acid, it functions as a natural preservative, preventing the growth of dangerous germs and extending the shelf life of dairy products that have undergone fermentation. By generating an acidic environment that prevents the growth of spoilage and pathogenic microbes. Fermented dairy products have a

longer shelf life because of this preservation characteristic (Ahansaz et al., 2023). Numerous dairy products are produced by fermentation procedures, which can involve lactic acid bacteria or probiotics. These procedures not only add to the distinctive tastes and textures of fermented dairy products, but they may also have health benefits because they involve the ingestion of living, active cultures. Intentionally utilizing beneficial bacteria during fermentation fits in with both conventional and contemporary methods of producing dairy products, satisfying the tastes, health, and variety desires of consumers.

8.1.3 Freezing

To maintain texture, flavor, and overall quality in ice cream and frozen desserts, freezing is an essential preservation technique. In order to produce ice cream and other frozen desserts, freezing is an essential step that affects the products' sensory qualities and shelf life (Solanki et al., 2024). A mixture of milk, cream, sugar, and flavorings is made to make ice cream. To integrate air and avoid the production of big ice crystals, the mixture is rapidly frozen while being agitated or churned. To preserve its texture until consumption, the frozen food is kept in a cold environment (Solanki et al., 2024).

The purpose of freezing is to preserve the texture of ice cream by preventing the creation of huge ice crystals, which helps to give ice cream its smooth and creamy texture. By quickly freezing the ice cream mixture, tiny ice crystals are formed instead of larger, unwanted crystals, which could give the finished product a grainy texture. The addition of air during the freezing process also results in a smooth and light texture. The frozen dessert's intended flavor is preserved due to the low temperatures, which prevent flavor loss. Ice cream's flavors are efficiently prevented from deteriorating by low temperatures (Solanki et al., 2024). This guarantees that the flavors of added substances, such as fruits or chocolate, will remain consistent until consumption, maintaining the intended taste profile.

Ice cream's shelf life is increased by freezing, enabling extended storage times without noticeably lowering its quality. By delaying the chemical and microbiological processes that can cause quality degradation, freezing serves as a preservation technique. Long-term ice cream quality and texture are preserved under ideal storage conditions. Throughout the freezing process, constant swirling or churning keeps the ice crystals from getting too big, preserving the frozen dessert's desired creamy smoothness (Solanki et al., 2024).

8.1.4 Freeze Drying

A dehydration method used for several dairy products, including powdered milk, is freeze-drying, sometimes called lyophilization. A complex preservation method called freeze-drying uses sublimation to remove water from dairy products, giving them a longer shelf life and better-quality retention. By applying a lower pressure to

the frozen product, the ice sublimates (goes straight from ice to vapor) without going through the liquid phase. At a marginally higher temperature, the last of the bonded water molecules are extracted. The purpose of freeze-drying is to Preservation. The dairy product can be kept for a long time without refrigeration because the moisture removed during the freeze-drying process severely hinders the growth of bacteria preserve food by removing moisture from it, which inhibits the growth of bacteria and the risk of spoiling (Gaur et al., 2024). The dairy product's original flavor is preserved through the low-temperature procedure, guaranteeing that the freeze-dried version maintains the fresh product's flavor. Vitamins and other delicate components are preserved through freeze-drying, which reduces the amount of nutritional value lost. The delicate process of freeze-drying reduces the loss of heat-sensitive ingredients like vitamins and enzymes. Because of this, freeze-dried dairy products such as powdered milk offer a longer shelf life and are a convenient source of nutrition. Dairy products that have been freeze-dried are lighter, lower in volume, and simple to rehydrate when needed. Because of their convenience, they can be used for a variety of tasks, such as cooking, baking, and as a handy way to get powdered milk (Klinkesorn & Sophanodora, 2006).

In the dairy business, freeze-drying and freezing are crucial preservation methods that are used to preserve the flavor, texture, and quality of dairy products. These techniques help make a wide variety of dairy products more accessible and convenient for customers, from the smooth and creamy texture of ice cream to the light and shelf-stable nature of freeze-dried powdered milk (Klinkesorn & Sophanodora, 2006).

8.2 *Packaging Considerations for Dairy Products*

8.2.1 **Fresh Milk Packaging: Materials, Challenges, and Solutions**

A variety of materials are usually used to package fresh milk, each selected for its capacity to preserve the product's safety and quality. Typical fresh milk packing materials consist of:

Plastic Bottles: Plastic milk bottles are often made of low-density polyethylene (LDPE) or high-density polyethylene (HDPE). These materials offer a packing solution that is affordable, strong, and lightweight. They are also readily recyclable (Barukčić et al., 2021; Marsh & Bugusu, 2007).

Carton: Another common packing option is paperboard or paper-based cartons, which are frequently lined with a layer of plastic or aluminum. These boxes are thought to be environmentally beneficial, lightweight, and air- and light-tight.

Pouches: Milk is packaged in flexible pouches composed of multilayer laminates, which include materials like aluminum and polyethylene. Pouches have benefits including less space and weight for packaging and also covers less space (Barukčić et al., 2021; Marsh & Bugusu, 2007).

In order to guarantee that fresh milk reaches consumers in the best possible condition, packaging fresh milk requires overcoming some obstacles. The main factors and difficulties are as follows:

Preserving Freshness: One of milk's most important qualities is its freshness, thus packaging needs to shield the product from outside influences that can degrade its quality. This includes being in contact with light, air, and pollutants that could alter the food's nutritional value and flavor. Because fresh milk contains water, proteins, lipids, and carbohydrates that all foster the growth of microorganisms, it is highly perishable. Packaging needs to be made with a barrier against outside elements that can taint the product in order to keep it fresh (Rejeesh & Anto, 2023).

Oxygen Barrier: Oxygen encourages milk's lipids to oxidize, which results in rancidity and bad tastes. Milk is shielded from oxidative processes by packaging materials that have strong oxygen barriers, such as laminates and some plastics (Awulachew, 2022; Rejeesh & Anto, 2023).

Light Protection: Milk's vitamin content may degrade due to light exposure, particularly UV light. Milk's nutritional value is protected by packaging materials that provide light protection, such as opaque plastics or cartons with layers that block light. Vitamins like riboflavin can be harmed by light, especially ultraviolet (UV) light, which milk is sensitive to (Marangoni Júnior et al., 2022). It is imperative to use light-resistant packaging materials, including opaque or tinted plastics, to preserve the milk's nutritious value. Milk needs packaging techniques that guard against light-induced degradation because of its susceptibility to light, especially UV light (Joglekar & Mestry, 2020; Rejeesh & Anto, 2023).

Preventing Contamination: To avoid microbiological contamination, the packaging process must be kept sterile and clean. To ensure the milk's microbiological safety, the packaging material should serve as a barrier against external pollutants and bacteria. As contamination can cause spoiling or put consumers' health at risk, it is a major problem in milk packaging. Contamination prevention requires the use of barrier-forming materials and hygienic packing techniques (Awulachew, 2022). Aseptic packaging techniques guarantee that the milk and the packing material are sterilised prior to sealing, resulting in a sterile atmosphere that reduces the possibility of microbiological contamination (Joglekar & Mestry, 2020).

8.2.2 Cheese Packaging: Materials, Challenges, and Solutions

Vacuum-Sealed Bags A popular way to package different kinds of cheese is using vacuum-sealed bags. These bags create a vacuum around the cheese by drawing air out of the package. By keeping cheese's lipids from oxidizing, vacuum packaging lowers the likelihood that it will go sour. Moreover, it reduces oxygen content, which inhibits the growth of aerobic spoilage microorganisms.

Hard and semi-hard cheeses are commonly packaged in vacuum-sealed bags. Modified Atmosphere Packaging (MAP) entails modifying the gases surrounding the cheese, usually by lowering oxygen concentrations and regulating nitrogen and carbon dioxide levels. By preventing the growth of bacteria that cause spoiling and maintaining the texture and flavor, MAP prolongs the shelf life of cheese. It also lessens the chance of mold formation (Nájera et al., 2021).

Wax-Coated Paper Some cheese varieties are wrapped in wax-coated paper. The wax layer acts as a barrier to keep out outside pollutants. The paper with wax coating helps hold moisture in, keeping the cheese from drying out. It also acts as a physical barrier to keep out pollutants and smells from the outside environment (Nájera et al., 2021).

Cheese is prone to moisture loss, which can alter its flavor, texture, and general quality. Cheese, especially types with more moisture in them, can lose moisture while being stored. Changes in texture, flavor, and general quality may result from this (Majid et al., 2018).

By minimizing air exposure, vacuum-sealed bags lower the possibility of moisture loss. Low-oxygen environments produced by vacuum-sealed bags reduce the possibility of moisture loss. Soft and semi-soft cheeses retain their freshness and creaminess longer when there is no air present. The wax coating on paper acts as a moisture barrier, stopping the cheese's water from evaporating (Rejeesh & Anto, 2023). This is particularly helpful for specialized and artisanal cheeses when it's important to maintain a certain moisture content.

Preserving the freshness and quality of cheese requires maintaining the proper gas composition. While too little oxygen can harm aerobic microorganisms, too much oxygen can cause oxidation. The cheese's ability to be preserved depends critically on the makeup of the gases that surround it. Vacuum sealing and MAP are useful techniques for managing gas composition (Barukčić et al., 2021).

MAP provides exact control over the gas composition, guaranteeing ideal circumstances for various cheese varieties. By modifying the concentrations of nitrogen, carbon dioxide, and oxygen, MAP produces an environment that prevents spoilage microbes from growing. By eliminating extra oxygen, vacuum-sealed bags produce a regulated environment that reduces the chance of oxidation. Vacuum-sealed bags produce a low-oxygen environment by sucking out air from the container (Nájera et al., 2021). This stops aerobic spoilage germs from growing and helps preserve the cheese's color and flavor by preventing oxidation.

This type of paper helps maintain the integrity of the cheese by acting as a physical barrier against microbiological contamination. The wax coating on paper serves as a physical barrier to keep impurities out. This is especially helpful for cheeses that have natural rinds, as they need to be protected from outside microbes (Espitia et al., 2014).

8.2.3 Yogurt Packaging: Materials, Challenges, and Solutions

Plastic Cups: High-density polyethylene (HDPE) or polypropylene (PP) are the most frequent materials used to package yogurt. These materials provide an affordable and lightweight option (Awulachew, 2022). Plastic cups offer a portable and easy-to-use packing solution. Additionally, they can be sealed, which keeps the yogurt's texture and freshness intact (Rejeesh & Anto, 2023).

Polypropylene Pouches with Lids: Flexible plastic pouches, frequently composed of laminates with many layers for barrier qualities, are another way that yogurt is packaged. Sealable lids guarantee the pouch's airtight closure (Awulachew, 2022). Pouches provide for more creative packaging options and are a popular choice for single-serve or portable yogurt products. The ability to seal the lids helps to preserve the freshness of the product (Marsh & Bugusu, 2007).

Light Resistant Packaging: Yogurt packaging materials with light-resistant qualities, like opaque or colored plastics, are used to maintain the probiotic content of the product. Since probiotics are light-sensitive, shielding yogurt from sunlight helps avoid their deterioration (Marangoni Júnior et al., 2022). This guarantees the survival of advantageous microorganisms for the duration of the product's shelf life (Campos et al., 2019).

8.3 Challenges and Remedies

Maintaining the product's intended consistency and texture over the course of its shelf life is a challenge that yogurt packaging must solve. Keeping yogurt's texture intact is crucial to providing customers with a positive experience. A key component in reaching this objective is packaging solutions. To help, keep an airtight atmosphere, plastic cups and pouches frequently have sealable lids (Barukčić et al., 2021). By doing this, the yogurt's creamy quality is maintained and moisture loss is avoided. By creating an airtight seal, sealable lids on plastic cups and pouches stop yogurt's moisture from evaporating. This aids in preserving the smooth and creamy quality that customers need. Modified Atmosphere Packaging (MAP) technique helps to preserve the texture of yogurt by controlling the gas composition in specific situations. Yogurt texture can be maintained by utilizing MAP to modify the gas composition inside the container. Reducing variables like carbon dioxide and oxygen concentrations helps stop unfavorable texture alterations over time.

Yogurt quality and safety are at risk due to contamination. Ensuring a tight seal and upholding hygienic standards are essential factors to take into account while packing. Airtight lids protect yogurt from airborne particles by acting as a barrier against external contamination. They are commonly seen on cups and pouches. Dust, bacteria, and other foreign particles are kept out of the container by airtight sealable lids. This is essential to preserving the yogurt's safety and hygienic qualities (Barukčić et al., 2021).

Probiotics, or good bacteria that support digestive health, are frequently found in yogurt. The probiotics' viability must be guaranteed by the packaging for the duration of the product's shelf life. Live bacteria known as probiotics, which are good for digestive health, are frequently found in yogurt. Probiotic viability preservation is a crucial factor in yogurt packaging. Probiotics are shielded from light-induced deterioration and their viability is maintained by the use of light-resistant materials, such as opaque or colored plastics. The viability of probiotics depends on maintaining the right storage temperatures during shipping and storage. Yogurt is delivered to customers in the best possible condition. The viability of probiotics in yogurt is preserved by cold chain logistics, which include maintaining appropriate refrigeration during transportation and storage, guaranteeing that customers receive a product with the greatest possible health advantages (Campos et al., 2019).

8.4 Packaging Innovations in the Dairy Industry

The dairy industry has benefited from major improvements in packaging technologies in recent years, especially in the area of smart packaging. These developments are meant to increase supply chain efficiency, boost consumer safety, and increase product handling transparency. Radio-frequency identification (RFID) technology and Time-Temperature Indicators (TTIs) are two prominent smart packaging options for milk and milk products (Salgado et al., 2021).

Modified Atmosphere Packaging (MAP) To increase the shelf life of dairy products, MAP entails changing the air's composition around them. This is accomplished by altering the packaging's nitrogen, carbon dioxide, and oxygen concentrations delaying oxidation, MAP helps to prevent dairy products' lipids and vitamins from degrading. It also increase the shelf life of products by preventing the formation of pathogenic microorganisms (Pal et al., 2019).

Vacuum Packaging To create a vacuum environment before sealing, the air inside the package must be removed. This technique aids in preventing aerobic microbes from growing. It reduces oxidative reactions and stops the formation of harmful bacteria and spoiling, extending the shelf life of dairy products (Marangoni Júnior et al., 2022).

Aseptic Packaging Sterilizing the dairy product and the packaging material together before filling and sealing them in a sterile setting is known as aseptic packaging. This keeps the product fresher longer without requiring refrigeration. It preserves dairy products' flavor and nutritional value without requiring refrigeration (Kalpana et al., 2019; Pal et al., 2019). This technology is perfect for dairy items that are liquid, like cream and milk.

Smart Packaging Real-time information regarding the state of the dairy product and its surroundings is provided by smart packaging, which uses technologies like sensors and indicators. It provides producers and customers with real-time monitoring of variables including freshness, temperature, and expiration dates to ensure ideal storage conditions. Smart packaging helps to reduce food waste and improve quality control, especially for high-value dairy products (Majid et al., 2018).

Time-Temperature Indicators (TTIs) Time-Temperature Indicators are labels that provide important details about the environmental circumstances to which a product has been subjected from point of manufacturing to the point of final consumption. To guarantee the safety and quality of milk and dairy products, the cold chain must be maintained (Majid et al., 2018). With TTIs, customers can see whether a food has been exposed to temperature conditions that would have harmed its freshness. For example, a TTI label might show a time-temperature scale or change. This invention encourages adherence to appropriate storage and transportation methods, which not only empowers consumers to make correct decisions but also fosters accountability throughout the supply chain (Pal et al., 2019).

RFID Technology RFID technology, also known as radio-frequency identification, uses tiny, wireless devices known as RFID tags or labels. RFID readers can read the electronically recorded data on these tags from a distance. RFID technology is used in the dairy business to track and monitor products in real-time along the whole supply chain. RFID tags can be affixed to the packaging of milk and dairy products to offer comprehensive details on the product's journey, such as the date of production, the routes taken during transit, and the circumstances in which it was stored (Salgado et al., 2021). To guarantee the quality and safety of products, this degree of traceability is essential. Furthermore, RFID technology lowers the possibility of mistakes in product tracking, streamlines inventory management, and helps avoid problems like tampered or expired goods reaching customers (Pal et al., 2019).

Smart packaging developments such as RFID technology and TTIs are essential for preserving the purity of milk and milk products. TTIs give customers an easy-to-use method of determining how fresh milk is on store shelves, which lowers the possibility that they may buy a product that has been exposed to bad storage condition. On the other hand, complete supply chain visibility is provided by RFID technology. An RFID-tagged milk carton, for instance, may be followed from the dairy farm to the processing facility, then throughout the distribution network to the store. This makes it possible to precisely monitor the cold chain and guarantee that milk is constantly kept at the ideal temperature. Additionally, RFID makes effective product recalls possible by enabling the prompt identification and removal of particular batches from distribution (Lee et al., 2017).

9 Sustainable Packaging in Dairy Industry

The dairy industry has made sustainable packaging a priority as consumer knowledge of environmental issues rises. The greater usage of recyclable materials and biodegradable films are two noteworthy examples of sustainable packaging solutions used in dairy technology.

9.1 *Biodegradable Films*

The adverse environmental impact of conventional packaging materials is a problem that biodegradable films appear to be able to solve. These films are frequently made in dairy technology using natural materials like cellulose, starch, or other plant-based polymers. The use of biodegradable films in the packaging of dairy products lessens the environmental impact of packaging disposal while also reducing dependency on non-renewable resources. The purpose of these films is to decompose organically over time and return to the environment without leaving behind any residue (Majid et al., 2018). Dairy packaging that uses biodegradable films gives consumers an environmentally beneficial option while also supporting the industry's commitment to sustainability. Biodegradable films support a circular economy in the dairy supply chain and help reduce plastic pollution while guaranteeing the freshness and safety of the food (Burgos et al., 2021).

9.2 *Recyclable Materials*

Using recyclable materials in the packaging of dairy products is a big step in the direction of a more circular and sustainable system. This entails making use of resources that can be gathered, processed, and used to create new products again. Paperboard, high-density polyethylene (HDPE), and polyethylene terephthalate (PET) are often utilized recyclable materials in dairy packaging (Awulachew, 2022). Dairy packaging that uses recyclable materials encourages consumers to take part in recycling programs while simultaneously lowering the demand for virgin plastics. Utilizing recyclable materials helps create a closed-loop system where packaging materials are recycled or turned into new goods, lowering environmental impact and helping the dairy industry's aim to minimizing it (Majid et al., 2018).

An expanding number of dairy product packaging applications, such as cheese wraps, yogurt cups, and milk pouches, are being investigated for biodegradable films. In milk bottles, yogurt containers, and other dairy packaging styles, recyclable materials are frequently used (González-López et al., 2023). The dairy industry's shift to recyclable materials is in line with customer expectations for more sustainable practices and supports the ideas of a circular economy.

9.3 *Active Packaging for Extending Self-Life of Milk and Milk Products*

Active packaging methods have become popular for prolonging shelf life and guaranteeing the safety of milk and milk products in the dairy industry, where maintaining freshness and quality is crucial (Pal et al., 2019). Within the category of active packaging, antimicrobial films and gas scavengers are two notable innovations.

Antimicrobial Films To extend the shelf life of milk and other dairy products, dairy packaging is using antimicrobial films. These films form a barrier that prevents the growth of harmful bacteria, molds, and yeasts by incorporating antimicrobial chemicals right into the packing material (Yan et al., 2022). Antimicrobial films are vital for preventing microbial growth and preserving the freshness of milk products, which are very vulnerable to spoiling because of the presence of water and nutrients. Active films ensure that milk and dairy products reach consumers with optimal quality and safety, satisfying the industry's high criteria for cleanliness and customer satisfaction by establishing a controlled antimicrobial environment within the package (Kalpana et al., 2019; Pal et al., 2019).

Gas Scavengers The purpose of these scavengers is to eliminate harmful gases from the packaging environment, like ethylene and oxygen. Oxygen can trigger oxidative processes in milk, which can result in unpleasant tastes and a decline in nutritious value (Yan et al., 2022). Gas scavengers are used in packaging to lower oxygen levels, which slows down oxidative processes and prolongs the shelf life of the product (Salgado et al., 2021). For milk and other dairy products that are susceptible to oxygen exposure, gas scavengers are very helpful in preserving the products' freshness, flavor, and nutritional value for customers. This method is particularly useful in reducing the formation of off-flavors that may arise from milk's lipid oxidation, hence improving the sensory parameters for customers (Ramos et al., 2020).

In dairy packaging, in cheese wraps and milk cartons, antimicrobial films are useful because they prevent the growth of microorganisms. Antimicrobial films add to the overall freshness of dairy products by halting deterioration and preserving. Scavengers increase the product's shelf life by reducing oxygen exposure, guaranteeing that consumers obtain dairy products that preserve their nutritional content and sensory qualities (Marangoni Júnior et al., 2022). Future developments in active packaging are expected as technology progresses, giving dairy producers more resources to improve product preservation and satisfy changing consumer needs.

The packaging and preservation of dairy products, are dynamic industries propelled by an ongoing pursuit of sustainability and innovation. New developments in materials science, technology, and preservation techniques help to improve dairy products' quality, safety, and shelf life. Future dairy packaging will be shaped by the

incorporation of sustainable materials, innovative preservation methods, and smart packaging as the sector develops, taking into account customer demands as well as environmental concerns.

10 Conclusion

In the year 2015, US adopted Sustainable Development Goals (SDGs) and provide an indicator framework to solve various aspect of global challenges which the developed and developing nations are facing globally. The SDG-Goal- 2 which include Zero hunger eradication by the year 2030 in the Global South. The main concern is to minimize the food waste in the supply chain of agricultural products through food packaging. The wastage occurring in the process of farm to fork is tremendous and need to immediate attention worldwide. Various innovative technologies are engaged in developing bioplastic and contribute in the sustainable environment ecosystem. The packaging advancement in the dairy products contribute to the maximum protein accessibility in the body especially to the vulnerable groups like women and children's. Various breakthrough has been achieved using emerging technology in the field of active and intelligent packaging to reduce wastage of agricultural produces. Antimicrobial films are gaining popularity as it prevents the growth of microbial population especially in high water content food items like dairy products. Hence, Food Packaging indeed pave way in minimizing the global issues of the food insecurity/food wastage and balancing the supply chain process.

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Chapter 11

Advances in Food and Dairy Processing Technologies



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1 Introduction

Significant advancements in food processing technologies over the past few decades have entirely transformed how we produce and consume food. These developments have increased food products' shelf life and nutritional value while also increasing food manufacturing efficiency and safety. The scientific community is still debating how the food supply fits into the demand-supply system. Choosing the right techniques from contemporary, sustainable practices can increase output and successfully satisfy demand. In comparison to other industries, the food business has historically been described as a mature, slowly expanding sector with modest levels of investment in research and development. Technical processing methods and creative food manufacturing have been made possible by recent developments in the food processing units. An array of food products, comprising of functional meals, have become more and more popular over the last 50 years since they are recognized as essential for encouraging a healthy lifestyle. The food industry has adopted a number of food processing processes to comply with the consumer's demand and the requirement of enhanced production efficiency. Using technical advancements, the agriculture and food processing industries make major contributions to the world's food supply, producing and processing about 64% of the food consumed worldwide (Kakani et al., 2020).

Rise in the milk and milk products demand globally has been the driving force in development of contemporary dairy farms, dairy product processing facilities, and use of artificial intelligence in the dairy industry. This significant shift in the industry has raised output while lowering the negative effects of milk processing on the

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environment, together with greenhouse gas emissions, poverty alleviation, and other worldwide issues. Automated technology, like computerised feed supply and dairy systems, automatic olfactory equipment, and farm computers for recording dairy records, have been discovered in the last 20 years. Additionally, cutting-edge dairy processing techniques that have the potential to lower energy use and greenhouse gas emissions include high hydrostatic pressure, pulse electric fields, microwave heating, microfiltration, homogenization of high pressure, pulse light, and UV light processing. (Gebeyehu, 2023).

Technologies such as non-thermal processing, pulsed electric field (PEF), and high-pressure processing (HPP) are becoming more popular for enhancing food quality and effectiveness of production processing. In the matter of food safety, shelf life extension, and nutrient retention, these technologies are advantageous. Reducing the amount of water and energy used in food processing through innovations such as dry milling and process intensification is becoming more and more important. Through waste reduction and resource optimisation, the sector is transitioning to more environmentally friendly methods. Nutrient content in food products can now be optimised thanks to developments in food processing technologies. These advancements support the promotion of health and well-being by increasing the bioavailability of nutrients and boosting nutritional quality (Augustin et al., 2016). Owing to the creation of materials with special qualities, nanotechnology—a technology operating on the nanoscale—has completely changed the food processing sector. The development and utilization of structures, materials and systems with novel qualities in a variety of fields, including food, medicine, and agriculture, is made conceivable by the vast range of options presented by nanotechnology. Researchers are searching for ways to improve food quality and health advantages without sacrificing a product's nutritional worth. Because of its fundamental components, non-toxicity, and stability at high temperatures and pressures, materials based on nanoparticles are highly sought after. From production to packaging, nanotechnology provides comprehensive food solutions that improve food quality, safety, and health benefits (Singh et al., 2017).

Cold plasma has emerged recently as a technological advancement in preserving food safety and quality. In the food industry, the cold plasma approach has proven effective in eliminating hazardous and sporulating organisms from food products. The inventiveness of this process is in its production diversity and prospective uses in indirect or direct plasma, functional coatings, water-treated plasma and its non-thermal effect without adversely affecting the quality of food. Foods are also rendered microbially inactive by this innovative technique (Sainz-García & Alba-Elías, 2023). High-pressure processing (HPP) is gaining popularity in the food industry as an alternative to preservation and processing techniques based on heat treatments. Its primary application is to inactivate microorganisms and enzymes, resulting in less flavor and nutritional deterioration and minimal loss of vital components, giving foods their distinctive organoleptic characteristics (Santos et al., 2019). Because HPP distributes pressure uniformly throughout the meal, it prevents overtreatment and has no effect on food quality in comparison to thermal treatment. This method

develops distinctive products while minimally impacting food's chemical properties (Nottagh et al., 2020).

Although food-borne diseases are global significant concern in the public health concern, food post-harvest losses are perceived to be the primary cause of famine and malnutrition worldwide. Development of numerous methods has reduced food spoilage and improve food safety. Pasteurization, canning, freezing, refrigeration, and chemical preservatives usage are examples of conventional preservation techniques. A non-thermal method of food preservation is food irradiation. It involves treating food exposure to energy in the form of speed particles or radiation. A variety of outcomes, including decreased storage losses, extended shelf life, and enhanced microbiological and parasitological food safety, can be attained depending on the amount of radiation absorbed. The primary reason for possible use of ionizing radiation in food preparation is its exceptional ability to cause damage to DNA molecules. Applications range widely, from preventing tubers and bulbs from growing to producing.

Through loss reduction and spoiling management, food processing is essential in solving concerns related to food security. Ultrasound technology among the most advantageous non-thermal processing techniques. When using ultrasound processing, by its own or in addition to other techniques, greatly enhances food quality, and is therefore thought to be advantageous. The food processing sector uses ultrasound for numerous processes, including cutting, freezing, drying, homogenization, foaming and defoaming, filtration, emulsification, and extraction. Without compromising the food's quality, ultrasounds can be utilized to eliminate bacteria and deactivate enzymes. Because of this, ultrasonography is being marked as a revolutionary processing method for lowering nutritional and organoleptic waste. Around the world, microwave technology is utilized for heat production using electromagnetic energy from microwave region of spectrum. This is distinguished through rapid heating, even energy transference, and reduced energy consumption—all these helps to retain a large portion of the nutritional content of food goods. Since medicinal plants and food ingredients are from similar plants, microwave heating is frequently used in food processing applications like drying. Although plant parts are also processed and extracted using microwave technology for medical purposes, the special characteristics of microwave radiation give reactions energy to convert one set of chemical components into another through processes like esterification, condensation, oxidation, hydrolysis, and rearrangement.

The food processing sector is increasingly adopting sustainable practices to lower its impacts on the environment and encourage ways of sustainable production and consumption. Efforts to optimize resource use, minimize waste and lower greenhouse gas discharges are key priorities in recent developments (Augustin et al., 2016). Addressing consumer perceptions and concerns about processed foods is a key focus in recent developments. Clear demonstration of the benefits and safety of new technologies is vital for strengthening consumer reliance and acceptance of processed food products. The industry is continuously innovating to cater the appetite of an increasing population with changing consumer preferences. Adapting to

global megatrends, such as the digital revolution and increased focus on health and sustainability, is driving innovation in food processing.

2 Overview of Global Food and Dairy Industry

The challenge of feeding 9 billion people by 2050 requires increasing food production but also a focus on minimizing the food losses encountered in the supply chain and enhancing food preservation, safety, and nutrient content through food processing. There are opportunities for reducing water and energy use in dairy processing through innovations like process intensification. Increasing milk's total solids concentration can lead to energy savings in milk powder production. Consumer sentiment towards dairy products is influenced by factors such as safety, processing methods, and nutritional content. Clear demonstration of benefits and safety of dairy technologies is essential for customer approval (Jaeger et al., 2015).

Globally, production of milk has dramatically increased from 530 to 843 million tones in years 1988 to 2018. Outrunning most of the agricultural produce, this rise in production of milk is anticipated to continue at the rate of 1.6% for the next 5 years (Gebeyehu, 2023). The dairy industry must address sustainability challenges, including reducing environmental impacts and developing strategies for sustainable consumption and production patterns. Efforts to improve resource efficiency and reduce greenhouse gas emissions are crucial. Environmental sustainability is essential, and in order to produce more food, the agrifood production and food processing industries must utilise fewer resources. Emerging nutritionally appropriate and innovative food products with long shelf lives is important for promoting health and well-being (Augustin et al., 2016; Gebeyehu, 2023). The industry is evolving with advancements in processing technologies to meet rising population's demands. Adapting to global megatrends and consumer preferences for healthier dairy products is essential for industry growth. Dairy products are important sources of essential nutrients, and innovations in dairy processing can enhance the safety and nutritional quality of dairy foods. Meeting consumer demands for healthy and sustainable dairy options is a key focus for the industry (Jaeger et al., 2015).

Statistics show that a variety of elements, including customer psychology, food type, current trends, quality control, and human wellness, have an impact on the food processing sector. Due to these limitations placed on the food processing sector, technology must be included in order to increase production values, reduce waste, and meet consumer demand (Kakani et al., 2020). Trends like digital revolution, increased productivity in the agricultural sector, and growing food demands with health benefits will shape the food industry future. Adapting to these innovations for addressing consumer preferences are key for industry success. The global food industry is evolving to meet the challenges of providing safe, nutritious, and sustainable food to a growing population. Innovation in food processing, sustainability practices, and consumer engagement are key factors in shaping the future of the industry.

3 Recent Advances in Food and Dairy Processing Technology

In the past 20 years, significant mechanical advances have been noticed in the liquid milk and food handling industry, with a critical enhancement in all food processing unit operations. In combination with this, much progress has been made with regards to production capacity, computerization and cleaning or sanitation activities. In the dairy processing sector, milk is normally pasteurized by heating to a certain temperature for a predetermined duration (Gebeyehu, 2023). However, until recently developed non-thermal treatment strategies are great for milk and other foods with better execution of the killing of microorganisms or other natural substances without critically increasing the temperature, thus preventing unfortunate chain of reactions in food the varieties. Innovative technologies in food processing have gained enormous traction as they improve food storage and maintain the quality characteristics including nutrition, sensory properties and freshness of the product (Allai et al., 2023). High pressure processing, cold plasma, pulse electric field, microwave, irradiation, ultrasound, nanotechnology and artificial intelligence tools are a few of the evolving technologies discussed hereafter.

3.1 *High Pressure Processing*

3.1.1 Introduction

High-pressure processing (HPP) is a non-thermal processing method used to enhance food quality, preserving freshness, and nutritional content as well as extend the shelf-life of food products. When food is compressed inside a vessel that exerts high pressure, it can be processed to preserve its nutrition, flavor, and fresh appearance while inhibiting harmful microorganisms and preventing deterioration. This technique is known as high-pressure food preservation (Abera 2019).

3.1.2 Equipment and Principal

High-pressure processing (HPP) is a non-heat treatment for preservation of food that employs pressures between 50 and 1000 MPa to treat food products. The principles and mechanisms of HPP are based primarily on the isostatic law and Le-Chatelier's principle. Le Chatelier's Principle states that pressure intensifies phenomena that cause a decrease in volume, such as phase transitions, chemical reactions, and changes in molecular configurations. Conversely, pressure slows down events that produce a rise in volume. The second concept is the isostatic law, stating pressure applied to a product will uniformly distribute throughout the pressurized sample, irrespective of its shape, size, packaging, or direct contact with the product. Contrary to the thermal process, food systems are subjected to rapid and

uniform pressure (isostatic pressure), hence the amount of time needed for HPP is independent of sample size (Abera, 2019).

A material pressurizing system, a pressure vessel, a pressure transmitting fluid, and auxiliary units like heating or cooling elements are the fundamental parts of a High-pressure processing (HPP) system. High-pressure food treatment entails the application of water vapor condensation around the food, followed by its placement into a high-pressure chamber and pressurization using a pressure-transmitting medium. Water is frequently utilized, although alternative liquids such as castor oils or silicon, glycerol, ethanol, and sodium benzoate solution are also viable options. The viscosity and the temperature range of the pressurized fluid are crucial elements. In the chamber, the medium is introduced through pressure pumping or piston action to compress the volume, thereby subjecting the food to elevated pressure. When the pressure attains the specified threshold, no additional energy is required to maintain it, and both the pump and piston halt. The processed item is removed from the depressurized setup and can be loaded with other food items manually by operators or automatically by machines. The operational cycle encompasses the entire duration involving application, holding, and release of pressure, with the time and load capacity crucial in determining the system's suitability (Ravash et al., 2022).

Pressurization can be accomplished either directly or indirectly. Direct pressurization involves a piston and low-pressure pump to generate pressure, which is quickly achieved when food is positioned within the chamber. Indirect pressurization involves a pressure transfer medium like water passing through an intensifier before entering the pressure chamber. This technique necessitates high-pressure conduits and appropriate connections to convey the pressure-transmitting medium into the pressure chamber (Mandal & Kant, 2017).

3.1.3 Effect on Nutritional Components of Food

HPP causes alterations in noncovalent linkage, including hydrophobic interactions, and H-bonds. High molecular weight components in foods influence their nutritional as well as sensory characteristics, affected by high pressure, and low molecular weight components. As a result, when compared to heat processing, vitamins, flavor components, and pigments are substantially unaffected by HPP, preserving the nutritional profile, sensory attributes of food. Lipids may undergo modifications, impacting the texture and stability of the food product. HPP results in changes in the size, aggregation, and structure of fat globules in milk. Carbohydrates can be gelatinized using pressure rather than heating. Covalent bonds may also change under pressure, with protein molecules experiencing alterations in their structures, particularly in hydrophobic and ionic bonds. At pressures greater than 200 MPa, substantial modifications occur to the hydrophobic and ionic bonds that comprise the tertiary and quaternary structures of protein molecules. Interactions that are hydrophobic and electrostatic are impacted more frequently. HPP can impact the activity of enzymes present in milk, leading to enzyme inactivation or activation (Ravash et al., 2022).

3.1.4 Application in Food and Dairy Processing

HPP is a promising method for processing fruit and vegetable products, retaining most of their nutrients. HPP can reduce the firmness and texture of fruits. Studies have shown a reduction in hardness and chewiness in fruits like peaches, pumpkins, and strawberries after High-pressure processing treatment (Zhou et al., 2014; Gao et al., 2016). HPP can preserve the colour of fruits and vegetables by deactivating enzymes such as polyphenol oxidase and peroxidase. Studies on cocoyam, carrot, cucumber juice, and pumpkin purée have shown minimal color changes immediately after HPP treatment, with some changes observed after storage (Tribst et al., 2016). HPP generally well preserves vitamins like vitamin C and carotenoids in fruit products. Studies have reported minimal losses of vitamin C and an increase in the carotenoids content in products like tomato purée, orange juice, and pomegranate juice after HPP treatment (Santos et al., 2019). HPP can improve the extraction efficiency of bioactive compounds from fruits and vegetables, resulting in increased yields of substances such as total phenolic compounds in beetroot. The technology can also promote the biosynthesis and accumulation of health-promoting bioactive compounds in horticultural crops (Paciulli et al., 2016).

HPP can impact the textural properties of meat products. For instance, in reduced-fat sausages, and meat batters, HPP treatment yielded comparable sensory outcomes to traditionally processed sausages that contain higher levels of fat. The texture of meat products can be influenced by the pressure level and processing conditions (Yang et al., 2016). HPP can influence the color of meat products. Studies have shown changes in the levels of volatile compounds in HPP-treated samples compared to untreated samples, which can influence the color perception of products like Serrano dry-cured ham. The color stability of meat products during storage after HPP treatment is also an important consideration (Santos et al., 2019). HPP can help in preserving the nutritional content of meat products. Research has indicated that HPP can maintain the nutritional content of meat-based products, ensuring minimal degradation of nutrients and flavors. Studies have focused on the impact of HPP on the nutritional properties of meat products to ensure consumer acceptability and safety. HPP can influence the sensory characteristics of meat products. Research indicates that consumer preference does not significantly differ between high-pressure processed (HPP) meat products and their untreated counterparts, such as ready-to-eat pastrami, Strassburg beef, export sausage, and Cajun beef. The sensory quality of meat products can be maintained over extended periods of refrigerated storage after HPP treatment (Hayman et al., 2004).

HPP can lead to alteration in the dimensions, aggregation, structure of fat globules in milk, and can induce modifications in the structure and functionality of milk proteins like whey proteins, and casein. High-pressure processing (HPP) can influence the enzymatic activity of proteins in milk, leading to enzyme inactivation or activation which can affect the shelf stability and quality attributes of dairy products. HPP can affect the dissolution of colloidal calcium phosphate in milk, resulting in an alteration to the dissolution capacity of phosphorus and calcium. Cheese treated with HPP may exhibit improved shelf life due to reduced

post-contamination and microbial growth. HPP-treated starter cultures may enhance the fermentation process and play a part in the formulation of specific cheese varieties. HPP can alter the microstructure of yogurt, leading to changes in texture, consistency, and syneresis resulting in improved sensory properties and extended shelf life. It also helps in maintaining the viability of probiotic bacteria in yogurt by selectively inactivating undesirable microorganisms while preserving beneficial probiotic strains. HPP in butter production can increase the product's shelf life, improve consistency, and enhance fat aggregation (Ravash et al., 2022). HPP can enhance the stability of ice cream by enhancing foam stability and creating an even texture through the formation of small crystals (Huppertz et al., 2002).

3.2 *Pulse Electric Field*

3.2.1 Introduction

Another technique for processing food is called Pulsed Electric Field (PEF), which applies brief, non-thermal bursts of high voltage electric fields to food items. Being a potential minimal processing method, PFE has been studied as a tool for preservation of food via means of inactivation of spore or microorganism in the stationary and growth phase. The electric pulses cause changes in the cell membranes of the food, leading to various effects for instance enzyme inactivation, electroporation, microbial inactivation, and enhanced bioactive compound extraction. The primary mechanism of PEF is electroporation, where the electric fields of high-voltage create temporary pores in cell membranes, allowing for the passage of ions, molecules, and other compounds. This increased permeability of cell membrane can induce improved mass transfer, extraction efficiency, and food products preservation. PEF has been studied for its potential benefits in food processing, including improved protein digestibility, texture modification, enhanced extraction of bioactive compounds, and microbial inactivation. It is considered a promising technology for solid foods processing, offering opportunities for pretreatment before drying, cooking, and freezing operations. Overall, the application of PEF shows potential for enhancing processing efficiency, quality, and safety through its unique mechanism of action on food constituents (Zhang et al., 2023; Wang et al., 2019).

3.2.2 Equipment and Principal

The PEF technology's principle is founded on subjecting food product to quick pulses of high-voltage electric fields. The main principle revolves around the concept of electroporation, which is the development of temporary pores in cell membranes. The primary mechanism in PEF is electroporation, where the electric field of high-voltage generates temporary pores in cell membranes of the product. These newly formed pores allow ions, molecules, and other compounds to pass across the

membrane that would not normally be capable of passing through. Electroporation leads to increased permeability of the cell membrane, allowing for enhanced mass transfer of intracellular components, including nutrients, bioactive molecules and enzymes (Zhang et al., 2023).

PEF technology requires specialized equipment for applying high-intensity electric field on food products. Key components in PEF equipment frequently used for processing of food include pulse modulator, treatment chambers, electrodes, high-voltage power supply, control and monitoring systems and cooling systems. The pulse modulator is a crucial component of PEF equipment that controls production and delivery of PEF to the food product. It regulates the intensity, frequency, and interval of the electric pulses given during PEF treatment process. PEF treatment chambers are designed to hold the food product between the electrodes where the electric fields are applied. These chambers are constructed to ensure uniform distribution of electric fields across the food product for effective treatment. Electrodes are the conductive elements that deliver the electric pulses to the food product within the treatment chamber. Typically, they are made from materials like stainless steel, but there is ongoing research to find more suitable and durable electrode materials to mitigate corrosion issues. PEF equipment requires a power supply of high-voltage to generate the intense electric fields needed for the treatment process. The power supply must provide continuous and stable electric fields of high-intensity to accommodate industrial-scale production requirements. PEF equipment is often equipped with control and monitoring systems to regulate the treatment parameters and monitor the process in real-time. These systems ensure that the PEF treatment is applied accurately and consistently to achieve the desired outcomes. In some cases, PEF equipment may include cooling systems to manage the heat generated during the treatment process. Cooling systems help in temperature control of the sample within the chosen range to prevent overheating and ensure product quality. PEF equipment is designed with safety features to protect operators and ensure the safe operation of the system. Safety measures may include emergency stop buttons, insulation to prevent electric shock, and protective enclosures around high-voltage components (Zhang et al., 2023).

Overall, PEF equipment is designed to deliver precise and controlled electric pulses to food products for various processing applications. Advances in equipment design and technology continue to enhance the efficiency, safety, and scalability of PEF systems in food processing operations.

3.2.3 Effect on Nutritional Components of Food

Pulsed Electric Field (PEF) technology can have both beneficial and harmful consequences on food product's nutritional value based on several factors including processing parameters, food composition, and intended outcomes. PEF treatment can help preserve the nutritional content of food by minimizing heat exposure, which can degrade heat-sensitive nutrients like vitamins and antioxidants. Along with this the food treated with PEF technology has revealed to preserve the original taste,

flavor and color of the product (Bai et al., 2021). PEF-induced cell membrane permeabilization can improve the bioavailability of certain nutrients by facilitating their release and absorption in the digestive system. PEF treatment has been shown to improve the digestibility of proteins in meat products, potentially improving the utilization of protein by the body. Improved digestibility with specific regards to in-vitro digestibility protein has been observed in case of beef prepared by applying PEF by Bhat et al., 2019. The more amount of connective tissue and compact structure makes it hard to digest despite being a protein rich commodity, however PEF treatment improves proteolysis thereby enhanced myofibrillar breakdown and protease release from lysozymes hence better meat digestion and emulsification (Bhat et al., 2019).

Modification of macromolecules by PEF also show improved protein and starch digestibility. This is caused by the conversion of complex starch to easily digestible form along with partially altering the crystalline and amorphous region of starch granules (Wu et al., 2019). PEF processing may help retain minerals in food products by minimizing losses during traditional thermal processing methods. Extraction assisted with PEF enhances the recovery of bioactives, comprising antioxidants as well as polyphenols, from sources like plant tissues, leading to higher levels of these beneficial compounds in the end product. Changes in structure and texture of food induced by PEF might as well be the influencing factors of digestibility of nutrients, potentially affecting their absorption and utilization in the body (Zhang et al., 2023). 10 kV electric field strength has been found to improve polyphenol release in oranges, pomelos, and lemons by 39–135% (El Kantar et al., 2018). While PEF can deactivate enzymes, which may impact certain food functionalities, it can also prevent enzymatic degradation of nutrients, thereby preserving their nutritional value (Zhang et al., 2023).

Along with nutritional changes PEF treatment induces several other variations in food constituents owing to implication of short pulses of high-voltage electric fields. PEF induces cell electroporation, which increases cell membranes permeability, enabling improved mass transfer of compounds such as ions, sugars, and other molecules (Shorstkii et al., 2022). Electroporation leads to increased permeability of the cell membrane, allowing for enhanced mass transfer of intracellular compounds, such as nutrients, enzymes, and bioactive molecules. The improved energy and mass transfer by electroporation makes PEF a suitable pretreatment before freezing, drying and cooking of solid foods (Meneses et al., 2011). Changes induced by PEF treatment, such as cell membrane disruption and altered cell structure, causes modifications in the structure, texture and digestibility of foodstuffs due to the reduction in turgor pressure. PEF treatment can lead to tissue softening in fruits and vegetables, making them easier to process and potentially improving the texture of the end product.

PEF treatment is reported to decrease the cutting force by softening tissue, as required for processing certain foods, such as potatoes, even at low energy intake levels, resulting in easier handling and processing. PEF treatment of raw potato sticks can make them more flexible and less prone to breakage, resulting in higher

product yield and improved quality. The fries absorb 10% less oil, less breakage and exhibit more consistent browning due to the homogeneous softening of the raw material, enhancing visual appeal and consumer preference (Cruz et al., 2018). PEF treatment can enable the peeling of fruits and vegetables by separating the skin from the pulp more easily, leading to improved efficiency in processing operations. PEF treatment of 1.0 kV/cm reduces the freeze-drying time and improves the rehydration quality and ability of strawberries and red bell peppers (Fauster et al., 2020).

PEF treatment, although non-thermal, can still cause the deterioration of certain heat-sensitive nutrients, such as vitamins and antioxidants, especially if the processing parameters are not optimized. While enzyme inactivation by PEF may be helpful for certain applications, it may also inactivate beneficial enzymes that are responsible for food digestion and nutrient absorption. Alterations in food texture and structure caused by PEF treatment may impact the digestibility and absorption of nutrients in the body, potentially reducing the bioavailability of certain nutrients (Zhang et al., 2023). PEF treatment, particularly in combination with freezing and storage, may affect the oxidative stability of food products, leading to lipid oxidation and potential degradation of essential fatty acids (Ma et al., 2016). PEF-induced changes in cell membranes can lead to the leakage of water-soluble nutrients from cells, potentially resulting in nutrient losses and mineral leaching from food matrices during processing.

3.2.4 Application in Food and Dairy Processing

Overall, the utilization of PEF in food processing offers an assortment of benefits, including microbial inactivation, enzyme deactivation, texture modification, extraction enhancement, and improved rehydration properties, making it a versatile technology for enhancing food quality, safety, and processing efficiency. PEF has been applied extensively in liquid food processing units for the inactivation of enzymes and sterilization for products including milk, juice and egg products (Zhang et al., 2023). PEF treatment effectively deactivate microorganisms and enzymes, including bacteria, yeasts, and molds, in liquid foods such as juices, milk, and egg products, leading to extended shelf life and improved food safety (Farag et al., 2021). PEF can be employed in the extraction unit to boost the bioactive compounds extraction including antioxidants, vitamins, flavonoids from solid foods by disrupting cell structures and improving mass transfer efficiency. It can improve the yield of juice extraction from fruits like oranges, pomelos, and lemons, leading to increased productivity and higher quality beverages (El Kantar et al., 2018).

In the drying unit, mass transfer efficiency is enhanced by PEF upon inducing cell membrane electroporation, facilitating moisture evacuation and reducing drying time. PEF can improve the rehydration properties of dehydrated food products, leading to faster and more efficient rehydration without adversely affecting the food's nutritional quality (Shorstkii et al., 2022). Strawberries and bell peppers

pretreated with PEF at 1.0 kV/cm before air-drying and freeze-drying exhibit lower freezing time and higher rehydration quality ((Fauster et al., 2020). PEF treatment in the freezing unit can help improve the thawing and freezing processes by enhancing mass transfer efficiency while maintaining the frozen food's quality. It can reduce the maceration time of certain food products, such as Grenache grapes, leading to improved processing efficiency. Electrical field application in food items causes water molecule's realignment post polarization, subsequently decreased ice-nucleation time and increased temperature hence faster freezing rate with small crystal formation (Wang et al., 2019). PEF-assisted cooking has boundless potential in kitchen procedures, with commercial E-cookers being developed for fast preparation of food products like fish, meat, and vegetables. PEF treatment can modify the texture of rice and meat, by improving tenderness and reduce oil content in fried foods, enhancing their quality. Collagen-rich meat treated with 50–100 J/kg, 1.0–1.5 kV/cm PEF is found to have reduced cooking time and enhanced tenderness (Alahakoon et al., 2016).

Continued research and development in PEF applications can lead to improved efficiency, reduced processing times, and enhanced product quality in the food processing units. Future progressions in PEF technique may focus on optimizing processing parameters to further enhance sensory attributes and overall consumer acceptance of PEF-treated foods. PEF technology has advantages such as lower consumption of energy, shorter processing times, and eco-friendliness compared to conventional thermal processing methods. The future scope of PEF includes exploring ways to enhance sustainability in food processing, reduce waste, and improve overall energy efficiency in food production. As PEF technology continues to evolve, there is potential for its wider adoption in industrial-scale food processing operations. Overcoming challenges related to power supply, electrode materials, and process optimization will be key to realizing the full industrial potential of PEF processing technology.

3.3 Cold Plasma

3.3.1 Introduction

Cold plasma (CP) is an innovative technology with advanced applications, first developed by Sir William Crookes in 1879. He initially identified plasma as the fourth state of matter. It is typically seen as an arc or discharge of intense fluorescent light. Regarding physical characteristics, it comprises a mixture of gases (partly or fully ionized) that includes reactive species including electrons, free radicals, positive and negative ions, excited or non-excited gas molecules, and photons (Saremnezhad et al., 2021).

3.3.2 Equipment and Principal

CP generates plasma at atmospheric temperatures. Plasma can be created from a variety of gases, including H₂, O₂, He, N₂, Ar, Ne, CF₄, CH₄, and NH₃, by subjecting them to electric fields like direct current, alternating current at high frequencies, heat, microwaves, radio frequencies, and magnetic fields. Plasma particles are generated that collide with higher kinetic energy, including ions, electrons, and free-radicals. The plasma system remains electrically neutral. Factors such as gas flow rate, environmental conditions, power input, humidity, and voltage levels can impact plasma characteristics (Misra et al., 2016).

Based on the generation method, the plasma can be split into two categories: equilibrium called thermal plasma (TP), and non-equilibrium called as low-temperature plasma (LTP). TP (Thermal plasma) includes gaseous molecules, ions, and electrons in thermodynamic equilibrium typically reaching temperatures around 20,000 K. Quasi-equilibrium plasma (100–150 °C) and non-equilibrium plasma (<60 °C) are additional divisions of the low-temperature plasma (LTP). In quasi-equilibrium plasma, components like gas molecules, and electrons are in a state resembling local thermodynamic equilibrium. In LTP (non-equilibrium plasma), local thermodynamic equilibrium is not achieved. The temperature of the entire system is lowered as the electrons are at elevated temperatures, while the gas molecules remain at a moderate temperature. Non-equilibrium plasma is also termed as NTP (Non-Thermal Plasma), ACP (Atmospheric Cold Plasma), and CP (Cold Atmospheric Plasma or Cold Plasma), which involves electrical discharges in gases (Mandal et al., 2018).

CP (Cold plasma) can be produced by ionizing various gases, either under partial vacuum conditions or at atmospheric pressure. Various electrical discharge techniques can generate plasma, including glow discharge, microwave discharge, dielectric barrier discharge (DBD), corona discharge, high-frequency, and plasma jet discharge.

- *Corona discharge*: It is generally produced under atmospheric pressure conditions. The gas is primarily ionized at a sharp electrode. The device operates with a simple setup and minimal operational costs, capable of running on direct current or pulsed voltage. The limitations of this system include inconsistent treatment and a restricted sample area (Coutinho et al., 2018).
- *DBD devices*: These are used to generate plasma using two electrodes covered with dielectric materials (silicon, ceramic glass, or plastic). Insulators inhibit arc discharge and the formation of thermal plasma (Sakudo et al., 2020). DBD devices function at particular frequencies ranging between 0.05 and 500 KHz across a broad spectrum of gas pressures (usually 104–106 Pa). The key advantages of DBD devices include the capacity to use a broad spectrum of gases, homogeneous discharge, absence of gas flow, rapid DBD generation, and the ability to use various electrode geometries (Phan et al., 2017).
- *Glow discharge*: When low-pressure gas (between 1 and 1000 Pa) is subjected to direct voltages of 100 V or more, glow discharge is produced. Advantages of this

discharge include the generation of plasma at relatively low temperatures across a substantial volume (Sakudo et al., 2020).

- *High-frequency discharge*: A RF (Radio-frequency) power source operating at 13.56 MHz produces a high-frequency discharge (HFD). Plasma can be produced either capacitively (between two opposing electrodes), or inductively (within a coiled antenna). This system can effectively generate dense plasma at reduced atmospheric pressures while minimizing thermal output (Sakudo et al., 2020).
- *Microwave discharge*: Microwave discharge is generated by a magnetron. Microwaves are absorbed by the electrons, increasing kinetic energy, ionization processes, and inelastic collisions. According to Coutinho et al. (2018), microwave discharges are controllable and operationally convenient, while Sakudo et al. (2020) reported that a plasma discharge with a broad cross-sectional area can be produced at reduced gas pressures.
- *Plasma jet discharge*: This method uses two parallel electrodes to allow carrier gas to flow at different speeds. It produces flames or plasma jets at atmospheric pressure by using radio frequencies, and the excited species emerge through an aperture or valve and head toward the electrode terminal. The high gas flow rate of the plasma jets makes them directly applicable, but they can be expensive (Harikrishna et al., 2023).

3.3.3 Effect on Nutritional Components of Food

Cold plasma treatment can lead to denaturation of proteins altering the secondary, tertiary, and quaternary structure. Structural transformation in α and β -sheet helical structures and the reactive species produced during plasma discharge interact with protein structures potentially changing their functional properties, thermoresilience, and bioavailability of proteins (Segat et al., 2015). Reactive oxygen species generated during plasma treatment can commence lipid oxidation reactions, resulting in the formation of lipid peroxides, free radicals, and other oxidation products. These can affect the fatty acid composition, sensory attributes, storage duration, and nutritional content of lipid-containing foods. Cold plasma treatment may accelerate lipid rancidity causing off-flavors and odors development, while some studies have revealed that certain plasma treatments can enhance the concentration of bioactive compounds with antioxidant properties in lipid-containing foods, potentially improving their oxidative stability (Saremneshad et al., 2021).

CP (Cold plasma) treatment can also induce starch modification resulting in their physicochemical, functional, and thermal properties change, which can impact the structural integrity and textural properties of food products. It also cleaves the glycosidic bond consequential of the development of smaller carbohydrate fragments influencing nutritional value, digestibility, and glycaemic response of

carbohydrate-containing food (Ekezie et al., 2019). Cold plasma has been reported to influence the concentration and activity of bioactive compounds in food, such as phenolic compounds and gamma-aminobutyric acid (GABA). The treatment can enhance the bioavailability and functionality of these compounds, contributing to the nutritional value of food products (Saremnezhad et al., 2021).

3.3.4 Application in Food and Dairy Processing

Cold plasma sterilizes the packaging materials and surface of food to remove bacteria, viruses, and other potentially harmful microorganisms, hence promoting the longevity and safety of food items (Mandal et al., 2018). It can also prolong the shelf life of perishable goods by lowering microbial populations and preserving the fruits and vegetables quality, minimizing food waste and enhancing storage stability. CP treatment can influence the antioxidant activity and has the potential to modify the pH and acidity of vegetables and fruits, impacting their sensory characteristics and overall quality. Some studies have stated an increase in phenolic concentration in specific fruits, while others have shown a decrease in antioxidant components like Vitamin C in diverse produce. The texture and nutrient retention of food products may be modified by the application of cold plasma (Nisha & Narayan, 2019; Herceg et al., 2016; Berardinelli et al., 2012). Food products subjected to cold plasma effectively reduce microbial contamination. It can improve the safety and prolong the shelf life of meat-based products by reducing bacterial load like *Salmonella*, *Listeria monocytogenes*, and *Escherichia coli*. Cold plasma treatment maintains the nutritional content without significantly reducing the vital components including proteins, vitamins, and minerals (Misra et al., 2016).

The implementation of cold plasma has effectively inhibited mold growth in dairy products such as cheese, by utilizing various gas compositions, enhancing the shelf life and safety of dairy products. Cold plasma treatment decreases lipoxygenase activity, phytates, and oxalates while increasing lipid oxidation in dairy products. By preserving microbiological safety, this balance aids in preserving the nutritional value of dairy products. Traditional thermal processing techniques, including pasteurization, can be substituted with cold plasma. It provides a non-thermal method of maintaining the safety and quality of milk, avoiding issues such as non-enzymatic browning, protein denaturation, and flavor changes induced by prolonged heat treatment (Dharini et al., 2023). Grains and legumes treated with cold plasma reduce their chewiness and hardness, which shortens the time needed for cooking and soaking. It also reduces antinutritional factors like tannins and phytic acid in dietary items, which may improve the bioavailability of nutrients in foods. It also helps in reducing the presence of hazardous mycotoxins by inhibiting microbial activities and altering grain composition. (Harikrishna et al., 2023).

3.4 Irradiation

3.4.1 Introduction

Food irradiation is subjecting food to suitable ionising radiation dosages to eradicate molds, insects, and other potentially hazardous microorganisms for safety and preservation. X-rays, High-energy, gamma rays and electron beams are sources of radiation. Food's chemical makeup remains mostly unaffected by radiation. However, some vitamins may be reduced throughout the process, which is also valid for other traditional food preservation techniques, including smoking, drying, and canning (Shahi et al., 2021). The World Health Organization (WHO), The International Atomic Energy Agency (IAEA) and the United Nations Food and Agriculture Organization (FAO) have been working together to determine the safety and quality of irradiated food products. Their findings demonstrated that food contamination and insect infestation might be avoided by using radiation alone or in conjunction with existing food preservation techniques (Qadiri et al., 2021).

According to the Codex General Standard for Irradiated Foods, three forms of ionising radiation can be employed in food irradiation applications: accelerated electrons, X-rays, and high-energy gamma rays (^{60}Co and ^{137}Cs). High-energy gamma photons can be generated from the radioactive decay of radionuclides like ^{60}Co or ^{137}Cs . X-ray machines can also produce them with energies reaching up to 5 MeV or electrons accelerated to energies as high as 10 MeV (Pavani et al., 2023). The process by which ionising radiation inactivates microorganisms because of the immediate or secondary harm caused by the Microbial nucleic acids (DNA), which is impacted by free radicals (OH) produced when water is radiolyzed—cleaning of herbs, spices, etc. Condiments continue to be the most often used application of radiation (Mostafavi et al., 2012; Jung et al., 2015). Radiation technology is a valuable sterilisation method because it can extend shelf life by preventing food-borne illnesses and spoilage and because consumers are willing to pay for food safety processing. However, the misconception that food irradiation is a nuclear technology limits its development in the food industry. Therefore, critical strategies for advancing this technology include convincing consumers to buy irradiated food, designing safer and more reliable equipment, and enhancing the treatments used.

3.4.2 Equipment and Principal

Gamma, electron beam, and X-ray radiation are the primary forms of ionising radiation sources used to radiate food. The methods used to irradiate food with all three radiation sources are the same because they expose the meal to a precise amount of ionising radiation. This is conducted on a conveyor belt in a dedicated processing area (the radiation room) for a predetermined time. Food will be exposed to radiation on a conveyor belt at the loading site. After the food is exposed to a certain amount of ionising radiation in the irradiation chamber for a particular time, the

conveyor belt moves the food to the unloading area (Bisht et al., 2021). The type of food, the target insect or microbes, and how long the food will last before consumption affect the radiation source, amount, and duration of exposure. When the radiation beam—whether gamma rays, electrons, or X-rays—enters the food, it eradicates pests, disrupts chemical bonds, and alters the DNA of microorganisms, rendering them inactive and unable to reproduce (Indiarto et al., 2020).

These keep most agricultural products from spoiling and prolong their shelf life while preserving their flavour and texture. Most farming products are exposed to radiation in gamma facilities. The idea is to produce radiation with energies up to 1.33 MeV using cobalt-60. The radiation sources are submerged in water when not in operation to absorb energy and prevent exposure (Mshelia et al., 2023). Electron beams are produced in electron beam facilities by speeding an electron stream concentrated on a small beam spot. Electron beams are usually employed to inactivate germs in food because of their high dose levels and low penetration depth. In X-ray facilities, a heavy metal like tungsten is bombarded by high-velocity electrons produced by a machine to produce X-ray streams. While many food items can be irradiated with X-rays, not many products are irradiated using this method (Zehi et al., 2020).

3.4.3 Effect on Nutritional Components of Food

Food containing specific vitamins, especially thiamine and vitamin C, may become less abundant after gamma irradiation. Due to their radiation sensitivity, these vitamins could deteriorate when exposed to radiation. However, several variables, including the type of food consumed, the radiation dose, and the starting vitamin level, affect how much vitamin loss occurs (Singh & Singh, 2019). Gamma irradiation may alter protein structure and lead to protein denaturation. This may influence the digestibility and functional properties of proteins in food products. However, the extent of protein denaturation may differ based on the specific protein composition in the food (Obodovski, 2019).

Gamma irradiation can change food lipids, leading to lipid oxidation and the creation of lipid oxidation products. This may change the taste, aroma, and stability of food items that include fats. Variables, including the type of fat, the presence of antioxidants, and the radiation environment, affect the degree to which lipid oxidation occurs (Perko, 2011). Gamma irradiation is not known to affect carbohydrates in food substantially. Carbohydrates are stable to irradiation and are often unaffected in terms of their nutritional value or functionality (Fan & Wang, 2020).

3.4.4 Application in Food and Dairy Processing

The utilisation of irradiation in food and dairy processing has been an interesting topic because of its potential benefits in enhancing product safety, quality, and shelf life. Irradiation is a non-thermal technology that involves exposing food products to

either gamma rays from radioactive isotopes or electron beam radiation to destroy harmful microorganisms and pests (da Silva Aquino & KA, 2012). In dairy processing, irradiation has been researched for its ability to improve the microbial quality of dairy products like milk, cheese, and butter. Studies have revealed that irradiation can effectively reduce pathogens in dairy products without compromising their organoleptic properties when applied at low doses or in frozen conditions (Friday, 2020). Electron beam irradiation improves mozzarella cheese's sensory, nutritional, and microbial properties.

Despite the potential benefits of irradiation in dairy processing, its application has been limited, owing to concerns about off-flavours in irradiated products and consumer scepticism. Nevertheless, research has established that irradiated dairy products can be safe and nutritious for consumption, with approved doses in various countries for microbial control and disinfestation.

3.5 *Ultrasound*

3.5.1 Introduction

“Ultrasound” refers to sound waves higher than 20 kHz or the audible frequency range. The medium particle composition experiences rarefaction (decompressions) and compressions because of the acoustic waves' propagation. Increased mass transfer and turbulence generate much energy (Režek Jambak, 2012). A new, environmentally friendly technology called ultrasound speeds up and improves the efficiency of several food processing industry processes. Its effectiveness can be further increased by applying pressure (mano sonication) and temperature (thermosensation) to create a synergistic effect. Ultrasound waves employed in food applications can be sorted into two categories based on intensity and frequency: Low- and high-powered ultrasonography (Condón-Abanto et al., 2016).

There are numerous potential applications for ultrasound technology in the food processing sector because of its many systems, frequencies, and energy densities in food preservation (inactivation) and food processing techniques, including degassing, defoaming, filtration, and emulsification of microbes and enzymes) and the removal of the food's active components. In emulsifying food, ultrasound can be used due to the cavitation effect, which makes the oil-water interface unstable and reduces the size of oil droplets (Arvanitoyannis et al., 2017). This will enhance the quality of foods, including dairy products, during storage and ensure that two-phase solutions are uniform.

3.5.2 Equipment and Principal

A sound wave at a frequency higher than the human hearing threshold (>16 kHz) is known as ultrasonic. Frequency ranges allow us to categorise sound waves into three groups. Infrasonic waves, or waves with frequencies below the hearing range (<20 Hz); ultrasonics, or waves over 16 kHz; audible waves, or waves of the frequency range 16 Hz–20 kHz, are among them. Sound waves are created when electrical energy is converted to vibrational sound energy using ultrasonic transducers. Ultrasonic transducers come in various sizes and frequencies depending on their intended application, and they can also convert sound waves into electrical energy. The most used types are magnetostrictive and piezoelectric transducers. Numerous studies have reported using different transducers to generate low- or high-frequency ultrasonic waves for various food and non-food applications (Mattiati, 2013). Ultrasound frequencies suitable for food processing and preservation range from 20 to 1000 kHz, while higher frequencies are typically used for diagnostic imaging and food quality evaluation. High-frequency ultrasonic waves are used for nondestructive food quality assessment as they have minimal physical or chemical impact on the food (Zhang et al., 2019). Conversely, high-intensity waves in low-frequency ultrasound, often called power ultrasound, induce the necessary physical and chemical changes in food products.

Cavitation is a fundamental principle of ultrasonography. Sound waves that are very intense for human ears to detect produce ultrasound, a type of energy. Since the medium particles are compressed and rarefied, a significant quantity of energy is produced when sound waves are transmitted through any product. Accordingly, cavitation is the development, expansion, and burst of bubbles that produce focused chemical and mechanical energy (Li et al., 2021). Gas bubbles form inside a liquid due to cavitation when ultrasonic frequencies travel through a liquid medium. It is the interplay of liquid, dissolved gas, and sound waves. It causes oscillations and a change in pressure around the dissolved gas nuclei. Moreover, the oscillating bubbles were surrounded and filled with dissolved gas and solvent vapour. The bubbles will then expand in cycles until they reach an unstable size and finally rupture. When bubbles burst, the surrounding area experiences extreme heat and pressure, which breaks the liquid's components (Suslick et al., 2018). Depending on the applied sound strength, it can produce particle dispersion, cell disintegration, and localised sterilisation or pasteurisation.

The correct quantity of acoustic energy must be applied to maximise the utilization of power ultrasonography for food applications. There are various ways to estimate the amount of energy input; calorimetry is the most widely used technique. The energy transferred to a food medium can be expressed in various ways, such as acoustic energy density (W/mL), cavitation intensity, ultrasound power (W), and ultrasonic intensity (W/cm²). Changes in sample volume and the placement of the ultrasound transducer can cause variations in the ultrasound treatment and cavitation activity within a treatment chamber, even when the ultrasound intensity remains the same. Equations for calculating ultrasonic power, intensity, and acoustic energy density can be.

$$Power(W) = mC_p \left[\frac{dT}{dt} \right]_{t=0} \quad (11.1)$$

$$Ultrasonic\ intensity \left(\frac{W}{cm^2} \right) = P / A \quad (11.2)$$

$$Acoustic\ energy\ density (W / mL) = P / A \quad (11.3)$$

Here, (m) represents the mass, (C_p) is the specific heat capacity, (A) is the area of the radiating surface (for an ultrasonic probe, ($A = \pi D^2/4$), where (D) is the diameter of the probe), (V) is the volume, and (dT/dt) is the initial rate of temperature change during sonication.

3.5.3 Effect on Nutritional Components of Food

Ultrasonication has been demonstrated to improve the nutritional value of food items. Preservation of Nutrients and shelf life: Ultrasonication preserves food's nutritional value by deactivating pathogenic enzymes and microbes, preserving sensory attributes and vital nutrients. It prolongs shelf life by eliminating spoilage and pathogenic microbes, ensuring food safety without compromising nutritional value (Zhang & Abatzoglou, 2020). Minimisation of Nutrient Loss: Thermal processing involves high temperatures and lengthy processing times, which might result in nutrient loss from traditional food preservation methods. A more delicate method is provided by ultrasonication, which reduces the loss of vital nutrients like vitamin C and proteins (Jose, 2014). Phytochemicals: Food's bioactive ingredients, such as phenolics and flavonoids, can be impacted by ultrasonication. As per the studies, ultrasonication can cause specific molecules to degrade, affecting the food's anti-oxidant capacity (Fernandes et al., 2020). Total Nutrient Retention: Ultrasonication can increase the extraction of bioactive molecules from plant materials, which may increase the overall bioavailability of nutrients, even if it can also destroy some nutrients (Huang et al., 2020).

3.5.4 Application in Food and Dairy Processing

Ultrasonication has various applications in food and dairy processing, helping to improve efficiency, quality enhancement, and preservation. By rupturing cell membranes and deactivating dangerous germs, ultrasonication inactivates microorganisms in food products, especially dairy products. Ultrasonication can assist in inactivating enzymes during processing to prolong shelf life and preserve the quality of dairy and food products (Yuting et al., 2013). In food processing, especially for drinks, ultrasonication degasses liquids to eliminate dissolved gases and enhance the quality and stability of the final product (Shankar et al., 2011; Jose et al., 2014).

In dairy processing, the emulsification and homogenisation operations are conducted using high-power ultrasonication, which enhances the end product's texture and consistency. By decreasing droplet size and increasing the mixing of immiscible liquids, ultrasonication is used in food processing to produce stable emulsions that improve the texture and stability of the final product (Kahraman et al., 2017). Strengthening the renneting process during the cheese-making process and ultrasonication may enhance the quality of milk and increase the yield and quality of the finished product. As a non-thermal processing option, ultrasonication is used in liquid food pasteurisation to lower the microbial load, increase shelf life, and minimise the influence on sensory and nutritional quality (Bhandari & Zisu, 2016). Ultrasonication is a useful technique in dairy processing for eliminating undesired gases and foam from products during degassing and defoaming.

3.6 *Microwave*

3.6.1 Introduction

Electromagnetic waves of frequencies of 300 MHz to 300 GHz range are known as microwaves. Although microwave systems at the industrial level operate at both the frequencies of 2.45 GHz and 915 MHz, microwave appliances at the domestic level typically work at 2.45 GHz (Chandrasekaran et al., 2013). The polarity of molecules from the initial random thermal motion alters the microwave field, which is an alternating magnetic field, depending on the orientation of the electric field. The penetration increases with decreasing the microwave frequency (Menéndez et al., 2010). Food materials' dielectric characteristics help explain their capacity to transform microwave radiation into heat. Dielectric properties, typically described as dielectric constant and dielectric loss, reveal the characteristics of electrostatic energy saving and loss in the electric field. One feature of microwave processing is non-uniformity. Hot and cold spots are produced by the microwave pattern, with the hot spot being localised in an area with higher electromagnetic field strength (Kumar et al., 2016).

Over several decades, microwave heating has been applied extensively in the food industry. Microwave-assisted heating is used in food processing for various purposes, such as baking, pasteurisation, thawing, tempering and drying food ingredients. The application of microwaves in food processing has grown in popularity because of their high heating rates, capacity to reduce cooking times significantly, ability to provide more uniform heating, safety features, convenience of use, and inexpensive maintenance (Gupta & Wong, 2007). When cooking vegetables in a microwave without water or with little water maintenance, prominent levels of bio-active components, antioxidant activity, and visually appealing colour can all be retained (Póltorak et al., 2015). Anti-nutritional factors decrease while in vitro protein digestibility increases. There is also a great decrease in nutrients while microwave cooking due to leaching and thermal liability (de Lima et al., 2017).

3.6.2 Equipment and Principal

Heat is not produced by microwaves but primarily by intermolecular frictional forces (BeMiller & Huber, 2015). When exposed to microwave radiation, polar molecules in food (such as water) transform from a disordered state to an ordered structure aligned in a specific direction. Under the influence of an alternating electric field, the structure varies as the frequency does. Heat is produced by the friction created by the stimulated molecules' fast motion. According to studies, materials can be heated, dried, or cured quickly because polar molecules can vibrate 2.45 billion times per second on exposure to microwave radiation at 2450 MHz (Wary & Ramaswamy, 2015). Microwave heating is a standard method for dehydrating food. The basic idea behind an electrical field is that water molecules interact and align in different directions due to polarized molecules and frequent dipole interactions. The pace at which internal water diffuses from an object's interior to its surface increases because of these factors (Dehghannya et al., 2018). Additionally, the water becomes more fluid due to mechanical action and temperature effects, which increase motion (Talens et al., 2017).

The energy that microwave radiation imparts to water molecules also helps to maintain the water's internal temperature by pushing water from the materials' interiors to the exterior (Tsuruta et al., 2015). There are three stages of the microwave drying process (Heating period, rapid drying period and reduced drying rate period). The objective of heating and drying plant material can be accomplished by gradually increasing the movement of polar molecules excited by microwave radiation. This process produces sufficient heat to transfer to the water in the heated material (Karam et al., 2016). Heat is produced during the first stage of microwave energy conversion. Diffusion causes water to evaporate quickly in the second phase. When thermal energy surpasses the energy needed to evaporate moisture entirely, there is a duration of decreased drying rates in the third phase.

3.6.3 Effect on Nutritional Components of Food

When cooking vegetables in a microwave, considerable amounts of bioactive ingredients like vitamins and antioxidants can be preserved. This is especially true when cooking the veggies without or with little water. Due to the brief exposure period, microwave sterilisation has been revealed to have no discernible impacts on the antioxidant activity and bioactive compounds of foods, helping to preserve these advantageous components. (Akdaş & Bakkalbaşı, 2017). Because microwaves have shorter cooking times and expose veggies to less water, they can retain more of their beautiful color and lose less of their nutrients. The texture and color characteristics of food items are unaffected by microwave sterilisation; few studies reveal no appreciable variations in the firmness of food items after microwave treatment (Lu et al., 2011). Food proteins' bioavailability may be improved by microwave cooking, as evidenced by its ability to increase in-vitro protein digestibility. The nutritional value of food may be increased overall by reducing anti-nutritional elements through

microwave cooking. By lowering the activity of the enzymes, microwave sterilization can inactivate food products' enzymes, which is advantageous for preserving food quality (Xu et al., 2016).

3.6.4 Application in Food and Dairy Processing

Fruits, vegetables, herbs, and grains can all be dried in the microwave to remove moisture while maintaining nutrition, color, and flavor. When compared to conventional drying techniques, it may produce food with a more porous structure (Tian et al., 2016). Dairy products, including cheese, yoghurt, and powdered milk, can be dehydrated using microwave drying while keeping their nutritional value and quality (Chen et al., 2017). Ready-to-eat meals, meats, and vegetables are among the food items that are frequently cooked and reheated in a microwave. In vegetables, it can aid in preserving their appealing color, bioactive components, and antioxidant activity (Domínguez et al., 2014). Milk, cheese, and sweets can all be pasteurized, sterilized, and heated using microwave heating in the dairy processing industry.

Microwave sterilizing effectively lowers germs in food goods while preserving nutritional content. Additionally, it can inactivate enzymes to enhance the food's shelf life. Ensure the quality and safety of dairy products; dangerous bacteria and pathogens can be eliminated from milk, yoghurt, and other dairy products using microwave sterilisation (Marszałek et al., 2015). Bioactive chemicals, tastes, and essential oils are extracted from plant materials using microwave-assisted extraction, improving extraction efficiency and maintaining the derived components' quality. Microwave extraction can be employed to process dairy products to extract bioactive components from by-products or ingredients for functional food applications (Piasek et al., 2011). Utilising microwave pasteurization preserves food products' nutritional value and sensory qualities while lowering the bacteria load. Liquid foods such as soups, sauces, and drinks are frequently pasteurized using this technique. To ensure product safety and prolong shelf life, microwave pasteurisation can preserve milk, cream, and other liquid dairy products (Valero et al., 2014).

3.7 Nanotechnology

3.7.1 Introduction

Nanoparticles with diameters ranging from one to one hundred nanometers are utilized in the diverse and interdisciplinary domain of nanotechnology. Packaging of food, illness treatment delivery systems, pathogen identification, and the distribution of bioactive components are just a few of the many opportunities it presents to the food business. According to Srinivas et al. (2010) and Chandra (2016), it is essential for food safety, manufacturing, pigmentation, nutrient assimilation, flavor, nourishment, delivery, disease detection, ecological protection, distribution, and

economical storage. A nanocomposite is a material having distinctive features, such as thermodynamics, diffusivity, solubility, magnetic behavior, toxicity, colour, mechanical strength, and optical characteristics, that is produced when other nanostructures or aggregates are joined with nanostructure components, such as proteins and polymers. Numerous sectors, including food, cosmetics, medicine, agriculture, clothing, and public health, use these nanoparticles. (Bhushan, 2010).

The utilization of nanotechnology offers numerous advantages in food, including the prospect for developed and emerging countries to enhance the quality and safety of food, diminish post-harvest losses, and advance food security and safety management by enhancing the nutritional content, shelf life, and efficacy. A key challenge for nanotechnologies is the development of safe and affordable formulations and processing techniques. (Arora & Padua, 2010). By extending shelf life, improving efficacy, and adding nutrition, nanoparticles improve food safety. Nanotechnologies depend on the development of affordable, secure, and biocompatible nanostructures made of food-grade materials. According to experts, safe, nontoxic, and biocompatible nanostructures can be created using simple, affordable, and ecologically friendly methods. Additionally, the body's bioavailability and absorption of vitamins and supplements can be improved by nanotechnology. Nanocarriers, nano capsules, nano sensors, nano packaging, and nanotubes are examples of delivery systems for nanoparticles. (Chaudry & Castle, 2011).

3.7.2 Methods

- *Nanofabrication methods:* Peptides, essential oils, and plant extracts are examples of nanostructures that have made a wide range of antibacterial medications possible. To improve their characteristics, these medications can be combined with liposomes, polymer nanoparticles, nanotubes, and nanofibers. Both bottom-up and top-down methodologies are employed in fabricating nanostructures and nanomaterials. Top-down processing, which involves reducing bulk materials to nanoscale and using colloidal protectants to stabilize nanoparticles, has a sluggish production rate and increases the risk of contamination, surface defects, and the introduction of stress. Conversely, bottom-up approaches create materials from individual atoms that autonomously assemble and correct themselves, leading to reduced defects, enhanced uniformity, and increased long and short-range order (Hsieh and Ofori, 2007).
- *Methods for Fabricating Nanofood Particles:* Several techniques, including high-pressure homogenization, ultrasonic emulsification, and dry milling, can be used to create nano food particles. Materials are reduced in size to coarse particles by dry milling, and emulsion droplets of a very thin consistency are produced by high-pressure homogenization. By using additional chambers for homogenization, the texture is improved and the particle size is reduced and emulsified. This method is used to make emulsions, fillings, yoghurts, icings, salads, and chocolate drinks. A new technique for creating nano emulsions utilizing high-intensity ultrasound waves is called ultrasonic emulsification. Due to

cavitation, this process can alter the treated matter's properties by generating shear forces, temperature, and pressure changes. Molecules self-assemble into supramolecular structures, microstructures, and higher hierarchical structures in bottom-up processes. Molecular recognition enables the creation of biological nanostructures and template-based molecular and atomic structures (Jagtiani, 2021).

- *Nanostructures in the food system:* Polymeric nanoparticles, microemulsions, liposomes, and nano emulsions are examples of artificially nanostructured food systems. These substances enhance the bioactive components' solubility, bio-availability, controllability of release, and protection. These molecules are shielded from harm by encapsulation, which also speeds up their absorption into food products. For food's bioactive compounds to be absorbed safely and effectively, encapsulation is essential. (Koo et al., 2005).
- *Nano emulsion:* Nano emulsions are colloidal suspensions with particle sizes typically ranging from 50 to 1000 nm, and they are employed in a variety of industries, such as salad dressing, oil flavouring, beverages, sweeteners, and processed goods. They don't change the flavour or look of the product and can be used for equipment cleaning and increased clarity. Functional nano emulsions and encapsulated nano-compounds are employed to deliver lutein, beta-carotene, lycopene, vitamins A, D, E3, coenzyme Q10, and omega-3 fatty acids to targeted locations. Nano emulsions containing capsaicin are stabilized using natural biopolymers, including alginate and chitosan (Choi et al., 2011). Lipids, antioxidants, and vitamins can be encapsulated in micro-emulsions, which are protein-biopolymeric nanostructured particles ranging between 5 and 100 nm. They are employed in the synthesis of glycerides for food products and the solubilization of insoluble materials in water. Although polylactic acid is frequently found in biodegradable nanoparticles, its rapid excretion from the bloodstream and accumulation in the liver and kidneys render it inappropriate for administration. (Taylor et al., 2005). Nanocomposites are polymer matrices strengthened with nanofillers smaller than 100 nm in size. There is a growing demand for environmentally friendly packaging materials, such as polyglycolic acid, polylactide, and polyvinyl alcohol due to environmental considerations. (Silvestre et al., 2011).

3.7.3 Effect on Nutritional Components of Food

Nanoparticles can interact with proteins in food systems, affecting their structure and functionality. For instance, nanomaterials like nanoemulsions can improve the solubility and stability of proteins in food products. Nanoencapsulation of carbohydrates can enhance their bioavailability and stability, leading to improved delivery of nutrients. Nanostructured lipid carriers can be used for encapsulating bioactive lipids, improving their absorption and bioavailability. Nanoencapsulated vitamins and minerals can be incorporated into food products to fortify them with essential nutrients. Nanoemulsions and nanoliposomes can encapsulate volatile compounds,

preserving their sensory attributes in food products. Nanocomposites with antioxidant nanoparticles can prolong the shelf-life of food products by inhibiting oxidation reactions (Adeyeye & Fayemi, 2019).

3.7.4 Application in Food and Dairy Processing

Nanotechnology is utilized to develop edible coatings for vegetables and fruits which can help lengthen the product's shelf life by providing a protective barrier against moisture loss, microbial contamination, and physical damage. Examples include polymeric nanoparticles, solid lipid nanoparticles, and inorganic/organic nanocomposites. It is also employed in packaging materials to enhance their barrier characteristics and incorporate antimicrobial agents. This helps in preserving the freshness and quality of vegetables and fruits during storage and transportation. Nanocomposite or nano-emulsion coatings are examples of such applications. Nanotechnology plays a vital part in the development of nano sensors for monitoring the quality and safety of fruits and vegetables. These sensors are capable of detecting volatile compounds, like ethylene, to indicate the ripeness of produce and evaluate its freshness. Nano sensors can also help in identifying harmful bacteria and fungi in storage environments. Nanotechnology is utilized to develop functional foods by encapsulating bioactive compounds in nanoparticles (de Oliveira Filho et al., 2022).

Nanoparticles such as silver nanoparticles possess antimicrobial properties that can inhibit the proliferation of harmful bacteria in meat products, thereby prolonging their shelf life. Antioxidants like vitamin E can be nano-encapsulated to improve their stability and bioavailability, enhancing their effectiveness in preventing lipid oxidation in meat products. Nanotechnology enables the controlled release of bioactive compounds in meat products, ensuring a continuous supply of nutrients during processing, storage, and distribution. Nanoparticles can be employed to alter the texture of meat products, improving their moisture retention and tenderness. Colorants encapsulated at the nano scale can be added to meat marinades to enhance the visual appeal of the finished product. Nanotechnology can be employed to detect adulteration in meat products, ensuring their authenticity and quality. Nanoscale systems can improve the protective properties of packaging materials, thereby reducing the chances of contamination and spoilage during storage and transportation. Nanotechnology enables the development of functional meat products enriched with specific nutrients that promote consumer health and well-being (Ulloa-Saavedra et al., 2022).

Nanotechnology is a significant advancement in the dairy industry, enhancing the properties of dairy products like cheese, milk, yogurt, butter, fermented milk, and buttermilk. It uses various techniques like nano emulsion, nanoencapsulation, nanoliposomes, nanotubes, nanofiber, and nano capsules to process dairy products. Nanotechnology also provides effective packaging through nano sensors, nanolaminates, and nanocoating, ensuring product safety, stability, and quality. It also aids in detecting foodborne pathogens and microorganisms, such as *Listeria*

monocitogenes, *Salmonella typhimurium*, and *Pseudomonas aeruginosa*. Nanotechnology also aids in food fortification, encapsulating nutrients and ingredients to improve texture, flavor, aroma, quality, and nutritive value. However, the high consumption of nanomaterials can lead to heart diseases, asthma, cancer, bronchitis, colon cancer, and chronic diseases. Therefore, regular assessment is necessary before adding nutrients to dairy products (Guleria et al., 2023).

3.8 Artificial Intelligence Tools

3.8.1 Introduction

The term artificial intelligence (AI) describes how machines, computer systems in particular, may simulate intelligence processes of human brain. Learning, perceiving, reasoning, solving problems, along with making decisions are few out of many processes. Artificial intelligence technologies enable robots to perform jobs including speech recognition, visual perception, language translation and data-driven decision making that would otherwise require human intelligence. AI has shown the ability to convert industries by automating processes, improving efficiency, and enabling new capabilities that were previously not possible. In the food processing, predictive maintenance, quality control, supply chain optimisation and customised client experiences are among the jobs that AI is being utilised for (Vries et al., 2023).

AI tools have been introduced in the food processing industry through a combination of technological advancements, research initiatives, and industry collaborations. The integration of AI in food processing has been driven by the need for improved efficiency, quality control, and innovation in the production and distribution of food products. Researchers and scientists have been exploring the application of AI techniques like machine and deep learning, in food processing. Studies and experiments have been conducted to demonstrate the potential benefits of AI in tasks like predictive maintenance, quality control and supply chain optimization. Food processing companies have been collaborating with technology providers and research institutions to implement AI tools in their operations. These collaborations help in customizing AI solutions to encounter the specific requirements and challenges in the food industry. (Ramirez-Asis et al., 2022). AI has emerged as an important study area in recent years, helping to advance studies in numerous industries, comprising engineering, science, medical, food and nutrition, marketing, and stocks. AI has emerged as a major component in fourth industrial revolution. Intelligent creation and enhanced AI research efforts employing a variety of AI-based methodologies are among the viewpoints that are necessary for new creation to improve manageability (Addanki et al., 2022).

It is expected that emerging techniques like computer vision and AI will take usage of large data availability to enable active training, resulting in functional smart machines, real-time and expectable models. Terms “computer vision and AI driven food industry” denotes this trend of utilizing vision and learning methods to

make progress in the food processing sector. With the rise of 4IR technologies like artificial intelligence and computer vision robotics during the past 10 years, a significant drastic change in business models and investments has been observed. Artificial Intelligence, or AI as it is known scientifically, has been surpassing humans in a number of areas in recent years, including computer vision and object identification tasks. AI is the culmination of many different phenomena and techniques, out of which two basic ideas, Deep Learning (DL) and Neural Networks (NN), are accountable for the remarkable development of AI. This breakthrough was previously unachievable due to the massive processing capabilities of modern Graphics Processing Units (GPU).

Artificial intelligence (AI) can now learn complicated tasks by using vast amounts of training data because neural nets can emulate the functions of the human brain thanks to this computational power. Facebook, Google and other tech giants have confirmed the possible application of AI along with graphical processing units (GPUs) and Big Data, even if there is still more to be accomplished in this field. Several investors and economists were drawn to this new generation of AI because it seemed to provide limitless business opportunities (Kakani et al., 2020).

3.8.1.1 Artificial Intelligence

Artificial intelligence (AI) systems can be made to learn from data, adjust to new inputs, and carry out tasks with different levels of autonomy. These fall into two primary categories: AI based on knowledge and AI based on machine learning.

Knowledge-based AI: This type of AI relies on predefined rules and patterns based on human expert knowledge or physical principles to perform tasks. Among the earliest successful AI models to be applied across a range of industries are knowledge-based systems (Thapa et al., 2023).

Machine learning-based AI: It is based on data-driven model and does not rely on predefined rules. Instead, it learns from data, identifies patterns, and makes processed information based decisions. Machine learning techniques, like deep learning and neural networks, have witnessed significant interest in current times owing to its ability to self-learn and improve accuracy in various applications, including the food industry (Vries et al., 2023).

3.8.1.2 Computer Vision

In the subject of artificial intelligence known as computer vision, visual data from the actual world can be interpreted and understood by computers. It entails the creation of methods and algorithms that enable computers to operate on visual data—such as pictures and videos—in a manner that closely resembles human vision. Computer vision algorithms can process and manipulate digital images to extract useful information. This may involve tasks such as image enhancement, segmentation (dividing an image into meaningful parts), and feature extraction (identifying

specific patterns or objects). Computer vision systems may be skilled to identify and categorize objects as videos and images. This capability is utilized in various practices, for instance facial recognition, object detection and autonomous driving (Addanki et al., 2022).

Many computer vision tasks are powered by machine learning techniques, including neural networks and deep learning. These algorithms allow computers to acquire information from labelled data and over time enhance their performance (Mansuri et al., 2022; Saikumar et al., 2023). There are several uses for computer vision in many different industries, including healthcare (medical image analysis), security (surveillance systems), automotive (autonomous vehicles), and agriculture (crop monitoring). In food processing sector, computer vision has been utilised for tasks like quality inspection, food sorting, and packaging. Overall, the ability of robots to “see” and comprehend the visual environment is made possible largely by computer vision, creating opportunities for automation, analysis, and decision-making based on imagery. It involves multiple processes, including recording, converting, processing, and digitising images. The process of obtaining images involves using the image analysis method to convert visible spectrum light falling on a reflective absorbent surface into electrical signals, which are then converted into numerical form by an image sensor using camera lenses (Lukinac et al., 2018; Addanki et al., 2022).

3.8.2 Application in Food and Dairy Processing

AI tools have been increasingly applied in various aspects of food processing operations to enhance efficiency, quality control, and innovation. Systems powered with AI can examine visual data from cameras as well as sensors to inspect food products for defects, contamination, or irregularities. This helps in ensuring consistent quality standards and reducing the risk of faulty products reaching consumers. AI is used for detecting contaminants, pathogens, and foreign objects in food products to ensure food safety standards are met. AI-powered systems can analyze images and videos to identify defects, discoloration, or irregularities in food products during processing (de Sousa Silva et al., 2020). AI systems are able to evaluate sensor data to anticipate maintenance requirements and avert equipment failures in the food processing industry. This proactive approach helps in minimizing downtime, optimizing maintenance schedules, and reducing operational costs.

AI tools can study huge volumes of data associated with supply chain operations, for instance inventory levels, demand forecasts, and transportation logistics. By optimizing supply chain processes, AI can help in reducing waste, improving efficiency, and enhancing overall operational performance. AI algorithms can optimize energy usage in food processing operations by monitoring equipment performance and adjusting settings for maximum efficiency. AI tools can analyze production data, demand forecasts, and resource availability to optimize production schedules and minimize downtime. AI can help in reducing food waste by optimizing production processes, inventory management, and distribution channels. AI tools can analyze environmental impact data to implement sustainable practices in food

processing operations, such as reducing water usage and energy consumption (Thapa et al., 2022).

AI technologies can be used to analyze consumer preferences, market trends, and ingredient combinations to develop new food products. By leveraging data-driven insights, food companies can create innovative products that cater to changing consumer demands. AI can analyze sensory data to develop new food products with specific flavors, textures, and nutritional profiles. AI tools can suggest ingredient combinations, cooking techniques, and formulations to create innovative and appealing food products (Thapa et al., 2022; Addanki et al., 2022). AI systems can ensure accurate labeling of food products by analyzing text, images, and barcodes on packaging materials. AI-powered cameras can inspect packaging quality, seal integrity, and product placement to maintain product freshness and safety (Roy et al., 2022).

Techniques for genetic computation and fuzzy logic have been used in the food business to improve the handling and engineering of neural systems in particular. AI has been applied to wine analysis, quality control, and sorting of food samples in food science and processing. To maintain the quality and hygiene of its goods, the food industry uses CIP and COP systems. AI is used to make even these systems function. We refer to these as SOCIP, or Self-Optimizing Clean In Place. All-encompassing strategies can be used to create incentives to promote development and achieve greater food security (How et al., 2020; Addanki et al., 2022).

4 Conclusion

Over the past three decades, there has been a notable increase in the production and consumption of dairy products worldwide. Scientists and analysts have anticipated its expansion to last in the upcoming times. Similar to this, advanced food processing technologies have also been created, and these will play a significant part in the production of dairy goods which are healthy as well as suitable for human consumption. In addition, the majority of modern processing techniques provide significant promise for lowering greenhouse gas emissions during manufacture, processing, and storage. Future research in PEF technology may focus on elucidating the mechanisms of PEF processing in solid foods, optimizing processing parameters, and exploring new applications in different food matrices. Collaborative efforts between researchers, industry stakeholders, and regulatory bodies can drive innovation and pave the way for PEF technology's commercialization in various food processing applications. Globally, CP systems are being considered for research and advancement. Due to customer preferences for healthful foods and growing awareness, there is an increasing demand for raw or non-heat-treated foods. CP is a promising non-thermal method known to enhance food safety without affecting its quality in optimal conditions. Plasma technology can prevent chemical, sensory, and physical changes while enhancing the food's microbiological quality. It extends products shelf life and has shown positive results in quality and microbial activity in various food groups.

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Chapter 12

Food and Dairy By-products Utilization



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1 Cereal Industry By-products

Cereal grain is structurally comprised of bran, endosperm and germ and diverse unit operations of primary and secondary processing like cleaning, sorting, grading, milling, sieving etc. are employed to transform the whole cereal into valuable products and processable ingredients like flour, semolina, grits etc. and thus generating various by-products also. These by-products includes predominantly bran, husk, germ, outer layers from milling grains, brewers' spent grain etc. and possess numerous biologically active compounds that can be harnessed in the food industry, pharmaceuticals, and cosmetics. Now a days, various researchers have made tremendous efforts in valorisation of these by-products as natural antioxidants, preservatives, fortificant, prebiotic ingredient, animal feed and supplements. The valorisation of these by-products can contribute to the reduction of food loss and waste by utilizing these valuable resources instead of sending them to landfills or other waste disposal methods. Recently, emphasis has been on exploring novel & innovative techniques to use by-products directly or for extraction of valuable components like fibres, anthocyanins, phenolic compounds, tocopherols, and phytosterols for diverse usage. These practices may open new ventures for the development of value-added products and ingredients that align with the growing consumer preference for natural and sustainable food options. Further, this will also contribute to sustainable and economic viability of food industries by harnessing the nutritional potential, waste valorisation and management. Cereal bran is the outermost layer of grain containing dietary fibre, phenolic acids, tocopherols, anthocyanins, vitamins and minerals. These bioactive compounds are proven to reduce the chronic disease risk and

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promote overall health on regular consumption and this has led to favouring the consumption of whole cereals. Bran from different cereals like rice, barley, millet, sorghum, oat, and corn has been analysed for its chemical and antioxidant composition, with treatments like extrusion, roasting, baking etc. for improving fibre content while potentially reducing total phenolic content (TPC), total flavonoid content (TFC), and antioxidant activity (Pasha et al., 2020). However, the presence and bioavailability are immensely influenced by cereal grain structure and processing methods viz., milling, baking, popping, extrusion, roasting etc. Contradictions arise in the effects of processing on bran's nutritional quality. For example, different milling techniques can affect the fat and protein content of rice bran, with abrasive milling producing bran with higher protein content and total dietary fiber compared to friction milling (Kalpanadevi et al., 2018). The phytochemicals present in cereal bran, such as phenolic acids and alkylresorcinols, have been associated with antioxidant activity and other physiological mechanisms that support health (Figueiredo et al., 2023). The presence of antinutritional factors such as phytic acid can limit the bioaccessibility of bran's functional components, necessitating treatments to enhance their bioavailability (Nemes et al., 2022). Further, darker colour of bran, technological challenges on bran addition, impact on dough matrix and product quality and consumer preference are limiting factors for bran as ingredient usage and amount used. Studies have shown that bran can enhance the nutritional profile of bakery products, although higher percentages of bran incorporation may affect sensory qualities (Mrunal et al., 2020). Technological advancements aim to improve the functional properties of bran, making it more suitable for food applications by enhancing nutrient bioavailability and reducing anti-nutritional factors (Luithui et al., 2018; Singh et al., 2014). Moreover, innovative processing techniques such as enzymatic hydrolysis and fermentation are being explored to further improve the nutritional and functional attributes of bran (Kaprelyants et al., 2019). Bran is utilized in the food business by adding it to baked products, pasta, snacks and breakfast cereals. Bran from wheat, rice and corn has been incorporated to produce breakfast cereals to enhance dietary fibers e.g. Quaker, General Mills, Kellogg's, Healthy Valley, Nature's Path, Oatwell. The non-starch polysaccharides known as dietary fibers, such as β -glucans, cellulose and arabinoxylans are either gradually or not at all broken down by the body's own enzymes in the small intestine of both humans and animals. This improves the health of the digestive system by controlling the gut microbiota. Bran also contains arabinoxylans in varied amounts in different cereals, arabinoxylans are integral part of cell wall and are polysaccharides containing xylose units with linked arabinose unit. In corn and rice, complex arabinoxylans comprising additional xylose, galactose and glucuronic acid are also present which further affects the biological activity. Arabinoxylans produces short chains arabinoxylan-oligosaccharides (AXOS) and non-substituted xylooligosaccharides (XOS) on hydrolysis conferring prebiotic activity.

In past decade, rice bran has gained popularity for extraction of nutritionally and antioxidant rich oil. Its balanced fatty acid profile, including a good balance of monounsaturated, polyunsaturated, and saturated fats, makes it a heart-healthy choice. RBO's high smoke point and delicate flavor make it an excellent choice for

cooking, contributing to its description as a “heart-healthy oil” (Ali & Devarajan, 2017; Singh et al., 2015). Rice bran oil contains various biologically active compounds like oryzanol, tocopherols, tocotrienols, and phytosterols, accounting for antioxidant, anti-inflammatory, and cholesterol-lowering properties. Keeping in mind about these advantages, conventional oil extraction methods have been replaced by supercritical and enzyme assisted extraction as green and efficient methods while maintaining quality attributes (Sookwong & Mahatheeranont, 2017). The germ is the embryo of the seed, which contains essential nutrients and oils needed for the plant to grow. The composition of cereal germs is rich in bioactive compounds, including antioxidants, dietary fibres, and fatty acids, which have been shown to have potential health benefits. Cereal germ is rich in healthy fats, particularly unsaturated fats, such as omega-3 and omega-6 fatty acids. These fats are necessary for many body processes, such as the synthesis of hormones and the formation of cell membranes. These bioactive compounds are known to play a role in preventing chronic diseases such as neoplasms, diabetes mellitus, and cardiovascular diseases (Gil et al., 2011). Additionally, the bioactive compounds found in cereal germs have been linked to potential therapeutic properties, including immune system modulation and anti-infective effects (Adhikari et al., 2015). Cereal-based husks are mainly composed of cellulose (40–50%), hemicellulose (20–35%), and lignin (10–25%) along with minerals, pentosans etc. During primary processing, husk is separated from the kernel accounting for about 70–80 million tons worldwide every year (Chen et al., 2023). While they provide structural support to the grain, they are generally not consumed directly by humans due to their tough and fibrous nature. However, they are often used in various industrial applications such as animal feed, composting, biogas, biodiesel, biofuel production, bioplastics, biodegradable films, packaging paper and even as a source of fiber in some food products (Kaniapan et al., 2022). Husk has been employed for removal of different dyes, pollutants, heavy metals, pesticides and contaminants and thus helps in achieving sustainable development goals for environmental sustainability. However, tough & fibrous structure, low bulk density, space requirement, varied composition, transportation issues are numerous factors which are challenges faced in valorisation of husk at industrial level. This has led to employ various unit operations like size reduction, enzymatic and microbial degradation, extraction of valuables, thermo-mechanical treatments to produce biochar, biofuels and biogas, composite packaging material are few technological interventions for valorisation of cereal husk (Kordi et al., 2024). The primary byproduct of the brewing industry, brewers’ spent grain (BSG) makes up approximately 85% of all brewing waste produced. BSG is composed of the hull of the barley grain, the seedcoat layers and endosperm residuals. BSG are rich in fiber (30–46%) and protein rich (18–3%) and is converted into flour and further used in different snacks, beverages by various industries. However, addition of BSG can be done in a limited amount as it substantially reduces the overall acceptability. Research indicated that adding 10% BSG to bread or 30% cereal bran to pasta could significantly change the textures and flavors of the items, making them less appealing to the senses and lowering consumer approval of them as a whole (Table 12.1).

Table 12.1 Recent studies on the utilization of cereal industry by products

Cereal byproduct	Source	Application	Impact	References
Miscellaneous				
Spent grains	Cereal industry	Biofuel production through anaerobic digestion & microbial fermentation	Hydrogen gas production as renewable energy source	Bai & Lee (2016)
Husk	Rice	Building material (boards, panel, bricks)	Ecofriendly building material	Nguyen (2019)
Husk	Cereals	Livestock bedding	Comfortable and absorbent bedding material	Khan et al. (2020)
Spent grains	Cereals	Improve soil quality	Improve soil structure and fertility, providing organic matter and nutrients	McGinnis & Gagliardi (2016)
As food fortificant				
Bran	All cereals	Breakfast cereal, baked products, extruded products	Improved nutritional profile	Wang et al., (2015); Özbek & Ünal (2018)
Bran	Cereals	Yoghurt and beverages	Functional ingredient to increase nutritional, mouthfeel and product quality	Özbek & Ünal (2018)
Bran	Wheat	Bread & Spaghetti	Wheat bran protein concentrate was used to improve nutritional quality	Alzuwaid et al. (2021)
Brans	Maize, rice and sorghum	Bread fortification at 30%	Bread volumes decreased when brans were added to the formulation, but the amounts of water, ash, lipids, proteins, fibers, and phytates increased	Pauline et al. (2020)
Bran	Oat bran	Oat bran fortified raspberry probiotic dairy drink	The probiotic drink that contained simply <i>B. Lactis</i> had a considerably higher viability at the start of storage when the oat bran was added	Savas & Akan (2021)
Environment remediation				
Spent grains	Cereals	Used in wastewater treatment processes for the	Removal of pollutants and contaminants due to their adsorption properties.	Jain and Singh (2017)
Straw and grain husks	Rye	Pollutant absorption from aquatic environment	Efficient sorption materials for the extraction of metal ions from aqueous media	Shaikhiev et al. (2023)
Husk	Wheat, rice, corn, barley	Waste water purification	Heavy metal, dye removal, antibiotics, pesticides and other petrol contaminants	Hassan et al. (2023)

(continued)

Table 12.1 (continued)

Cereal byproduct	Source	Application	Impact	References
As packaging material				
Husk	Rice	Packaging material	Sustainable, biodegradable packaging	Das et al. (2019)
Spent grains	Cereal industry	Packaging material	Biodegradable, ecofriendly, alternate to plastic	Agu et al. (2020)
Hulls	Oats	Filler in packing material	Contribute strength and skeleton to packaging material, renewable	Khalil et al. (2012)
Starch	Corn	Bioplastic packaging	Compostable and renewable	Chan et al. (2013)

2 Fruit and Vegetable Industry by Products

Global food waste has increased as a result of an imbalance between supply and demand brought on by both population growth and technological developments. Regarding food waste, fruits and vegetables make up around 42% of all commodities consumed worldwide. Raw, cooked, or added to other dishes are all acceptable forms of consumption for fruits and vegetables (Ganesh et al., 2022). Fruit peels, seeds, crops, leaves, straw, stems, roots, or tubers are among the waste compositions produced during the processing of fruit and vegetable waste, depending on the raw material selected (Md Salim, 2017). The waste derived from fruit and vegetable waste has a wide range of qualities, depending on the species and tissues of the plants (Choudhury et al., 2023; Dhar et al., 2023). For example, leftover peels and seeds have a high concentration of phytochemical substances, which may be used as food flavorings and preservation agents (Sridhar et al., 2021). Plant tissues high in vitamins, fiber, and carotenoids have anti-diabetic and antioxidant qualities, which exhibit wide array of medicinal properties. Up to 30–50% of the waste generated during the processing of fruit and vegetable juices is created. Both solid and liquid wastes, including as juice and wash water, are present in these waste by-products. Solid wastes include peels, skins, and pomace. In another instance, the processing of sugar beets yields between 40% and 70% vegetable pomace and 85% sugar beet residue. These leftovers and by-products from fruits and vegetables carry a lot of bioactive chemicals that can be used as animal feed additions or human food additives (Zhu et al., 2023). According to studies, the peels, seeds, and other commonly consumed parts of fruits and vegetables are rich sources of phytochemicals and important nutrients (Rudra et al. 2015; Muchahary et al., 2023). Compared to fruit pulp, the peel of avocados, grapes, lemons, jackfruit seeds, and mangoes has 15% higher phenolic contents. Approximately thirty percent of fruit and vegetable production waste can be sold worldwide as a feed and food ingredient. For instance, during the wine-making process, around 20–30% of the grape pomace is a waste by-product (Kumar et al., 2020).

The bioactive substances from FVW can be categorized into different groups based on the need for nutrition: polyphenols, vitamins, minerals, dietary fiber which are necessary components for both sustaining the body's fundamental requirements and preventing disease. Non-essential metabolites like carotenoids and phenolics, which help sustain cell metabolism and increase longevity, can also be present in food by-products. Numerous fruit and vegetable wastes and by-products can range greatly in composition. Their particular uses are intimately associated with the processing of food intended for human consumption as well as the animal feed sector (Zhu et al., 2023).

In order to reduce environmental problems and find sustainable solutions, it is therefore important to value waste products effectively in a variety of applications. Significant levels of phytochemical components found in fruits and vegetable wastes (FVW) have been studied for their potential to extract phenolic compounds, dietary fibre and other bioactive substances. The useful bioactive compounds found in fruit and vegetable waste and their use in food processing are presented in Table 12.2.

3 Utilization Trends of Different FVW in Food Processing

3.1 As Probiotics

Probiotics are considered one of the main functional food products and are consumed extensively throughout the world According to Abdul-Hamid et al. (2019), there has been a notable increase in demand for novel functional foods in recent times. In addition to being extremely valuable, the fruits and peels have a large number of therapeutic compounds. The peels of pomegranates, citrus fruits, mangoes, and *Opuntia ficus-indica* (barbary figs) are rich in antioxidants, fiber, and oligosaccharides, which act as prebiotics (Chan et al., 2018; Coelho et al., 2019). Dietary fiber and probiotics have both been shown to alleviate constipation and lower the risk of colon cancer. Furthermore, some fruit-based dietetic fibers have had a significant impact on the survivability of these bacteria and are advised for use as a component in dairy products that contain probiotics (Kumar et al., 2020).

3.2 As Microbial Growth Media, Biofuels

A number of fruits and vegetables, including cabbage, carrots, gooseberries, tomatoes, pumpkins, and others, have been used in place of nutrient agar in the cultivation of bacteria and fungi. In order to reduce the expense of the microbial media, some reports have substituted green, black, and cowpea grains for starch and protein (Jamal et al., 2013).

Table 12.2 Recent studies on the utilization of fruits and vegetable wastes

F&V waste	Bioactive compound	Application	Outcome	Reference
Pomegranate-peel, pulp, and seeds	Flavonoids, condensed &hydrolyzable tannins, triterpenoids, fatty acids, triglycerides, alkaloid, organic and phenolic acids, sterols, dietary fiber	Functional food	Anti-cancer, anti-inflammatory, and anti-aging Glucose retention capacity	Khatib et al. (2017)
Tomato peel	Lycopene	Nutraceutical	Used as food additives in the form of colorings and lowers the risk of atherosclerosis, prostate cancer, cardiovascular disease, and memory loss	Martinez-Hernandez et al. (2019)
Peach peels, tomato, apricot, pumpkin, sweet potato and pepper waste	Carotenoids (lutein, lycopene)	Nutraceutical	Antioxidant activity	de Andrade Lima et al. (2019)
Sweet cherry skin	Anthocyanins	As a functional ingredient in yoghurt and marshmallows	Antioxidant, neuroprotective characteristics, anti-cancer benefits, and arthritic and inflammatory pain alleviation	Milea et al. (2019)
Sour cherry pomace (SCP) extract	Polyphenols, anthocyanins	SCP encapsulated in soya and whey protein incorporated in cookies	Excellent sensory characteristics, improved functional properties and enhance shelf-life	Saponjac et al. (2016)
Orange, carrot, and papaya peels	β -Carotene	Biocolorant	β -Carotene (as a biocolorant) was prepared using microbial strain <i>Blakeslea trispora</i> in solid state fermentation	Kaur et al. (2019)

(continued)

Table 12.2 (continued)

F&V waste	Bioactive compound	Application	Outcome	Reference
Banana peels orange peels, cauliflower waste, peapods, apple pomace, pineapple waste	Cellulose, hemicellulose, pectin, minerals, vitamins, and low lignin content	Enzymes, ethanol, and biocolors	Utilizing fruit wastes as substrates enzymes viz., cellulases, amylases, pectinases, proteases, etc. can be produced using solid state and submerged fermentation	Sharma et al. (2016)
Microfibers prepared using pulp and peel of Japanese plum	Coextruded with β -carotene, lutein, and α - and γ -tocopherols	Antioxidant additives in meat products	Prevented lipid oxidation in breast chicken patties	Basanta et al. (2018)
Apple, melon, pineapple pomace	Dietary fiber	Baked products- biscuits	Increment in fiber, acceptable sensory characteristics of biscuits developed	de Toledo et al. (2017)
Mango and papaya peels	Catechin, mangiferin and quercetin-3- β - glucoside, carotenoids	Corn chips (extruded snacks)	Corn exudates with incorporated 15% mango or papaya peel produced chips with superior sensory qualities and higher antioxidant activity	Fontes- Zepeda et al. (2023)
Seeds of tropical fruits (guava, pumpkin, papaya, honeydew, mangosteen, rambutan, watermelon, mango, and durian)	Oil, protein, and carbohydrates, micronutrients	Phytonutrients, food ingredient, therapeutic use, waste management in agro-industries	Can be incorporated as such, used as powder to be utilized in food preparations-soups, cookies	Raihana,et al. (2015)
Grapefruit peels, sweet oranges peels, lemon peels	Pigments, polyphenols, essential oils, pectins, proteins and dietary fibers	Food-coloring, flavoring, and thickening agent	Can be incorporated in different food matrices to exploit nutraceutical/ bioactive compounds	Wedamulla et al. (2022)
Banana peels, potato peels, citrus wastes	Lignocellulose further hydrolyzed to form hexose sugars	Biofuels	Bioethanol production using solid state fermentation	El Sheikha and Ray (2023)

Bio-waste from fruits and vegetables has drawn a lot of attention because it contains simple and complex sugars that are broken down by microbes and can be used to produce biogas, bioethanol, and animal feed. As a microbiological growth medium, agar containing dragon fruit peel (DFP) was also employed (Wasas et al., 1999). Peels from grapefruit, bananas, and melons are rich in carbs, which serve as an excellent substrate for the enzyme amylase to be produced. It was discovered that the banana peel was an inexpensive and efficient medium for the growth of fungi (Kindo et al., 2016). Total proteins, reducing sugars, and lipids are among the macronutrients that are abundant in watermelon peel extract. According to the study, watermelon peel waste accelerated the multiplication of *Lichtheimia corymbifera*, *Fusarium oxysporum*, *Penicillium expansum*, *Aspergillus niger* and *Rhizopus oryzae* (Hasanin et al., 2020).

3.3 As Nutraceuticals

Food vegetable waste (FVW) is one of these sources because, in addition to their structural components (peels, seeds, roots, stems and leaves), they also contain substantial quantities of dietary fiber, carotenoids, phenolic substances, isoprenoids, proteins, lipids, saponins, and phytoestrogens in the residues that remain after their juices, oils, starches, and sugars are extracted (Sharif & Khalid, 2018). The well-established anti-inflammatory and circulatory properties of carotenoids and other phenolic components make them significant in the fight against several diseases, including cancer. They can postpone, impede, or suppress the oxidation of proteins, lipids, and DNA. These advantageous effects are mostly attributable to their antioxidant and antiradical qualities. The bioactive compounds' antioxidant properties are attributed to their low oxidation potential and ability to serve as electron donors for the inactivation of free radicals, including reactive oxygen species. Moreover, the increased consumer demand for food products to have fewer artificial preservatives is driving up the value of these natural compounds. It is indeed feasible to separate bioactive components from FVW and use them in associated businesses to great effect by converting them into nutraceuticals and functional foods (Jiménez-Moreno et al., 2020). Using strains of *Lactobacillus* and *Bifidobacterium* Khatib et al. (2017) isolated and reported raw polysaccharides from the pomegranate mesocarp, or interior yellow peel, which demonstrated prebiotic qualities in vitro. The extract obtained by a green extraction procedure has a composition of 10% crude polysaccharides and 12% ellagitannins, which makes it suitable for use in functional food compositions.

3.4 As a Source of Pigments

An abundance of naturally occurring pigments, including carotenoids, betalains, anthocyanins, and chlorophylls, can be found in these wastes and byproducts. Industries that process juices eventually generate trash and byproducts. Because of their high anthocyanin content (4.31 mg Cy3GlE/g), blackberry residues are considered to be significant sources of natural colorants and nutraceuticals.

These naturally occurring pigments have the ability to be separated from waste materials and byproducts and may have bioactivities including antibacterial, antioxidant, antiproliferative, and anti-inflammatory qualities (Sharma et al., 2021). These plants' secondary metabolites are regarded as "functional food ingredients" because of their powerful nutritional and health-promoting qualities as well as their phyto-pigment-antioxidant makeup. The industrial production of natural pigments can be satisfied by the value-adding of vegetal wastes (fruits and vegetables) and their byproducts (such as peels, seeds, or pomace), with the goal of utilizing them in food, medicine, and cosmetics (Jiménez-Moreno et al., 2020). Bioactive pigments are used as food additives, natural coloring agents, color enhancers, antioxidants, and as raw materials to create high-value goods. Several research investigations examined the bioactive pigments such as anthocyanins, betalains, and carotenoids, from particular fruit and vegetable wastes, like tomato, red beet, and grape wastes. Food processing industries, such as wine and juice, are thought to provide additional rich sources of anthocyanin pigments, which can be used as natural food colorings in a variety of applications.

4 Fermented Edible Products

Fermenting fruit wastes produces a variety of drinks, including vinegar, wine, beer, cider, and brandy. Cider made from apple pomace has been produced. It has also been investigated whether dried culled and excess apples, grapes, oranges, and other fruits could be used to make brandy. Fruit scraps can also be used to make vinegar. In the beginning, the fruit waste is fermented alcoholically using acetic acid produced by the microorganisms *Acetobacter*. There have been reports of pineapple and orange peel juice waste being fermented to produce vinegar (Omre et al., 2018). The anaerobic digestion of organic feedstocks using mixed culture fermentation (De Groof et al., 2019), the production of lactic acid from the fermentation of date palm waste to replace the costly raw material (Azam and Ahmad, 2019), the process of utilizing filamentous fungi, yeast, or bacteria to bioconvert cocoa byproducts into drinks, nutraceuticals, polysaccharides, and enzymes (Vásquez et al., 2019) and baking goods made from fermented sourdough that may reduce IBS symptoms and produce bioactive compounds related to the metabolism of phenolic compounds (Gobbetti et al., 2019) are a few current examples of valorization techniques based on fermentation..

5 Baked Products

Due to their high fiber content and bioactive ingredients, which help with the breakdown of glycemic carbohydrates like starch, baked goods are ideal food systems for accommodating fruit and vegetable wastes. Furthermore, the glycemic index of most baked foods is high. Fruit byproducts are widely known for being high in fiber, mainly composed of cellulose and hemicellulose, which are insoluble fibers. However, they also include significant quantities of pectin, especially from the pomace of guava and apples. In most situations, food acceptability has decreased as a result of the addition of FVW. Fruit and vegetable waste, which can contain up to 93.2% of total fiber, can have the same detrimental effects on food quality as pure fiber when added to baked items. However, a lot of phenolic chemicals are unpleasant to consumers because they are harsh, acidic, or astringent (Gómez and Martinez, 2018).

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Chapter 13

Enzymes and Biotechnology in Food Processing



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Abbreviations

AMS	Automatic milking system
CBP	Combined bioprocess
CIP	Clean-in-place
GABA	Gamma-aminobutyric acid
GM	Genetically modified

1 Introduction

Living organisms to form the biological macromolecules synthesize enzymes, which are often proteins. Enzymes play a crucial role in catalyzing biochemical reactions necessary for sustaining life by enhancing their reaction rates while remaining unchanged in their chemical composition. Enzymes are very specific, work very well, and only need mild temperatures and pH levels to work. Enzymes are important for all living things to be able to stay alive. They are very good at

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speeding up biochemical processes and can come from animals, plants, and bacteria, among other places (Hamza, 2017). Microorganisms are widely distributed throughout the natural world and possess the ability to endure a variety of challenging and extreme environmental conditions. Fauna is a fundamental component of the various ecosystems that encompass our surroundings, constituting roughly 55–60% of the overall biomass present on the planet (Schultheiss et al., 2022). At a global scale, it can be observed that the ocean and soil harbor about 3.6×10^{29} and 4.5×10^{30} microorganisms, correspondingly (Ahmad et al., 2011). The involvement of microorganisms is of great importance in promoting sustainable development of life on earth. The food industry's interest in enzymes arises from their ongoing pursuit of food products with extended shelf life, as well as their efforts to minimize waste and enhance product quality. The primary produces are formed from raw ingredients that are utilized by the enzymes. The enzymes also function as additives that alters the food properties which includes taste, consistency, and aroma (Singh et al., 2024). Enzymes have been playing a significant role in the food preservation since the olden days, and now they are helping in many food businesses improve the quality and security of their goods and get more out of their production. Enzymes made by microorganisms that are used to prepare food have not only made the food business more diverse, but they have also created financial assets.

Operational stability, storage life, recovery, and reuse are the four main factors that reduce enzymes' functional qualities over time. Enzyme immobilization provides a solution to these issues; it streamlines the process, improving repeatability and functional efficiency while decreasing contamination and labor requirements. This enhances the stability of the goods. The Japanese L-amino acid manufacturing process immobilized the primary enzyme, amino cyclase from *Aspergillus oryzae* (Sneha et al., 2019). Biotechnology plays a crucial role in the processing of food, predominantly in grain processing, fruits and vegetable processing, food and drink, fats and oils, confectioneries, dairy and poultries. Other than the above roles, enzymes with the help of biotechnology can convert perishable and unpalatable food into tasty, enhanced shelf life of the food that is safe and of higher quality in terms of nutrition, physicochemical qualities, and sensory attributes. The enhancement in the quality, texture, longevity of food by hindering the proliferation of toxin produced by microorganisms found in food naturally and generating antimicrobial properties to eliminate unwanted spoilage germs (Fig. 13.1). Using ELISA and microarray techniques, biotechnology aids in detecting diseases and pesticides in food (Jan et al., 2024).

The present chapter pertains to the microbial enzymes that are categorized in the domain of food processing and the industries related to food. Additionally, it encompasses an analysis of their physicochemical and biological characteristics, along with their industrial utilities. The present chapter also encompasses contemporary advancements in this domain. In addition, the function of enzyme immobilization in the industry related to food processing will be discussed. This article also examines and assesses various biotechnology advancements used in the industries of food processing.

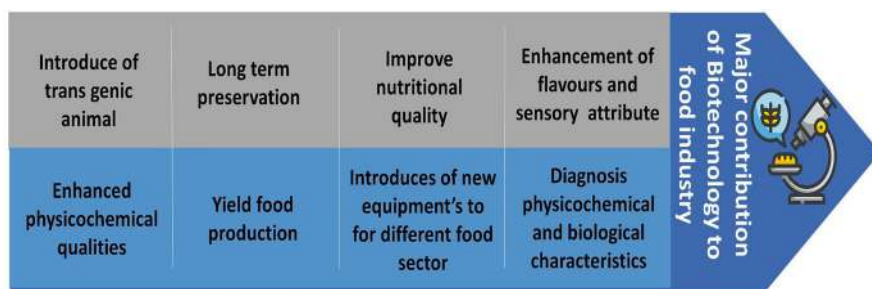


Fig. 13.1 Important role of biotechnology in food industry

2 Classification of Enzymes

Enzymes are considered to be macromolecules of significant size as the molecular weights ranged from 10 to 2000 kDa (Gillies & Fréchet, 2002). These macromolecules are composed of amino acids that are covalently linked by peptide bonds. Enzymes exhibit distinct discernible regions upon adopting their tertiary or quaternary conformations. The enzymes active sites are situated in a hydrophobic region of the enzyme. They are crucial in their tertiary or quaternary structures for their enzymatic activity. Enzymes exhibit specificity towards their substrate by means of their active sites, thereby conferring a distinct identity upon each enzyme in relation to other enzymes. There are now seven categories of enzymes, distinguished by the processes they catalyze.

1. **Oxidoreductases** represent a class of enzymes that facilitate the chemical reaction of substrate(s) by either oxidizing or reducing them. Different kind of oxidoreductases includes reductases, dehydrogenases, oxygenase, glucose oxidase, catalase, polyphenol oxidase (PPO), lipoxygenase, and Peroxidase (POD) (Vidal et al., 2018).
2. **Transferases** are an enzyme family that catalyzes the movement of functional groups between molecules. Numerous types of transferases include formyl transferase, kinase, acetyltransferase, transketolase, transaminase, glycosyl-transferase, methyltransferase, transaminase, sulfotransferase *etc.* (Okpara, 2022).
3. **Hydrolases** comprise of a type of enzymes, which use water as a catalyst for the breakdown of bonds in macromolecules, therefore reducing them to smaller sub-units. Examples of hydrolases include glycosidase, lipase, phospholipases, amylases, acylase, lactase peptidases *etc.* (Garske et al., 2017).
4. **Lyases** include a kind of enzymes, which can speed up either removal, or addition processes without being broken down or oxidized. Examples of lyases include aldehyde lyase, pectolyase, decarboxylases, dehydratases, hydratases *etc.* (Okpara, 2022).
5. **Isomerases** can convert a parent molecule into an isomer by facilitating the formation and dissolution of intramolecular connections. Cis-trans isomerases, epimerases *etc.* are examples of isomerases (Siddiqui & Dahiya, 2022).

6. **Ligases** are a class of enzymes that catalyzed the grouping of two or more molecules to form new molecules and chemical bonds using energy released by the hydrolysis of ATP or another energy-rich phosphate bond (Table 13.1). Examples of ligases include chelataes, synthetases, carboxylases, DNA ligase *etc.* (Lindh, 2012).
7. **Translocases** comprise of the most recently classified type of enzymes, having just been officially recognized by the EC in 2018. Enzymes known as transmembrane transporters shuttle chemicals and ions across biological membranes (McDonald & Tipton, 2023). Examples of translocases include ADP/ATP translocase, outer and inner membrane translocase.

3 Enzyme and Their Sources

3.1 *Alpha-Amylases*

α -amylases (EC 3.2.1.1) are classified as endo-amylases and function by breaking down starch into glucose and maltose. The initial identification of the enzyme responsible for starch degradation dates to 1811. Subsequently, in 1925, Kuhn named this enzyme α -amylases. Subsequently, numerous other variations, such as β -amylases, have been identified and characterized (Tiwari et al., 2015).

Table 13.1 Enzyme classification, reaction of enzyme and example

Class	Reaction mechanisms	Example	References
Transferases	Promote the movement of atom groups between molecules	Kinase, peptidyl transferase, transketolase, transaminase, acetyltransferase, glycosyltransferase, methyltransferase	Okpara (2022)
Hydrolases	Hydrolysis breaks links	Glycosidase, peptidases, amylases, phospholipases, lipase, acylase, lactase	Garske et al. (2017)
Lyases	Cleavage without water through addition or removal responses	Pectolyase, decarboxylases, aldehyde lyase, adenylyl cyclase, dehydratases, hydratases	Okpara (2022)
Isomerases	Group movement between different sites on the same molecule	Epimerases, racemases, cis-trans isomerases	Siddiqui and Dahiya (2022)
Ligases	Use covalent bonds to attach molecules, then supply energy into the system by way of ATP or related triphosphates	Chelataes, synthetases, carboxylases, DNA ligase	Lindh (2012), Deng and Walther (2020)
Translocases	Movement of ions and/or molecules across membranes	TIM, TOM	McDonald and Tipton (2023)

The classification of this entity is based on the type of glycosidic bond it possesses, specifically whether it is sessile or not. It is categorized into two distinct classes, namely endo-amylases and exo-amylases. Alpha-amylase is a prominent extracellular enzyme that holds significant industrial value and has been widely utilized for commercial purposes. The utilization of this method has effectively supplanted the hydrolysis of starch chemically within the sectors of starch-processing.

Even though α -amylases are found in many different bacteria, fungi, plants, animals, and people, only a few strains of fungus and bacteria have been used for industrial production. Most α -amylase comes from the pancreas and salivary glands of animals. Although it is found throughout a plant, its highest concentrations are found in the grains and starchy components. The primary byproduct of β -amylase, which is exclusive to plants, is maltose. Several types of fungus and bacteria generate α -amylase. Commercial production of the enzyme relies heavily on the mesophilic *Bacillus* sp., specifically *B. amyloliquefaciens* and *B. licheniformis* (Movahedpour et al., 2022). The thermostable α -amylase-producing bacteria *B. subtilis*, *cereus*, and *B. stearothermophilus* have all been the subject of much research. The halophilic amylases produced from halophilic type bacteria such as *Halobacillus* sp., *Chromohalobacter* sp., *Haloarcula hispanica*, *B. dipsosauri*, and *H. meridiana* have been demonstrated with potential benefits in various challenging manufacturing techniques that employ highly concentrated salt solutions. The fungi *Aspergillus* and a rare subspecies of *Penicillium*, namely *Penicillium brunneum* and *P. fellutanum*, are the predominant sources of α -amylase (Souza, 2010; Paul et al., 2021; Zhang et al., 2017).

3.2 Protease

Protease (EC 3.1.3.8) is an enzyme in the family of proteolytic enzymes, whose job it is to break down protein peptide linkages. Peptide sequences, created by proteases incomplete digestion, might be useful functional dietary additives with biological effects. Proteases are a significant category of enzymes of industrial origin, accounting for nearly 60% of the overall enzyme market (Mamo & Assefa, 2018). Proteases, due to their specificity and diverse range, have been extensively utilized in ample industries like food, therapeutic, detergent and leather tanning etc. (Fig. 13.2). The utilization of enzymes for commercial purposes is deemed environmentally sustainable due to the non-toxic and non-pathogenic nature of the enzyme's sources (Singh & Bajaj, 2017).

Proteases have been found in bacteria, fungi, viruses, plants, animals, and people. This is because they play important parts in the body. They are grouped into endo-peptidases and exo-peptidases based on where they work on protein targets. Proteases from plants that are well known are papain, bromelain, keratinases, and ficin. Microorganisms are a great source of enzymes because their genes are easy to



Fig. 13.2 Versatile applications of protease enzyme in various industries/sectors. (Figure adapted from Solanki et al. (2021) and is an open access article (Copyright © 2021 by authors) distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license)

change and they come in many different forms. On an industrial scale, they are always chosen because they are cheaper to make, can be made in large quantities in industrial fermenters, have extensive variety of physical and chemical properties, grow cultures quickly, and are not affected by seasonal changes. About 40% of all enzyme sales in the world come from microbial proteases. *Bacillus* species produce the vast majority of the world's commercially available neutral and alkaline proteases. Bacterial neutral proteases have a poor temperature tolerance and are only active between the pH values of 8 to 10. Proteases with an intermediate rate of reaction are widely utilized in the food sector because they produce hydrolyzed proteins that are less bitter than those produced by animal proteinases. The gram-negative bacteria *Pseudomonas* produce alkaline proteolytic enzymes. *P. aeruginosa* is a common source of proteases, and many different types have been isolated from the bacteria. *A. oryzae*, a kind of fungus, generates neutral, acid, and alkaline proteases, whereas bacteria only produce neutral proteases (Sharma et al., 2019a; Banerjee et al., 2017; Jisha et al., 2013).

3.3 Pectinase

The enzymatic activity of pectinase, which is found at plants cell wall, facilitates the outcome of pectic acid by converting from pectin through the procedure of de-esterification of the methoxyl group of pectin. The enzymes under consideration belong to the hydrolase category, specifically polygalacturonases and polymethyl galacturonases. Pectic acid and pectin are broken down by these enzymes because of their ability to catalyze the breakage of the -1,4-glycosidic bond (Jayani et al., 2005).

Pectinases may be obtained from many different types of microorganisms, including *Erwinia*, *Rhizopus*, *Kluyveromyces*, *Bacillus*, *Trichoderma*, *Penicillium*, and *Pseudomonas* are the three chief popular pectinase-producing fungus used in industry (Jayani et al., 2005; KC et al., 2020; Haile & Ayele, 2022).

3.4 Lipases

Lipases (E.C. 3.1.1.3) are biocatalysts that hydrolyze, alcohololyse, acidify, and aminolyse lipids and fatty acids. Lipases have risen to prominence as one of the most useful commercial enzymes because of their versatility. Several distinct kinds of lipases with varying catalytic characteristics have been uncovered. They speed up the process of transesterification, hydrolysis, and esterification. They are used a lot in the food, oils, baking, medicines, and dairy manufacturing industries, among others. Lipases usually speed up the process of producing fatty acids and glycerol from fats (Chandra et al., 2020).

The bacteria, fungal and yeast species are responsible for the synthesis of microbial lipases. The predominant industrial microbial lipase producers include several microorganisms such as *Penicillium restrictum*, *Candida rugosa*, *P. restrictum*, *C. antarctica*, *Pseudomonas mendocina*, *P. alcaligenes*, *P. mendocina*, and *Burkholderia cepacia*. Various types of fungi such as *Rhizopus*, *Geotrichum*, *Rhizomucor*, *Aspergillus*, *Candida*, and *Penicillium* have been documented to possess the ability to produce lipase enzymes, which are employed in the preparation of numerous food products for commercial purposes (Bharathi & Rajalakshmi, 2019; Sangeetha et al., 2011).

3.5 Lactase

The hydrolysis of lactose is done by the enzyme lactase (EC 3.2.1.108) which helps in catalyzation. The enzyme lactase (or α -galactosidase) is present in a wide variety of organisms, including plants, fungus, microorganisms, and animals. We can't say enough about how important lactase is to the dairy/food and drug businesses

(Kamalova, 2023). Industrial lactase is made from fungi like *Aspergillus niger*, *A. oryzae*, *Kluyveromyces lactis*, and *K. fragilis*. Industrial lactase is made from bacteria like *E. coli*, *Klebsiella oxytoca* ZJUH1705, *Bifidobacterium infantis* CCRC 14633, and *B. longum* BCRC 15708 (Ramana Rao & Dutta, 1978; Zhou et al., 2023; Panagopoulos et al., 2021).

3.6 Cellulases

Cellulases (EC 3.2. 1.4) degrade cellulose by hydrolyzing its α -1,4 bonds, thereby liberating oligosaccharides, glucose, and cellobiose. They are made by microbes like bacteria, fungi, protozoans, plants, and animals that live in mesophilic or thermophilic environments and need oxygen or do not need it. The most important germs that make cellulases are fungus (*Aspergillus*, *Trichoderma*, *Fusarium*, etc.) as well as bacteria (*Bacillus*, *Staphylococcus*, *Xanthomonas*, *Clostridium*, *Eubacterium*, *Erwinia*, *Ruminococcus*, etc.). *Aspergillus*, a cylindrical fungus, is thought to make the most cellulase by solid-state fermentation (Juturu et al., 2014; Bhardwaj et al., 2021; Jayasekara & Ratnayake, 2019).

3.7 Catalases

Catalases (EC 1.11.1.6) is also called hydroperoxidases. It is one of the enzymes that has been studied the most. It is a tetrametric enzyme with four known parts that are each 60 kDa. Catalase is one of the most important enzymes when it comes to making money. One molecule of catalase can break down hydrogen peroxide into lots of molecules per second into water and oxygen (Sharma et al., 2022). Catalase is an enzyme that is found in almost all living things. Most catalase enzymes come from the liver of cows and bacteria (Busalmen et al., 2002).

3.8 Esterases

Esterases belong to the class of hydrolase enzymes and are responsible for catalyzing the ester hydrolysis process, leading in the development of alcohol and acid (Bhatt et al., 2021). Like lipases, esterases can catalyze the hydrolysis of glycerides into their respective fatty acids and glycerol. However, it should be noted that esterases are specifically capable of hydrolyzing short-chain glycerides. Esterases are predominantly produced on an industrial scale through microbial means, with bacteria being the most utilized microorganisms. The microorganisms *Lactobacillus*

acidophilus, *L. amylovorus*, *L. farciminis*, *L. acidophilus*, *Bacillus licheniformis*, and *L. fermentum*, and are known to produce feruloyl esterase (Rueda-Rueda et al., 2020).

3.9 Phytase

Phytase is a kind of phosphatase that is responsible for accelerating the breakdown of phytic acid in grains and oilseeds to liberate inorganic phosphorus. Phytase facilitates the absorption of minerals like Ca, Zn, and Fe that are normally associated with phytic acid in grains and oilseeds (Sharma et al., 2019b). So, the action of water on phytic acid by phytase makes calcium, zinc, and iron more available to animals with only one stomach. Phytase can be found in mushrooms, bacteria, plants, and grazing animals. The majority of industrially produced phytase comes from fungi and bacteria. Phytase may be produced by a number of different microorganisms, including *Aspergillus ficuum*, *A. niger*, *Klebsiella terrigena*, *A. fumigatus*, *Schizosaccharomyces pombe*, *Klebsiella oxytoca*, *Bacillus amyloliquefaciens*, *E. coli*, and *B. subtilis* (Mukhametzhanova et al., 2012; Balwani et al., 2017).

3.10 Invertase

Invertase (EC 3.2.1.26) is an enzyme that breaks down sucrose into its component monosaccharides. Microbes, such as filamentous fungus and certain bacterial species, may be able to generate invertase, an enzyme that has several industrial applications (Table 13.2) (Ahlawat et al., 2018). One of the candidates for invertase synthesis is the fungus *Aspergillus caseiellus*. Invertase is commonly used in the industries of food sector and may be harvested from *Saccharomyces cerevisiae* also known as baker's yeast (Taskin et al., 2016; Lincoln & More, 2017).

3.11 Transglutaminase

Transglutaminase (EC 2.3.2.13) is classified as a transferase enzyme. Substances like this make it possible for the primary ϵ -amine groups of diverse compounds to join with the γ -carboxamide groups of glutamine residues (functioning as donors) to form isopeptides, such as proteins. These entities exhibit a ubiquitous presence within the natural world (Karaki et al., 2016). They are produced from *Physarum polycephalum* and *Streptoverticillium* sp.

Table 13.2 Enzyme sources and their food processing industrial applications

Enzyme	Sources	Applications	Industry	References
α -Amylase	<i>Bacillus amyloliquefaciens</i> , <i>B. licheniformis</i> , <i>B. subtilis</i> , <i>Bacillus acidopullulyticus</i> , <i>B. cereus</i> , <i>B. dipsosauri</i> , <i>Bacillus stearothermophilus</i> , <i>Pseudomonas fluorescens</i> , <i>Penicillium brunneum</i> , <i>P. fellutanum</i> , <i>Aspergillus</i> sp.	Baking, brewing, Flour adjustment, bread, liquefaction beer brewing process, softness starch	Beverage, Baking	Nath et al. (2023)
β - Amylase	<i>Bacillus</i> , <i>Streptomyces</i> , <i>Rhizopus</i>	Syrup manufacturing, Juice treatment, Starch hydrolysis, Low calorie beer	Beverage	Tiwari et al. (2015)
Cellulase	<i>Bacillus</i> , <i>Acidothermus</i> , <i>Staphylococcus</i> , <i>Xanthomonas</i> , <i>Streptomyces</i> , <i>Clostridium</i> , <i>Eubacterium</i> , <i>Erwinia</i> , <i>Ruminococcus</i> , <i>Aspergillus</i> sp., <i>Trichoderma</i> sp., <i>Fusarium</i> sp., <i>Penicillium</i> sp.	Fruit juices and winemaking, Animal feed Clarification of fruit juice	Animal feed, Beverage	Juturu et al. (2014), Bhardwaj et al. (2021), Jayasekara and Ratnayake (2019)
Pectinase	<i>Aspergillus oryzae</i> , <i>Penicillium funiculosum</i> ,	Depectinization, mashing, manufacture of oil extraction, and coffee and tea fermentation	Beverage	Shi et al. (2024)
Protease	<i>Aspergillus niger</i> , <i>Pseudomonas aeruginosa</i>	Improvement of bread quality, tenderization of meat, milk coagulation	Beverage, Meat industry	Sharma et al. (2024)
Lactase	<i>Escherichia coli</i> , <i>Saccharomyces fragilis</i> , <i>A. niger</i>	Prebiotic food ingredients, reduced milk and whey products	Dairy industry, Pharma industry	Alzahrani et al. (2024)
Lipase	<i>Aspergillus niger</i> , <i>A. oryzae</i> , <i>Candida</i> sp., <i>Penicillium restrictum</i> , <i>C. rugosa</i> , <i>P. restrictum</i> , <i>Burkholderia cepacia</i> , <i>P. alcaligenes</i> and <i>P. mendocina</i>	Faster cheese ripening, flavour customized cheese, cheddar cheese production Dough stability and conditioning	Dairy industry	Moodley et al. (2024)

(continued)

Table 13.2 (continued)

Enzyme	Sources	Applications	Industry	References
Esterase	<i>Lactobacillus acidophilus</i> , <i>L. amylovorus</i> , <i>L. farciminis</i> , <i>L. acidophilus</i> , <i>Bacillus licheniformis</i> , and <i>L. fermentum</i>	De-esterification of dietary fibre Production of short chain flavour esters	Beverage sector	Rueda-Rueda et al. (2020)
Invertase	<i>Saccharomyces cerevisiae</i> , <i>Aspergillus casingii</i>	Sweets in general, artificial honey, jams, confectionery, drinks	Sweet and Chocolate industry, Beverage industry	Rana et al. (2024)
Transglutaminase	<i>Streptovercillium</i> sp., <i>Physarum polycephalum</i> , <i>Streptomyces netropsis</i> , <i>Streptomyces lydicus</i> , <i>Bacillus subtilis</i>	Polymerization of milk proteins, increases the texture of meat products, quality enhancement of flour and bread's texture	Dairy industry, Meat industry, baking industry	Niamah et al. (2024)

4 Enzymes and Biotechnology

Nutritious foods serve as a valuable reservoir of essential nutrients that effectively regulate satiety and modulate physiological processes. Through processing and the application of various cooking techniques, foods can take on additional roles. Furthermore, food is a source of various health-enhancing nutrients, including vitamins, minerals, and nutraceuticals. Proteolytic activity of natural or bacteria enzymes was used in the early stages of food processing (Singh et al., 2019). Cheese, yogurt, bread, and syrup, among other things, are all made with the help of enzymes. The forthcoming bio-processing strategies for food production will be increasingly tailored to prioritize the creation of nutritious foods through the utilization of enzymes, resulting in the development of novel processed and functional food products (Chourasia et al., 2020). Enzymes derived from microorganisms have been utilized for an extended period. According to estimates, over 500 commercial products are currently being produced utilizing microbial enzymes. Approximately a decade ago, the global market value of these products was estimated to be US\$ 2.3 billion (Ahlawat et al., 2018). Microbial enzymes have extensive applications in various industries, including but not limited to food, detergents, paper, textiles, and pulp. Microbial enzyme-assisted mechanisms exhibit several distinctive attributes, including reduced processing time, lower energy requirements, environmentally benign and sustainable, and economically feasible. Due to these characteristics,

enzymatic processes are increasingly attracting attention in the food sectors. In addition, microbial enzymes offer various benefits in the realm of food processing such as simplified food processes, effective utilization of raw materials, consistent product quality, and enhanced sustainability (Picart-Palmade et al., 2019). Commercial food processing technologies can benefit from the untapped potential of the microbial world by providing an alternative source of novel enzymes. Bacterial enzymes are being looked at as a potential escape from the increasingly fragmented and divergent technological and business landscape. The catalytic activity of the enzymes produced by microbes are not geographically confined, thus they can be employed repeatedly. Nanotechnology is the newest tool that can help improve these unique enzymes made by microbes. It can also help the food business find more sustainable ways to prepare, store, and add value to food (Jagtiani, 2022). This can be done by making sure that all parts of the agri-food business have a wide range of tools, systems, and networks. In food sectors, microbial enzymes are utilized in many different areas, like baking, brewing, yoghurt and juice manufacture. The utilization of microbial enzymes in cheese processing has been significantly expanded through augmented applications. This has resulted in enzymes being extensively employed in the dairy manufacturing industries, making it the second most prominent sector utilizing these enzymes, following the beverage industry (Maghraby et al., 2023). Enzymes are utilized in diverse ways, ranging from their use as coagulants to their application as bio-protective agents, with the aim of enhancing the safety and shelf-life enhancement of dairy products. Rennet is an enzyme that is utilized for the purpose of inducing coagulation of milk into firm curds, a process that is integral to the production of cheese as well as liquid whey (Reig et al., 2021). Currently, approximately one-third of the worldwide cheese demand is satisfied through the utilization of microbial rennet. Additional proteases have been found to have potential uses in expediting cheese processing and mitigating the allergenic characteristics of dairy products. The primary components of milk are lactose, lipids, and proteins. The dairy industry's employment of these constituents is expedited by lipases, β -galactosidases, and peptidases correspondingly (Nadaroglu & Polat, 2022). Enzymes have shown great promise in dairy research, particularly for the breakdown of lactose and protein. Therefore, it can be inferred that there will be a sustained demand for microbial enzymes that have utility in the food sectors.

5 Enzyme and Biotechnology in Different Food Processing Industry

There are many microbial based enzymes are now being introduced, those are actively involved in various food industry (Fig. 13.3). Some of the major food sectors are bakery, dairy, meat, juice, soy sauce, beverages and so on are discussed below.

5.1 Bakery Industry

Microbial enzymes can change the way the gluten network works, so they can be used to change the way flour and dough behave and add flavor to baked goods. Enzymes called lipoxygenases are responsible for the oxidation of fatty acids. They are also used to bleach colors in fat-soluble flour and give dough flexibility. The aforementioned specimens have been procured from the *Ascomycota incertaesedis* fungal group, specifically from *Gaeumannomyces*, *Pyricularia*, and *Geotrichum candidum* (Miguel et al., 2013). The fungal lipoxygenase enzyme has been identified as originating from various fungal species, including *Gaeumannomyces graminis*, *Penicillium* sp., *F. proliferatum*, and *Fusarium oxysporum* (Sugio et al., 2018). Microbial enzymes such as proteases derived from *Bacillus* species, alpha-amylases from *Aspergillus* species, xylanases from *Bacillus*, *Aeromonas*, *Cephalosporium*, and *A. niger*, as well as lipases from *Acinetobacter*, *Aeromonas*, *Bacillus*, *Candida*, *Penicillium*, and *Pseudomonas* species, are commonly employed for uniformity, texture, color, shelf-life, and crispness improvement of bakery goods. Due to

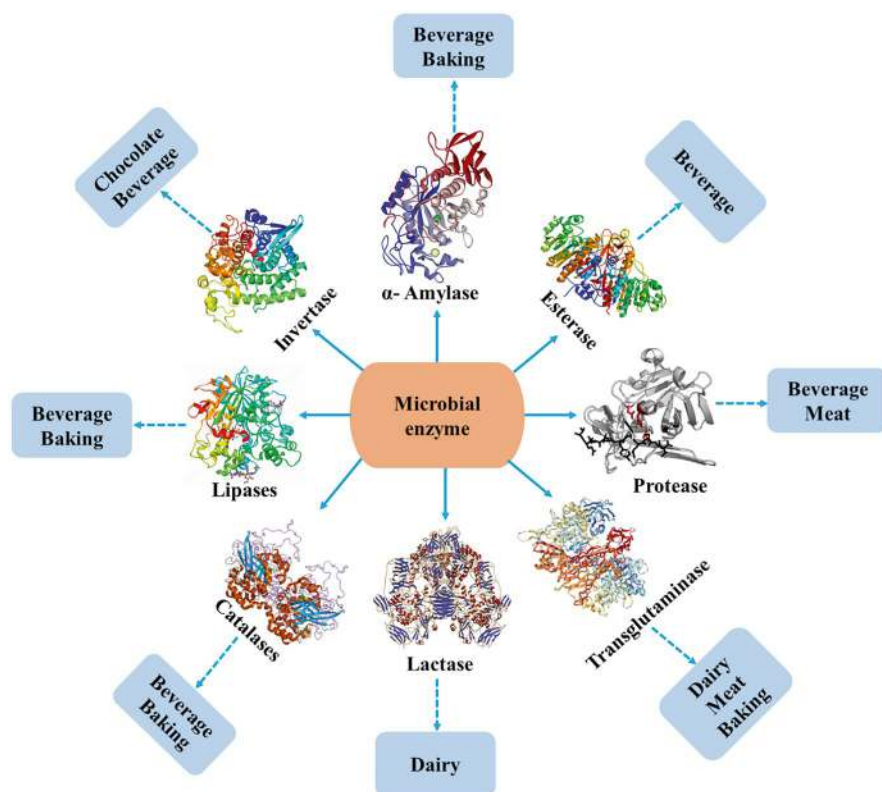


Fig. 13.3 Different enzymes from microbial origin used in the food processing industries

chemical reactions, the enzymes asparaginase and glucose oxidase often stop bad tastes from getting into the result. Microbial phytases cause phenol groups to oxidize and lower the amount of phytates and sticky. This makes bread dough stronger, more stable, and bigger. Transglutaminases (*Physarum polycephalum*) and laccases (*Lenzites*, *betulina*, *Marinomonas mediterranea*) are used to make bread which are free of gluten and extend its keeping quality (Tebben et al., 2018). Classic biotechnological products like bread have been around for a long time. Nevertheless, recombinant enzymes have recently entered the baking industry, serving as bread enhancers and possibly as ingredients sourced from genetically modified (GM) crops. These techniques are also great for improving the quality of fermented foods like leavened bread, as well as for creating new flavors, aromas, and colors (Aggarwal & Kumari, 2024).

5.2 Dairy Industry

Enzymes, which are produced from microorganisms, are widely used in the dairy industry for making cheese, hardening products, extending their shelf life, and changing how they work. Cheese gets its flavor and ripens when triglycerides are broken down in a controlled way. The makeup of the microbial population and the enzymes they make are important parts of how different types of cheese are made (Amer et al., 2023). Proteinases like rennet come from *Rhizomucor pusilus*, *R. meihii*, *Endothia parasitica*, *Aspergillus oryzae*, and *Irpexlactis*, which are used to make cheese. From *R. pusilus*, a protein that helps milk clot has been found. Rennet from both *Mucor miehei* and *Cryphonectria parasitica* is utilized in the dairy industry extensively. Lipolysis of fat present in the milk turning into fatty acids is necessary for taste formation in dairy products. Swiss-style cheese was aided by lipases that were isolated from *Propionibacterium* sp. Since these esterases are lipolytic in nature, they are commonly utilized in the dairy industries to enhanced the flavor of cheeses made from *L. plantarum*, *L. bulgaricus*, *L. lactis*, *L. paracasei*, *L. casei*, and *L. helveticus*. Lipolytic activity is low in *Micrococcus* and *Pediococcus* enzymes as well. Lipid breakdown in milk cheese is helped along by psychrotrophic bacteria like *Pseudomonas fluorescens* (Benkerroum, 2016). Proteolysis by enzymes released by psychrotrophs has been shown to mostly affect K- and β -caseins, whereas α -casein was less affected. Lipases are also used to make different kinds of cheese, such as Camembert cheese, which is made with lipase from *Penicillium camemberti*, and cheddar cheese, which is made with lipase from *Aspergillus niger* or *A. oryzae*. Lipase activation also makes dairy goods last longer before they go bad (Krishna et al., 2021). Bacteriolysins and other antimicrobial enzymes are employed to manage microbial infection. This makes dairy goods safer and extends how long they can stay on the shelf. Catalases, which are thought to come from the family *Bacillus*, are also used to treat milk to get rid of H_2O_2 before making cheese. Galactosidase made from *Kluyveromyces lactis*, *K. fragilis* yeast is usually utilized to break down lactose in whey milk (Pierezan et al., 2022).

Modern biotechnology in milk processing improves shelf life, nutritional value, and safety while maintaining the milk's physical properties. Modern milk production technologies reduce greenhouse gas emissions, alleviate poverty, and meet global demand for milk and milk products (Muhammed Nurye, 2023; Nath et al., 2024). An innovative robotic milking system that Wondatir suggested in 2010 could grasp the milking claws of cows (Wondatir, 2010). Commercial dairy farms in the Netherlands first utilized AMS in the 1990s, and by 2020, 50,000 units had been implemented worldwide (Filho et al., 2020). Automation technologies like membrane processing (ultrafiltration, reverse osmosis, microfiltration, nanofiltration, and electrodialysis), automated spray dryers, inclined film scraped surface heat exchangers, and clean-in-place (CIP) systems reduce labor costs and processing losses. Sonication, often known as ultrasonic processing, is a promising new food industry procedure that could improve milk and other dairy products' technical and functional properties (Muhammed Nurye, 2023).

5.3 Meat Industry

Microbial enzymes are widely utilized in the industry of meat processing. In response to the changes in the market, more attention is being paid to making meat products that are better for you by changing the way raw materials and products are made and using more modern technology. Several proteolytic enzymes are used to break down the proteins in muscle and to break down the proteins in myofibrils and connective tissue in meat and meat products (Arshad et al., 2016). For tenderizing meat, proteases from both fungi (*A. oryzae*) and bacteria (*B. subtilis*) are used. The bacterial proteases like neutral proteases and subtilisin are used a lot in the meat industries because of how specific they are and how low the temperature has to be for them to stop working (Solanki et al., 2021). Alkalophilic *Bacillus* sp. makes enzymes like alkaline elastase, which is used to break down collagen, elastin, and myofibrils. Transglutaminase is another enzyme that comes from microorganisms and is made by *Streptovorticillium mobarence*. It not only helps process food, but it also makes it healthier by adding important amino acids (Heldt-Hansen, 2006).

Biotechnology has introduced genetically enhanced animals, which has revolutionized the meat market. Through genetic selection using the phenotypic performance data of individual animals, the efficiency and quality of meat production have been enhanced. Though selection is already very effective, it can be much more so with the help of cutting-edge biotechnological methods. Transgenic animals can have their genes manipulated in such a way that they produce meat with less fat and cholesterol. Modern biotechnology procedures can now introduce polyunsaturated fatty acids and other beneficial fatty acids to transgenic animals (Wagh et al., 2024).

5.4 Juice Industry

The turgor pressure created by the water content of fruits and vegetables (50–70%) allows for their extraction via hand pressing or mashing with minimal intervention (such as heat or solvents) (Sabillón & Martínez-Monteaudo, 2022). For the dissolution of protopectin or breaking down pectin, pectinolytic enzymes such as pectin esterases, protopectinases, and lyases are employed. Most of these enzymes were found in mushrooms like *Aspergillus niger*, *Penicillium oxalium*, and others. Fruit juices and other beverages have greatly advanced thanks to biotechnology. Current biotechnology has been applied in various ways, such as improving functional fruit juices, enhancing flavor, ensuring long-term preservation, adding value, and modifying enzymes for fruit juice production (Malakar et al., 2020). Figure 13.4 presents the process involve in fruit juice processing industry in association with desire enzymes.

5.5 Soy Sauce Industry

Soy sauce is a prevalent fermented product in Asian cuisine, serving as a seasoning agent with a distinct salty flavor. The substance is produced through a process of fermentation which involves microbes, wheat and soybeans in a saline solution

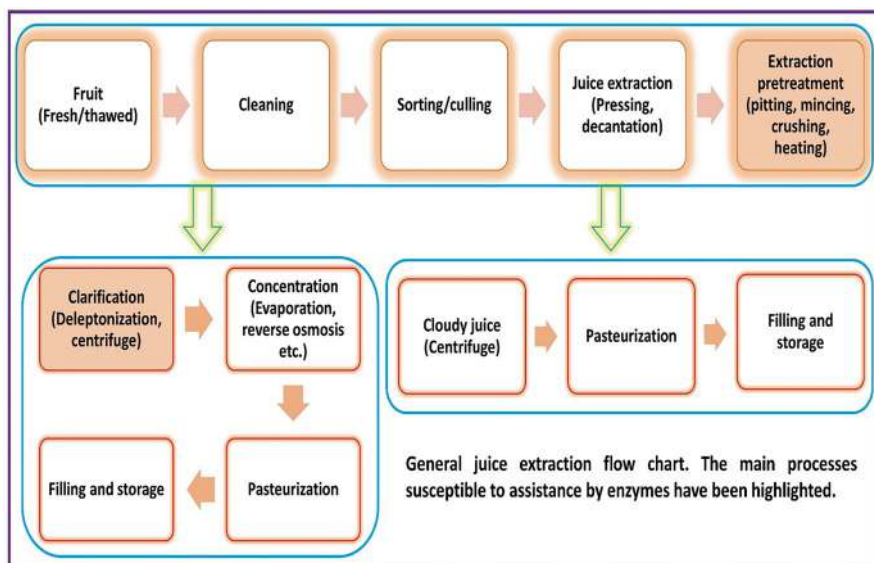


Fig. 13.4 A schematic presentation of different process involve in fruit juice processing industry

(Lioe et al., 2010). The amylase and proteolytic enzymes are employed in the hydrolysis of desiccated soybeans in saline solution for commercial purposes. This leads to a noteworthy reduction in the duration required for brine fermentation (Ahnann-Winarno et al., 2021). The mold *A. oryzae* is capable of producing significant quantities of protease and amylase enzymes following a 48-hour culture period in soybean koji fermentation (Deshpande, 2000). The current constraints in this sector have been attempted to address through genetic engineering techniques like enzyme alteration, mutagenesis, genome shuffling, mixed starter cultures, and microorganisms generating gamma-aminobutyric acid (GABA), among others, as well as through longer fermentation times and higher salt concentrations. The most recent technological developments in soy sauce production, detailing the feedstocks (both traditional and non-traditional), production steps, microbes, and their primary function (Sassi et al., 2021). One example is the use of microbiological engineering to improve the de-browning capabilities of the moromi-found *B. subtilis*, an organism that is useful in the fermentation of soy sauce (Det-udom et al., 2019).

5.6 Beverage Industry

By hydrolyzing and fermenting raw starch, a lot of ethanol, other distilled drinks, and biofuels can be made. Ethyl alcohol is often made from grains and potatoes, which have a lot of starch. But the usual way to turn starch into a liquid is to use strong chemicals like NaOH, CaO, and H₂SO₄, and then heat the mixture (Ohia et al., 2020). The cost of these processes goes up because they need energy to control the temperature and pH. Yeast is the most common organism used to make bioethanol in factories. This is because it is very productive, can handle stress better, and is usually thought to be safe (Vohra et al., 2014). A scientist recently looked at the growth and production of amylases which break down the starch by various species of yeast, called recombinant *Saccharomyces cerevisiae*, and compared it with the support of exogenous α -amylase. The ability of recombinant *S. cerevisiae* to make amylases that break down raw starch to directly process uncooked starch into ethanol or adding enzymes from outside the cell (Cripwell et al., 2020). This kind of combined bioprocess (CBP) for fermenting raw starch will cut energy costs by a large amount. Some excellent origins of thermostable α -amylase-producing microbial species used to break down starch suspensions are *B. licheniformis*, modified types of *E. coli*, and *B. subtilis*. The process of converting sugar fermentation into alcohol is a crucial step in the production of beer. In the process of mashing, enzymes sourced from malted barley act upon the starch present in various grains, resulting in the formation of sugars. The proteases derived from *B. subtilis* are employed in the process of protein solubilization from barley adjuncts, with the ultimate aim of wort production (Tiwari et al., 2015). The formation of haze in beer caused by

proteinaceous substances can also be hydrolyzed by microbial proteases. Barley is widely recognized as the primary grain utilized in the production of beer on a global scale (Jaeger et al., 2021). The lipid content of barley grains varies between 3% and 5% of their dry matter. In brewing and distilling, Lipase is employed for the hydrolysis of barley lipids and to enhance the fragrance (Sachan & Singh, 2015). Biotechnology significantly influences the manufacture of beverages due to its considerable role in innovation. A few instances of how current biotechnology has been utilized in the beverage industry include the development of functional beverages, the enhancement of flavors, the bio-preservation of beverages, the addition of value, and the modification of enzymes for the manufacture of beverages. The advancements that have been made in fermentation biotechnology have resulted in the introduction of a multitude of novel beverages to markets around the world (Malakar et al., 2020).

6 Future Prospects

Since enzymes are natural goods, people always choose them. Enzymes along with additional natural ingredients are increasingly being sought out by businesses as a replacement for chemical additions. This is especially true for food additives and preserves. Using enzymes to make gluten-free food and bread with lots of fiber has worked well. The ingredients of the product in question include glucose syrup and a natural sweetener. The utilization of microorganisms for the synthesis of industrial enzymes is currently being investigated due to their capacity for large-scale production and the concomitant decrease in expenses. Diverse methodologies are currently being utilized to achieve this objective, encompassing the isolation of novel enzymes from microorganisms derived from distinctive environments, genetic modification of microorganisms, rational protein development and engineering of regenerated proteins, controlled evolution to alter enzyme characteristics, and large-scale screening for protein selection. Biotechnology can improve food taste, consistency, and shelf-life. Genetically modified crops and organisms can be used to create scents, tastes, food additives, and other improved products through biotechnology. Biotechnology can boost food production by improving the harvesting index, nutritional and storage value, flavor and basic material production, and vaccine-containing food production. Biotechnology's promise to reduce food production strain could help accomplish future sustainable development goals.

7 Conclusions

Enzymes play an important role in our daily lives. They are the best catalysts because they are highly specific and stable. These tiny machines, which are mostly made of proteins, are the main subject of study around the world, and more and

more work is being done to find, design, and make them for use in industry. In the food and drink businesses, they play a huge part in making processes competitive and cost-effective. Now, the goal is to make enzymes that are better for technology than the ones we have now but do not change the taste or smell of the goods too much. Processes that use the new breed of enzymes will save money because they have qualities that are good for technology. It is hoped that DNA technology will lead to enzymes that can do what is now thought to be impossible. There is still a lot to learn about enzymes that come from microorganisms, and there are many ways they could be used in industry, especially in the food industry. The practical uses of biotechnology combined have resulted in the production of food that is both free from harm and beneficial to the environment. It is necessary to do extra research in the aforementioned field in order to generate processing and production processes that are both more efficient and secure.

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Chapter 14

Recent Developments in Sensory Assessment and Consumer Preference Techniques



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1 Introduction

The FAO/WHO food standards programme defines food security as ensuring that all persons have consistent access to adequate, safe, and nutritious food that fits their dietary needs for an active and healthy lifestyle (Casadei & Albert, 2015). With the world's population predicted to approach ten billion by 2050, improving global food security faces several problems. Sustainable solutions are urgently required to boost agricultural productivity, reduce waste, and promote the development of alternative, sustainable food processing components. Given the increased public interest in sustainable food products, consumer attitudes and acceptance of new sustainable food items or components are critical to their successful implementation and commercialization.

The study of “human sensory perceptions of and affective responses to foods, beverages, and their constituents” is critical in analysing the creation of food preferences and anticipations (Tuorila & Monteleone, 2009). By researching into this topic, we obtain insight into how consumers view sustainable foods and identify the variables that need to be adjusted to increase adoption. Research in this subject has the potential to improve the economic viability of food firms while also contributing to food security, environmental and social sustainability (Fig. 14.1). Such activities help to link the three pillars of sustainability: economic, social, and environmental (Asioli et al., 2020). Food product features may be divided into two categories: internal and extrinsic traits. Intrinsic characteristics are features that cannot be changed without altering the product's physical constitution (Ketelsen et al., 2020).

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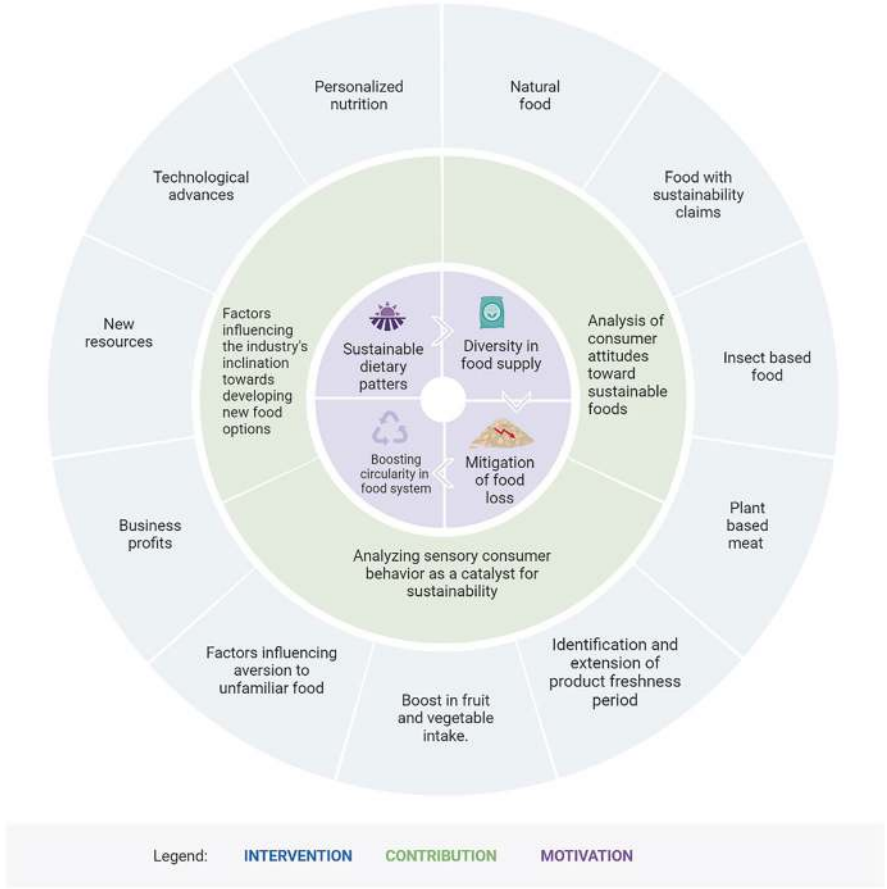


Fig. 14.1 An overview of sensory consumer science research directions that are driving critical changes for sustainable agriculture and food industries

These include sensory qualities (such as flavour, look, and texture), as well as the food’s chemical and physical makeup, such as its constituents (Grunert, 2002). Sensory qualities, which are classified as intrinsic, are also known as experience attributes since customers must directly feel them in order to assess the product. The appraisal of intrinsic qualities is important in customers’ product assessments, impacting their preferences and decisions (Chen & Antonelli, 2020). Extrinsic traits, on the other hand, are product-related aspects that are not inherent in the physical product and may be changed without affecting its core characteristics (Olson & Jacoby, 1972). Extrinsic factors that significantly impact customer decisions include brand, price, package style, and health claims (Lähteenmäki, 2013). While certain extrinsic features, such as price, layout, and brand, may be examined while shopping, others, such as health or sustainability claims, cannot be immediately seen and must be relied on (Fernqvist & Ekelund, 2014). Numerous studies

have shown the importance of interactions between intrinsic and extrinsic qualities in affecting consumer choices (Cardona et al., 2023; De Pelsmaecker et al., 2013; Endrizzi et al., 2015; Fakhreddine & Sánchez, 2023). As a result, research that incorporates both intrinsic and extrinsic aspects provides a more complete knowledge of consumer behavior in real-world purchase and consuming settings.

1.1 Objectives of Sensory Analysis

Sensory tests serve multiple purposes, including understanding consumer preferences, ensuring product quality, guiding product development, identifying trends, and complying with regulations. Sensory tests, also known as sensory evaluations or sensory analyses, have several objectives:

(i) Consumer Preferences and Acceptance

Understanding the sensory preferences and acceptability of a product among consumers is crucial for guiding product development, reformulation, and targeted marketing. Consumer preference and acceptance are integral to the success of any food product (Siró et al., 2008). This objective serves as an essential resource for food scientists, product developers, and researchers interested in comprehending and harnessing consumer preferences and acceptance to create successful food products (Tao et al., 2020).

(ii) Quality Control

Sensory tests are essential for ensuring products meet specific sensory standards, covering taste, texture, aroma, and appearance. Quality control (QC) processes ensure that each sensory test follows uniform procedures, leading to consistent, dependable outcomes. By adhering to strict QC guidelines, the likelihood of errors is reduced, enhancing the accuracy of sensory data. QC guarantees that sensory tests align with established protocols, enabling the comparison of results across various tests and over time. Rigorous QC practices bolster the credibility of sensory testing, fostering trust in the validity and accuracy of findings. QC is indispensable for guaranteeing the precision, reliability, and uniformity of sensory tests, thereby upholding the integrity of sensory data and the credibility of sensory testing practices.

(iii) Product Development

Sensory testing is integral to product development, aiding in the creation of new products or the improvement of existing ones to better align with consumer preferences and enhance sensory attributes. By utilizing sensory testing, developers can gain insights into consumer preferences, ensuring the final product meets desired sensory standards. This process involves refining product formulations through ingredient and processing adjustments to achieve specific sensory characteristics. Additionally, sensory testing identifies the key sensory elements driving consumer acceptance and preference, facilitating informed product decisions. Comparative

sensory analysis assists in determining which product versions consumers prefer, guiding optimization efforts. Overall, product development is a critical component of sensory testing, providing valuable insights into consumer preferences, optimizing formulations, identifying essential attributes, testing new ingredients or techniques, evaluating shelf-life, conducting comparative analysis, shaping marketing strategies, and ensuring regulatory compliance.

(iv) Comparative Analysis

Sensory tests are instrumental in comparing various products, formulations, or versions to identify consumer preferences or determine the optimal quality standard. Comparative analysis is a pivotal component in sensory testing, enabling the identification of superior products or formulations based on consumer preferences, thereby guiding product enhancement efforts. This process is vital for optimizing product formulations, as it involves comparing different versions or ingredients to pinpoint the most favorable sensory attributes. Moreover, comparative analysis yields valuable insights into consumer preferences, which can significantly shape market research and product development strategies. It also facilitates the benchmarking of products against competitors or industry standards, thereby pinpointing areas for improvement. By identifying products that are preferred by consumers, comparative analysis can boost consumer satisfaction and foster loyalty. Additionally, the data derived from comparative analysis is crucial for informing product development, marketing, and sales decision-making. In essence, comparative analysis is an indispensable aspect of sensory testing, playing a pivotal role in product improvement, optimization, market research, benchmarking, consumer satisfaction, decision-making, shelf-life studies, and regulatory compliance.

(v) Market Research

Sensory testing serves as a powerful tool in understanding consumer behavior, including how consumers perceive and react to sensory attributes, packaging, and marketing messages. This testing offers valuable insights into consumer preferences, a crucial element for developing products that resonate with market demands. Moreover, sensory testing plays a pivotal role in creating new products or refining existing ones to align with consumer preferences and enhance sensory attributes. It enables companies to identify emerging trends in consumer preferences, providing the opportunity to innovate and tailor products accordingly. Comparative analysis in sensory testing allows for benchmarking products against competitors or industry standards, offering critical performance insights. Furthermore, sensory testing can bolster marketing and branding efforts by showcasing the unique sensory qualities of a product, making it more enticing to consumers. Understanding the distinct sensory preferences of consumer segments is facilitated by sensory testing, allowing for targeted marketing and product development strategies. Importantly, sensory testing ensures that products align with consumer preferences, fostering consumer satisfaction, and ultimately leading to heightened brand loyalty and repeat purchases. Finally, sensory testing may be necessary to ensure that food products comply with regulations and standards pertaining to sensory attributes.

(vi) Understanding Consumer Segments

The results of these surveys can inform marketing and product development efforts by revealing which demographics of consumers have distinct sensory preferences. Companies can develop and adjust their products based on evolving patterns in consumer preferences shown by sensory assessments. To find out how storage conditions and time affect the sensory qualities and quality of a product, sensory testing can be employed.

Recent developments in neuroscience imply that, contrary to what people may have thought, the majority of people's reactions to food, drink, and packaging are unconscious and connected to the involuntary nerve system (INV) rather than recorded consciously through sensory questionnaires (de Wijk et al., 2014; Gunaratne, 2019). The way people react, accept, and perceive the stimuli tested during sensory assessments are greatly affected by elements including their social background and the assessment environment (Lichters et al., 2021). Therefore, to reduce the possibility of biases that might hinder successful product development in the food and beverage sector, sensory analysis is increasingly having to incorporate participants' physiological and emotional reactions. When it comes to collecting, storing, and analysing data, digital instruments include the gamut of electrical and computational technologies (Saileela & Kalaivani, 2019). A lot of the specifications and data collected by these tools are based on remote sensing or other non-invasive, non-contact techniques like thermal infrared imaging and video. In sensory activities, avoiding touch or intrusive sensors is the main goal of these systems. These cutting-edge methods of data collection and analysis, which make use of computer vision algorithms and remote sensing, also make it possible to automate procedures, which further lessens the bias that comes with human assessors' emotional interpretations (Duran, 2020; Gunaratne, 2019; Viejo et al., 2018). With the use of these methodologies and automated analysis, massive amounts of data can be collected. Then, with the help of machine learning (ML) algorithms, customised models can be developed to understand people's physiological and emotional reactions to different things. These things include their level of liking, their intention to buy, and detailed sensory profiles of food, drink, and packaging. We must stress that the goal of these research and models is not to supplant trained sensory panels or consumers, but rather to incorporate these new models into beverage and food manufacturing processes. Particularly important for packaging is real-time feedback, as sensory panellists may see designs on a screen using holograms and make immediate adjustments depending on their comments. The revolutionary potential of this approach in the food and drink industry has been recently demonstrated by advances in computational technology, which include software, biometrics, and sensor arrays used in sensory analysis of meals. (Kumar et al., 2021). These developments in sensory technology offer attainable solutions for businesses of all sizes to produce and maintain high-quality goods, meeting customer demands for environmentally friendly, socially responsible products. More and more, people are thinking about the moral and ecological consequences of the food and drink industry, including how it treats animals. These factors can influence their emotional and physiological

responses to items, which can be detected and studied by biometric data-based technological devices. The COVID-19 epidemic has shown that these technological advancements may help with sensory evaluation, which in turn helps with product development and testing even when lockdown levels and social distance norms are changing (Viejo et al., 2021). Sensory techniques are continually growing and developing. The integration of computer technology to enhance the interaction between panelists/consumers and their sensory experiences contributes to this expansion of methods. At the same time, conventional approaches offer fundamental outcomes, establishing a dependable and enduring foundation. Therefore, this chapter primarily addresses recent advancements in digital technologies utilized for data acquisition and analysis, along with basic categories of sensory tests available and practical application examples of the widespread self-reported methodologies. Additionally, it suggests how integrating these technologies with artificial intelligence (AI) could streamline product development and adjustments, offering vital insights to primary product producers for tailoring products to meet varying consumer preferences.

2 Sensory Methods: Difference Methods, Descriptive Methods, and Affective Methods

2.1 Difference Tests

It also known as discrimination tests, are sensory analytical tests designed to determine if there is a notable difference among two or more specimens. The outcomes of these tests can be smoothly interpreted by consulting established importance charts determined on the binomial distribution (Lawless & Heymann, 2010). Important discrimination tests contains: Paired comparison, Duo-tio, Triangle tests, A not A, The updated tetrad test (Drake, 2007). Additionally, there are various tests with important findings (Lawless & Heymann, 2010). The quantity of clients or participants required for these tests varies (from 20 to more than 100) depending on the selected test and the desired level of power (or the ability to detect a difference) (Ennis & Jesionka, 2011). Clients are provided programmed goods and requested to perform certain activities, such as selecting a different sample in a triangle test, choosing the sample that matches a coded reference in a duo-trio test, selecting the sample that exhibits a specific attribute more or to a higher degree in a paired comparison, choosing the specimen that is labeled “A” or “not A” in an A not A test, or sorting the specimen into two pairs in a tetrad test. These tests are relatively simple to set up and analyze (Table 14.1). However, it is crucial to remember the purpose is limited: to determine if a difference exists between two samples. They should not be used for more complicated sensory goals, such as assessing the type or extent of discrepancies, or determining liking or preference. Difference tests are commonly involved in assurance of quality for evaluating changes in different providers or

Table 14.1 Examples of basic sensory evaluation methods used evaluate various foods

S. No	Name of the test	Type of test	Questions	References
1	Discrimination test: 1. Triangle 2. Duo-trio 3. Two out of five	Analytical test	1. Identify the sample that differs from the others 2. Determine which sample deviates from the referred specimen 3. Which 3 specimens share the typical characteristics?	Świąder and Marczevska (2021)
2	Grading test: 1. Paired comparison test 2. Ranking test 3. Scoring test	Analytical test	1. Which sample exhibits the highest level of (sweetness, bitterness)? 2. Arrange the samples from least to greatest intensity for the specified attribute (sweetness, bitterness) 3. How would you rate the (sweetness, bitterness) of the sample?	Tuorila and Monteleone (2009)
3	Descriptive test: 1. Quantitative descriptive analysis 2. Flavor profile 3. Texture profile 4. Spectrum descriptive analysis 5. Free-choice profiling	Analytical test	Do the food products exhibit variations, and if so, what are the distinctions between them?	Stone et al. (2020)
4	Paired comparison test	Affective test	1. Which option do you favor? 2. Which option is your top choice?	Świąder and Marczevska (2021)
5	Ranking test	Affective test	Rank the products based on your preference, with the most favored product listed first and the least favored product listed last?	Lawless and Heymann (2010)
6	Hedonic scoring test	Affective test	Rate the level of enjoyment or satisfaction derived from products on a scale?	Resurreccion and Resurreccion (1998)

methods, and they can also be applied to specific research objectives (Schiano et al., 2017).

2.1.1 Threshold Tests

The threshold is a specific level of concentration at which the typical human can perceive a signal. There are a variety of thresholds, including.

- (i) Recognition Threshold: This refers to the lowest intensity that allows the trigger to be detected.
- (ii) Difference Threshold: This refers to the difference in range needed for a noticeable value change to be detected.
- (iii) Detection or Absolute Threshold: This is the minimum triggers intensity able of eliciting a result.
- (iv) Terminal Threshold: This refers to the concentration at which no further notable change in response occurs.

These thresholds are essential concepts in sensory analysis and are often used to understand human sensory perception and response (Lawless & Heymann, 2010). Among the specific thresholds, A threshold for detection is most used in food science studies. Thresholds can be difficult to manage in practice. Threshold tests require significant manpower and resources to carry out. Moreover, thresholds can differ significantly from person to person, including professional judges. Additionally, the parameters under which thresholds are established can also impact responses. For instance, factors like temperature and headspace height can affect Ortho nasal thresholds, as can the explicit directions be given to the participants. For a reproducible result, it's crucial to pay close attention to experimental control and ensure an appropriate number of panelists. Depending on whether consumers or trained panelists are used, the number of panelists can vary, but typically, a range of 40–80 is recommended. Multiple approaches can be utilized to establish thresholds (Jesteadt, 1980). However, the most widely recognized method for determining thresholds remains the ascending forced-choice technique of limits is standardized by the American Society of Testing and Materials.

The method involves a series of 5 or 7 ascending range triangle tests. Each participant tastes or sniffs each series of 3 specimens and then must select the specimen with a signal, even if making a guess. Individual thresholds are then analyzed, followed by the total of a group geometric mean (Lawless & Heymann, 2010). This geometric mean is then considered the best estimate threshold (Table 14.1). In practice, thresholds can be explored to understand the impact of changes in matrix on flavor perception (Leksrisompong et al., 2010) and to determine detection limits of both desirable and undesirable odorants and tastings (Wright et al., 2006).

2.2 Descriptive Tests

The distinction between quantitative and qualitative research lies in the method of data measurement: quantitative research is based on numerical data, while qualitative research focuses on non-numerical data. Contrary to quantitative consumer investigation, which demands a scale and statistical application, qualitative information arises from witnessed conduct, verbal reactions, and diverse recordings (scripted, auditory, and visual) procured by a proficient researcher (Drake, 2007). While established quantitative approaches are effective in identifying statistical

trends in customer responses, they frequently fail to capture consumers' sophisticated internal conversation about their alterations, viewpoints, convictions, conduct, and inclinations. Qualitative investigation is purposefully crafted to delve into the origins of this phenomenon, which might encompass a consumer's conflicting priorities and a lack of comprehension.

2.2.1 Ethnography

Ethnography is a qualitative approach that includes observing customers in their native cultural situations. In sensory and consumer investigation, this typically involves observing individuals in their residences, supermarkets, eateries, or any other site where food-related actions and product utilization are anticipated. In an observational ethnography conducted by, researchers assumed the role of a regular consumer in numerous coffee shops. Their aim was to observe and analyze patterns of consumer purchasing behaviors, demographic trends, the ambiance of the coffee houses, the duration of consumer visits, and overall consumer activities within the coffee shop environment. The purpose of this ethnography was to compile a comprehensive database of attributes for subsequent utilization in a follow-up conjoint survey. Ethnography, when integrated with quantitative methods, can serve various purposes: gathering preliminary information prior to quantitative analysis, supplementing quantitative results concurrently, or conducting in-depth investigations post-quantitative to explore identified concepts further. (Meyer & Simons, 2021) demonstrated a unique anthropological method, merging thorough dialogues (TDs), observations, assignments, and store excursions throughout a 9-month duration to acquire a comprehensive comprehension of the buying and usage tendencies of six environmentally aware households.

2.2.2 In Depth Interviews

Morgan et al. define a focus group as a research method where data is collected through facilitated discussions in groups overseen by an observer and a structured discussion framework (Morgan et al., 1998). It is a commonly used qualitative research tool. It is recommended to involve 6–8 adult participants; however, this number may vary depending on the study's specific objectives or structure. (Krueger, 2014) found a growing preference for shorter focus groups (3–6 people) as members may feel more comfortable expressing their ideas in a more intimate setting. Focus groups are often used to develop new products to evaluate customer responses and adoption of new products, advertising messages, and packaging designs (David, 2007). They are also useful for analyzing consumer behavior, expectations, and product usage patterns. The overall count of focus assemblies on a particular subject may differ based on the research objectives and requisites. Focus groups have been used to study how consumers think regarding environmentally friendly food items (Ulvila et al., 2009), the eating habits of kids (Ishak et al., 2013), high protein eating

habits with older people, the awareness about natural foods (Zepeda et al., 2006), consumer comprehension of dairy processing procedures (Schiano & Drake, 2021) and customer views regarding the ginseng plant food products (Chung et al., 2011). Conversations, alternatively identified as In-Depth Conversations (IDCs), are an effective instrument for obtaining qualitative data. They can utilize a comparable question format as focus assemblies or delve deeper into individuals' sentiments and ideals. The Means-End Chain (MEC) methodology, a qualitative exploration tactic customarily employed in conversations, aims to uncover consumer sentiments and principles that propel decision-making. In a laddering discussion, a sequence of inquiries are employed, frequently commencing with the query "Why is that significant to you?" and continuing until the fundamental value to the consumer is revealed, hence discovering connections between outcomes MEC discussions can be utilized to ascertain consumer inclinations.

2.3 *Affective Sensory Tests*

In the end, the success of a product in the marketplace depends on consumer preference and the consequent recurring acquisitions made by consumers. For a product to be repurchased, it must meet consumer expectations and be enjoyed by them. This is why researchers focusing on perception and consumer behavior must concentrate their efforts on understanding both the perceptual aspects and the consumer's enjoyment of a product from the consumer's perspective (Worch et al., 2012). The typical guideline for quantitative assessments is a minimum of 75–80 individuals for 1 or 2 cases; additional individuals are necessary if there are more than 2 cases. (Table 14.1). Although fewer customers can be employed in qualitative examinations, a substantial sample size is indispensable when extrapolating consumer preferences. Affective sensory tests assess the emotional or affective response of consumers to a product. Here are some examples:

2.3.1 **Preference Tests**

This involves presenting participants with multiple options and asking them to rank or rate the options based on their preference. For example, asking participants to rank different flavors of ice cream in order of their preference (Yeomans et al., 2008). Preference tests are crucial in sensory analysis for several reasons. Firstly, they allow manufacturers to understand consumer preferences and therefore cater products to meet market demand. This insight can inform product development, marketing strategies, and overall business strategy (Lawless & Heymann, 2010). Secondly, preference tests can be used to evaluate the sensory characteristics of a product, such as taste, appearance, and texture, and determine which elements are most important to consumers. Finally, preference tests can help identify and quantify differences between products, which is particularly important in areas such as

food and beverage, where slight variations can significantly affect consumer perception.

2.3.2 Acceptability Tests

This involves presenting participants with a single product and asking them to indicate whether they find it acceptable or not. For example, asking participants to rate their level of acceptability of a new salad dressing (Henriques et al., 2009). Acceptability tests are crucial in sensory analysis for multiple reasons. First, they offer manufacturers valuable insights into a product's overall acceptability, ensuring consumer satisfaction and encouraging repeat purchases (Drake, 2007). Second, such tests can detect any potential product issues, like off-flavors or undesired attributes, prompting necessary adjustments. Lastly, acceptability tests aid in product optimization and development by comparing different versions and determining consumer preferences (Mennella et al., 2016).

2.3.3 Hedonic Scaling

This involves asking participants to rate a product on a scale ranging from 'dislike extremely' to 'like extremely'. For example, asking participants to rate their level of enjoyment of a new brand of coffee. Hedonic scaling is an essential technique in sensory analysis for several reasons. For initial reasons, it enables researchers and producers to assess consumers' emotional reactions to a product's helpful information while creating and marketing items (Van Kleef et al., 2005). Second, it gives information about a product's general liking or dislike, which may be used for product optimization and development decisions (Giacalone, 2018). Finally, hedonic scaling can compare various product variants to decide which one a buyer prefers (Ginon et al., 2014).

2.3.4 Emotion-Based Tests

This involves assessing the emotional response of participants to a product. For example, asking participants to describe how they feel about a new type of chocolate bar (Boothby et al., 2014). Emotion-based assessments are useful in sensory analysis for several reasons. To begin, they give insight into customers' emotional responses to a product, which is a crucial factor in total consumer happiness and repeat purchases (Oliver, 2014). Furthermore, emotion-based testing may assist uncover the emotions connected with a product, which can then be used to guide marketing tactics and branding decisions (Babayev, 2018). Finally, emotion-based testing may be used to evaluate several versions of a product and discover which one generates the most favorable emotional reaction from customers (Tuerlan et al., 2021).

2.3.5 Motivation-Based Tests

This involves assessing the level of motivation participants have towards a product. For example, asking participants to rate their level of motivation to buy a new brand of toothpaste (Krystallis, 2015). Motivation-based assessments are useful in sensory analysis for a variety of reasons. For instance, they assist researchers in determining the amount of motivation that customers have for a product, which might impact their purchase decisions and overall happiness with it (Alba & Williams, 2013). Additionally, motivation-based assessments can give useful information about the elements that influence customer behaviors and purchase patterns (Guo et al., 2020). Ultimately, motivation-based testing may be used to evaluate multiple product versions and decide which one generates the most positive motivation from customers.

2.3.6 Conjoint Analysis

This involves presenting participants with a series of product attributes and asking them to indicate their preferences. For example, asking participants to choose between different combinations of price, flavor, and packaging for a new type of snack (Letona et al., 2014). Conjoint analysis is helpful in sensory analysis for a variety of reasons. For starters, it enables researchers to understand better how customers balance various product qualities while making purchase decisions (Skwara, 2023). This information is critical for product optimization and development since it allows producers to discover the most essential features that matter to consumers (Veryzer & Borja de Mozota, 2005). Second, conjoint analysis may forecast consumer preferences for new product concepts, influencing product design and marketing tactics (Sylcott et al., 2016). Finally, conjoint analysis may assist firms in comprehending how changes in product features, such as pricing or packaging, affect consumer preferences (Wang et al., 2022).

3 Recent Developments in Digital Technologies to Evaluate Quality and Consumer Preferences

3.1 Sensory Software

Due to the limitations associated with traditional sensory sessions, such as the need for physical materials and resultant waste, cumbersome paperwork, time-intensive data processing, and significant storage space requirements, there arose a necessity for the development of computer software to address these challenges. Various software solutions have been developed, each offering distinct advantages (Table 14.2). For instance, Compusense®, RedJade, Fizz Software, SIMS 2000 Software, and EyeQuestion® are among the commonly used commercial packages (Fuentes et al.,

Table 14.2 Applications utilizing computer vision, electronic sensors, and robotics in sensory research studies

S. No	Objectives	Techniques	References
1	Introduce an innovative virtual sensory system for analyzing coffee labels, employing video conferencing, self-reporting, and biometric evaluation software uses video records to collect sensory and mental reactions	Computer vision and virtual reality	Gonzalez Viejo et al. (2021)
2	A robotic system for sorting fruits by color and size within a packaging setup	Robotics and computer vision	Özdoğan et al. (2021)
3	a hybrid system based only on color changes in the bread crust to identify and categorize the various stages of bread baking	Machine learning and computer vision	da Silva et al. (2021)
4	Construct a remote sensory evaluation of beer quality by comparing standard emotional responses derived from affective images with biometric data and visual perception used to assess foamability	Computer vision and machine learning	Viejo et al. (2022)
5	Evaluating consumers' implicit and self-reported emotional reactions to different insect-based food samples can help understand how cultural backgrounds impact consumers' emotional responses	Bio-metric analysis and computer visions	Fuentes et al. (2020)
6	Using machine learning modelling and an electronic nose, develop a tool to predict beer aromas	A printed circuit board (PCB) containing processing electronics tailored to accommodate an array of nine sensors capable of detecting various gases. The data from the electronic nose (e-nose) were utilized as inputs to develop two artificial neural network (ANN) algorithms	Viejo et al. (2020)

(continued)

Table 14.2 (continued)

S. No	Objectives	Techniques	References
7	Utilizing eye-tracking technology to gather data, determine whether people in front of a virtual reality (VR) shop shelf or a physical supermarket shelf make decisions and process information similarly	Technologies integrating virtual reality and eye-tracking	Siegrist et al. (2019)
8	Provide a video camera-based, non-invasive method of monitoring heart rate reactions to taste stimuli	Utilize a video camera to capture consumers' facial expressions alongside electrocardiographic electrodes and electrode plethysmograph signals from images	Mohamed et al. (2020)
9	The study employed an electronic nose (e-nose) and machine learning (ML) method to assess the flavor acceptability of yogurt	Electronic nose (e-nose) alongside Back Propagation Neural Network (BPNN) and Random Forest (RF) models	Tian et al. (2020)
10	Utilizing contemporary AI techniques and analyzing brain waves to explore the correlation with gustatory sensations	Electroencephalography (EEG) sensors	Warnakulasooriya et al. (2020)
11	Determine the freshness of spinach	Digital imagery combined with machine learning techniques	Koyama et al. (2021)
12	This research describes a sensory analysis method that uses face expression recognition, galvanic skin reaction, and cardiac pulse to determine customer acceptability of food samples	The infrared imaging camera and depth sensor were integrated into a single device. The volunteers all had a sensor attached to their middle and ring fingers. And a device, which measures heart pulse and galvanic skin response was, on the other hand, attached to the index finger	Álvarez-Pato et al. (2020)

2018). These web-based applications facilitate the display of forms encompassing diverse sensory tests and scales, along with functionalities for panelist recruitment, experimental design, demographic reporting, result analysis, and interpretation. A newer advancement in software engineering is the BioSensory platform, crafted for Android tablets by The University of Melbourne. This innovative tool not only showcases sensory surveys but also records participants' video inputs for later scrutiny, extracting biometric data including emotional and physiological reactions via computer vision algorithms and machine learning (ML) methodologies (Fuentes

et al., 2018). Moreover, custom software solutions such as SensInspect™ Sensory Assessment Platform by Aroxa and TimeMonitor© by INRAE address distinct needs such as detailed sensory examination in manufacturing facilities and temporal dominance of sensation (TDS) assessments, respectively, facilitating the creation of surveys and electronic participant feedback for subsequent scrutiny (Visalli et al., 2011). Despite their utility, some of these software solutions may pose financial challenges, particularly for smaller enterprises. For instance, Compusense® has found applications in the beverage and food industries, as demonstrated by studies assessing mouthfeel and texture of red wines, consumer preferences for potatoes, and acceptability of sesame oil and chocolate samples (Kemp et al., 2019; Sharma et al., 2020; Yin et al., 2020). Similarly, RedJade has been utilized for evaluating sensory descriptors of soft-serve ice cream and chocolate products, while the BioSensory App has been instrumental in gauging the reception of consumers toward food items derived from insects, lentils supplemented with silicon, and various beer (Adhikari et al., 2020; Fuentes et al., 2020; Kong et al., 2020). Remarkably, the recent global health crisis has spurred the heightened utilization of digital tools for remote sensory sessions. Gonzalez Viejo et al., proposed a technique utilizing Zoom and Google Forms for remote sensory assessment of coffee labels, enabling participant engagement while capturing subconscious responses through biometrics (Gonzalez Viejo et al., 2021). While commercial software may offer similar functionalities, they often lack real-time supervision of participants and may be financially prohibitive for smaller entities.

3.2 *Biometrics*

Biometrics in sensory and consumer science encompasses various techniques, including face recognition, body temperature, retina scanning, and voice recognition, among others, utilized to perceive distinctive behavioral, cognitive and physiological characteristics in humans and animals (Jain et al., 2007). These methods have been employed in sensory science to elicit subconscious and emotional responses from consumers, particularly tapping into the autonomic nervous system (Table 14.2). Furthermore, physiological measurements have been combined with participant-provided feedback in sensory perception tests to assess both immediate reactions and conscious responses post-choice.

Prevalent biometric indicators used to evaluate physiological shifts comprise electrodermal activity and pulse rate or dermal temperature, galvanic skin response, and affective states. A variety of techniques are employed to gauge these criteria, classified into direct and indirect methodologies. Direct methods are predominantly used, although they may induce stress in individuals due to their invasive nature. To reduce bias, researchers have devised remote sensing techniques, such as computer vision analysis, to gauge physiological responses like heart rate (HR) and vascular pressure (VP) through visual inspection (Viejo et al., 2018).

For example, Alvarez-Pato et al. used a Neulog NUL-217 finger sensor to detect galvanic skin reaction and a sensor to monitor participants' heart rates while evaluating gelatin with various flavors (Álvarez-Pato et al., 2020). Samant and Seo used a Shimmer™ sensor (Shimmer, Dublin, Ireland) on participants' fingers to measure heart rate and skin conductance, and an eSense sensor (Mindfield Biosystems Ltd., Gronau, Germany) on their palms to assess skin temperature (Samant & Seo, 2020). Lagast et al. used 8 mm Ag/AgCl sensors to measure electrodermal responses and two sensors affixed to people's wrists to measure heart rate, all of which were connected to the Micromed System Plus Headbox (Micromed, Mogliano, Italy) to assess people's reactions to foods (Lagast et al., 2020). Thermal infrared cameras, such as the FLIR®, have long been employed in sensory research as non-invasive, remote ways for assessing skin temperature (Fuentes et al., 2018). Emotional reaction facial expression analysis relies on software that can analyse films of individuals assessing stimuli. Facial feature detection tools such as FaceReader™, Affectiva, and iMotions use ML modelling to infer emotional values (McDuff et al., 2016). The exploration of facial gestures is a contemporary sensory approach that has garnered significant attention from researchers (de Wijk et al., 2021; Li & Jia, 2020; Mehta et al., 2021). When individuals encounter stimuli, they often involuntarily display emotions through facial movements. This process acts as a route for the subconscious manifestation of feelings, a channel that researchers exploit to understand affective states. Despite its historical use by mental health professionals, this method is gaining traction among sensory researchers owing to the incorporation of mechanized frameworks for rapid analysis of these reactions. Emotional reactions have been employed to evaluate consumers' emotional reactions to various products such as chocolate (Mahieu et al., 2019), beers (Viejo et al., 2019; Wakihiro et al., 2022) sports drinks (Mehta et al., 2021), meat products (Torricco et al., 2018b), yogurt (Gupta et al., 2021). Although results fluctuated depending on the product category, initial observations suggest that facial reactions to food items are more receptive to adverse sentiments, like 'revulsion,' compared to favorable sentiments (Torricco et al., 2018a).

3.3 *E-tongue and E-nose*

Analytical assessment, a conventional method for appraising food and beverage commodities despite its efficacy, has been recognized for its laborious character, demanding thorough panel instruction for uniformity (Lawless & Heymann, 2010). Consequently, scientists have delved into alternative approaches to acquire sensory information, like the electronic palate (E-tongue), which evaluates primary flavors employing electrical receptors. The chemical receptors in the E-tongue, encompassing bio-detectors and electro-analytical tools, interact with analytes, producing

electronic impulses for pattern recognition and categorization. (Table 14.2). Nonetheless, obstacles like sensor longevity, time investment, and sample size prerequisites for validation and training persistence.

Similarly, the electronic nose (E-nose) has been developed to mimic the olfactory sense, specializing in odorant compounds (Nayak et al., 2020). Equipped with built-in software and algorithms, the E-nose links flavor components with recognized aromas from edibles, offering a cost-effective and rapid alternative to traditional gas analytical equipment. Widely employed for quality and flavor assessment across various products (Haddi et al., 2014; Li et al., 2022; Liu et al., 2022; Zhu et al., 2022), E-noses and E-tongues provide objective analyses, although they cannot entirely replicate human perceptions (Jung et al., 2017). Challenges such as sensitivity to environmental factors and the need for extensive training and validation samples persist, but coupling sensor data with artificial intelligence shows promise in enhancing sensory predictions. To facilitate standardization and training, there's a need for a shared online library for E-noses and E-tongues, compiling data from diverse laboratories worldwide. E-noses typically comprise metal oxide semiconductor sensors or conductive polymers, while E-tongues utilize electrochemical or optical (Podražka et al., 2017; Schweder & Neubauer, 2005), aiming to provide more objective analyses compared to human sensory evaluation, which can be influenced by memory recall (Kuswandi & Siddiqui, 2020). Various studies have demonstrated the effectiveness of these methods in assessing sensory characteristics across food and beverage categories. For instance, Štefániková et al., utilized a GC assisted electronic nose to estimate aroma, achieving significant differences compared to sensory analysis of cheese samples (Štefániková et al., 2020). Nomura et al., assessed banana juice aroma using an E-nose with promising results (Nomura et al., 2021). Farahmand et al., utilized an electronic nose to supplement the sensory analysis for evaluating the aroma of sourdough (Farahmand et al., 2021). Additionally, Gonzalez Viejo and Fuentes crafted an affordable digital olfaction system for assessing volatile compounds in beer, forecasting consumer approval through machine learning algorithms (Gonzalez Viejo & Fuentes, 2020). Within the domain of electronic taste sensors, Fukushima et al., distinguished between flavor enhancers and salts by employing an impedimetric electronic taste sensors (Fukushima et al., 2020). Paup et al., detected spicy compounds as a potential method for assessing spicy foods (Paup et al., 2019). Nery and Kubota successfully discriminated between beer and wine samples using a paper-based potentiometric E-tongue (Nery & Kubota, 2016). Despite their effectiveness, commercial development of paper-based E-tongues remains limited. Beyond food, E-tongues have found applications in medicine taste evaluation, providing a safer and more reliable analysis method.

3.4 *Computer Vision and Robotics*

Robotics and computer vision (CV) for automated analysis to evaluate food quality criteria are two of the many AI-driven methods that have recently emerged. Machine learning (ML) algorithms examine a wide range of data sources, such as videos and photographs, to ascertain the product's quality based on predetermined metrics (Dewi et al., 2020; Kakani et al., 2020; Xu, 2019). The CV process comprises three main steps: acquisition, pre-processing, and analysis and interpretation (Table 14.2). Acquisition necessitates a camera or scanner with uniform lighting, while pre-processing and analysis entail software equipped with image analysis capabilities like Matlab®, ImageJ®, or Image-Pro Plus (Solem, 2012; Marques, 2011). Specific algorithms are tailored to the visual assessment's nature and parameters, encompassing image enhancement, segmentation, recognition, and interpretation (Sarangi et al., 2014; Sun, 2000; Vala & Baxi, 2013). In the beer sector, robotic advancements have led to the creation of robotic beer dispensers equipped with servo motors for tap control and infrared temperature sensors for quality prediction (Peano, 2018). Additionally, automated pourers like RoboBEER, constructed using LEGO® blocks and servo motors, employ computer vision and ML to estimate beer superior using shade and foam-related metrics (Gonzalez Viejo et al., 2016, 2019). In the domain of non-alcoholic beverages, robots have been created for manufacturing and delivery reasons. Noteworthy examples include tea brewing machines designed for specific brewing times and water temperatures, such as Teforia and TeaBOT (Kayaalp et al., 2018). These developments underscore the growing role of computer vision (CV) in automated quality assessment across various industries. CV techniques, a subset of AI, extract information from images or videos akin to human visual perception (Awwad et al., 2019). When coupled with robotics, specific algorithms, and machine learning, CV enables stand-alone automation for product quality classification or prediction. Advantages of CV include non-destructiveness, reproducibility, and enhanced accuracy compared to traditional methods such as visual inspection and sensory analysis (Gill et al., 2011; Wu & Sun, 2013).

In recent years, researchers are examining the impact of remote, extended, or mixed reality technologies on Market Recognition Study by letting people test foods and drinks in different environments. Wearing a virtual reality (VR) headset blocks out the outside world and replaces it with a computer-generated, three-dimensional movie or image. Virtual reality (VR) allows people to try out different foods and drinks in simulated environments for the purpose of sensory assessment. By contrast, augmented reality (AR) makes use of goggles, headsets, or the displays of mobile devices to superimpose digital pictures or data onto the actual world, letting users see what they're evaluating. In mixed reality, users don augmented reality goggles that may display a virtual reality environment complete with real-life features, such as the samples being gathered or the users' own hands and arms. As a result, you'll feel like you're really there, and it'll be more immersive than virtual reality. To test how well people tolerate sucrose in different environments, (Torricco et al., 2021) set up a virtual reality sensory encounter in a forest and an old room,

respectively. How shoppers make decisions in a real-life supermarket aisle compared to a virtual reality (3D) store display was studied by (Siegrist et al., 2019). Virtual reality (VR) scenarios, such as a explore to a Portuguese sea shore town and a loud performance, were used by Kong et al. to assess consumer acceptability of cocoa items.[70]. Similarly, augmented reality has been utilized; for example (Ueda et al., 2020), used it to change the brightness of food products in order to gauge customer attitudes and intents. An analogous study by (Korsgaard et al., 2019) used a mixed reality design to find the effective simulated surroundings for older people with mobility issues to eat alone. Considering that context affects customers' emotional reactions to food stimuli, a recent study by Low et al. investigated how snacking makes them feel in different environments, such as stalls, a café, and a mixed reality simulation. The results indicate that mixed reality could be a useful tool for conducting sensory sessions in a variety of settings. While virtual reality (VR) has many promising applications, there are still some concerns about the intrusiveness of headgear and the possibility of bias in reactions caused by them, similar to biometric sensors. Despite being fully absorbed in virtual reality; participants frequently experience pain and anxiety due to their awareness of wearing the headset. Miniaturization should be the primary goal of future virtual reality headset improvements in order to minimize invasiveness, similar to augmented reality and mixed reality glasses/headsets.

4 Contemporary Research Areas in Sensory Consumer Science Focusing on Sustainability Aspects

4.1 *Natural Foods*

The selection of natural foods or natural food is often advocated as a sustainable consumer choice. Extensive research has delved into consumer responses to natural foods, particularly concerning sensory expectations and perception. Various researches consistently indicate that consumers typically hold favorable expectations toward natural food a phenomenon termed the 'natural halo (Ellison et al., 2016; Lee et al., 2013; Prada et al., 2017) Numerous investigations also demonstrate that this positive perception extends to sensory expectations and evaluations (Apaolaza et al., 2017; Bernard & Liu, 2017). Even when blind-testing reveals sensory perceptions that do not align with expectations, the favorable attitude toward natural food persists (de Andrade Silva et al., 2017). Factors associated with favorable expectations toward natural food include pro-natural attitudes, environmental concerns and frequency of natural food consumption (Bernard & Liu, 2017; Prada et al., 2017). An investigation suggests that individuals with more medical risks may be less susceptible to the halo effect (Apaolaza et al., 2017). Additionally, the halo effect may vary regardless on the scenario the natural item belongs to a 'vice' or 'virtue' food category (e.g., indulgent, or healthy food). A limited number of studies

indicate that the halo effect could also cause unfavorable perceptions, such as lesser expectations regarding taste and nutritional value (Schuldt & Hannahan, 2013).

4.2 Insect Based Foods

A further factor that helps consumers accept insects as a food source is their ability to anticipate and evaluate their sensory experiences. While a number of research dove into particulars such anticipated flavour (Palmieri et al., 2019; Sogari et al., 2019). In addition, Bartkowicz et al. looked at sensory features, which are specific insect-based goods that people tasted while they were surveying (Bartkowicz & Babicz-Zielinska, 2020). In their investigation of the role of general sensory expectations, Palmieri et al. found that they had a favourable effect on the acceptability of insect-based diets. The research aimed to assess how people felt about the flavour and look of dishes made from insects, and then averaged those feelings (Palmieri et al., 2019). One unfavourable effect was identified by Cicatiello et al., who discovered that people avoid eating insects because of their unpleasant taste (Cicatiello et al., 2020). On the other hand, Tuccillo et al. found a positive effect, suggesting that people could be more likely to eat insects if they liked the taste of them (Tuccillo et al., 2020). Also, whereas Americans, Spaniards, and Australians did not notice a detrimental effect, Castro and Chambers discovered one for British respondents. According to research by Wilkinson et al., who looked at the impact of anticipated flavour on various customer groups, “insect eating consumers” are particularly sensitive to this factor (Wilkinson et al., 2018). Yet, research showed that different measures of food quality were used. The researchers Bartkowicz and Babicz-Zielińska found that the acceptability of several insect-based protein bars was affected by factors such as flavour and fragrance, as well as texture and appearance (Bartkowicz & Babicz-Zielinska, 2020). Similarly, mealworm product intake was favourably affected by both anticipated and actual flavour, according to (Tan et al., 2017). While most research have looked at people’s eating habits in general, others have zeroed in on people’s preferences when it comes to meat. Separating meat eaters from vegetarians and vegans, the research examined meat intake generally.

Several research have investigated the possibility that dietary habits influence the likelihood that people would eat dishes made from insects. According to one research, general dietary habits have a detrimental impact on the adoption of insect-based meals, although several investigations have revealed no substantial effects of overall diet on this matter (Van Thielen et al., 2019). Grasso et al. and Naranjo-Guevara et al. both used participants’ use of animal products to divide their diets into two categories: those who restrict their meat intake and those who do not. Schlup and Brunner examined weekly and monthly trends of meat intake, whereas Schäufele et al. distinguished between meat eaters and non-meat eaters. On the other hand, Van Thielen et al. only counted how often people ate meat and divided it into two groups: daily eaters and others. The adoption of insect-based meals has been the subject of further research, which has shown both positive and negative

consequences related to certain dietary preferences (Berger & Wyss, 2020; Kane & Dermiki, 2022; Orsi et al., 2019). It would seem from the reviewed literature that being vegetarian does not automatically make people more tolerant of eating insects. Ethnic restaurant visits, experience with unusual foods like raw fish or offal, a preference for variety, and a rational approach to food consumption were also found to positively impact acceptance of insects as food, according to dietary patterns (Modlinska et al., 2020; Verneau et al., 2020).

4.3 Plant Based Meat Analogues

Customers' pre-consumption expectations are greatly influenced by a product's visual presentation. A disconfirmation of expectations occurs when these expectations are not fulfilled, particularly when visual cues distort the flavour, taste, and aroma of the product. Therefore, it's crucial to guarantee excellent sensory qualities before and during intake. In particular, meat analogues must resemble well-known meat items in order to create favourable expectations. Research has investigated a range of cooking parameters, including temperature and time, to improve the overall look of meat analogues. This is because these elements have an impact on the final appearance of the cooked product. Using the sous vide method, Gomez et al. examined the effects of varying cooking temperatures and times on the colour characteristics of a ready-to-eat soy beef substitute (Gómez et al., 2019). This required heating the product in a water bath at low temperatures while it was vacuum-sealed. The meat analogue and its beef counterpart were tested in the research. Both were marinated in either teriyaki or beer and cooked at various temperatures and periods. A hedonic test with seventy-three customers revealed no statistically significant difference in the visual appearance like ratings between the beef samples and the meat analogues. Additionally, colour analysis showed that samples cooked with identical parameters had comparable values for redness and brightness, suggesting that this cooking process, regardless of the marinade employed, may produce meat analogues with a colour close to their meat counterparts. Because of their lighter yellow colour, samples treated with teriyaki marinade also had greater yellowness values according to instrumental colour analysis. The effects of varying the proportion of texturized vegetable protein (TVP) to chickpea flour on the colour and appearance of vegetarian nuggets were investigated by (Sharima-Abdullah et al., 2018). According to the research, the presence of carotenoids, which give food an enticing yellow tint, caused higher hedonic ratings for colour and look when the proportion of chickpea flour was increased. However, when the quantity of chickpea flour grew, the nuggets were less well-liked overall, presumably as a result of a decline in taste preference. This emphasises how crucial it is to take into account a variety of sensory factors when determining customer approval. The colour of meat analogues may fade when exposed to light or oxygen, which may negatively affect the product's attractiveness. This is a difficulty when employing plant proteins. Meat analogues may be marinated to change colour

before cooking, and additional components like chickpea flour or marinades of teriyaki and beer can change the colour of the finished dish. In addition, the appearance of meat analogues may be influenced by cooking factors such as temperature and duration; higher temperatures may result in a brighter colour due to increased moisture content. These results demonstrate the range of variables that may affect how consumers view the colour and aesthetic appeal of meat analogues. One significant disadvantage of using plant proteins in meat substitutes is the release of volatile chemicals from the oxidation of unsaturated fatty acids in the lipids. These substances are involved in offensive flavours and odours (Asgar et al., 2010). Food experts create recipes using flavouring combinations made of seasonings, spices, and enhancers to solve this problem. These additions are designed to cover up any unwanted beany, grassy, or green smells associated with pulses, while also emulating the classic flavour of smoked meat. Samples of meat analogues are usually presented in a way that closely mimics their meat counterparts in order to assess customer acceptance. Three distinct kinds of mixed goods made of peanuts were compared to a traditional soy-based minced product in a flavoured puff pastry application by (Rehrah et al., 2009). Defatted peanut flour was reinforced with peanut protein concentration to create the peanut-based equivalents, which were then extruded and crushed into a mince that resembled beef. Then, to make them seem like a packaged snack, they were inserted inside folded puff pastry. Soy sauce and beef flavour have been added to each batch of structured peanut protein concentrate (PPC) to enhance flavour. Tomato powder was added to one sample, crushed red pepper was added to another, and there were no changes made to the third. A hedonic scale with nine points for meaty flavour, off-flavor, and spiciness was used by a panel of sixty sensory panellists to score the samples. Participants were asked to rate the three severity levels of capsaicin on a just-right scale. It was discovered that the formulation with crushed red peppers had the least amount of off-flavor aversion, the most agreeable meaty flavour, and just the right amount of spice. These results demonstrate how adding spices, flavours, and enhancers may increase customer acceptability of meat substitutes. However, although soy-based compositions were not as effective as textured PPC when it came to puff pastry consumption, the research lacked comparisons with a standard meat formulation. This emphasises how crucial it is to choose a suitable control when assessing meat analogues. Higher acceptance ratings for the most seasoned formulation might result from extra spices influencing hedonic reactions if the plant proteins in the test and reference samples vary. On the other hand, it would be easier to understand how a meat analogue satisfies the desirable sensory characteristics of a traditional animal item if a full-flesh item was provided as a comparison.

Using a similar approach, Wong et al. created three formulations of hybrid beef patties by substituting hydrated textured soy protein (TSP) for 10%, 20%, and 30% of the ground beef (Wong et al., 2019). Fifty-five consumers participated in the first hedonic testing, which found no discernible differences in the overall liking ratings for any of the formulations when compared to an all-beef control. The 20% TSP burger and the all-beef patty had somewhat lower flavor-like ratings in later testing with lower sodium levels, suggesting that substituting up to 30% of the beef with

plant protein may result in acceptable liking scores as long as the salt content stays constant. In a further study, Grasso and colleagues produced four types of mixed meatballs by adding TSP to 15–30% of the beef and using nutritional yeast as a taste enhancer with or without the substitution. (Grasso et al., 2019). Sixty people evaluated the products' flavour, texture, and general acceptability using an all-beef standard. In addition, participants used a list of 24 phrases associated with meat products to characterise the samples using the CATA approach. The addition of nutritional yeast and 15% TSP produced the highest like ratings for taste and overall acceptability, according to the data. Moreover, the CATA research demonstrated a correlation between off-flavors and samples with a high soy content and no flavour enhancers. This emphasises how crucial it is to use an appropriate control in order to correctly gauge customer acceptability of hybrid goods. When examining how various flavouring agent concentrations affect sensory characteristics, the sample without the additional component acts as the control. The effects of adding various amounts of Maillard-reacted beef bone hydrolysate (MRP) to a soy-based meat substitute were investigated by Chiang et al. (Chiang et al., 2020). The highest sensory ratings for meaty tastes and scents were obtained at 20% MRP, whereas higher concentrations produced bitterness and an unattractive look. Even though the meat analog's acceptance was increased by the inclusion of MRP, further investigation is required to compare it to a full-meat control. Similarly, Katayama and Wilson investigated the ideal ratio of vegetable-based “shrimp” and “chicken” flavours added to meat analogues made from soy that were produced in different forms and cooked in different ways (Katayama & Wilson, 2008). The findings showed that adding 4% flavouring improved the overall meatiness and saltiness. However, the cooking method significantly impacted consumer preferences, with fried samples being more favored despite their higher fat content.

5 Key Ethical Considerations for Sensory Analysis and Consumer Preference

5.1 *Informed Consent*

Everyone who takes part in the research has a right to know what it is, why it's happening, what risks and benefits they may face, how they may withdraw at any time, and how their data will be protected. When people participate in sensory testing or eat specific foods, it is important that they understand the hazards involved. Similarly, people need to know about the possible advantages, such helping to create better food items. Customers' expectations are greatly influenced by the way a product is visually presented before they buy it. When these expectations aren't satisfied, it may lead to disappointment, particularly when visual signals don't match the actual flavour, aroma, and taste of the product. So, it's crucial to make sure the sensory qualities are good before and throughout eating. In order to arouse

favourable expectations, meat analogues, in particular, should resemble well-known meat items. Due to the fact that cooking parameters like time and temperature affect the finished product's visual attractiveness, research has investigated these elements in an effort to improve the overall look of meat analogues.

5.2 Voluntary Participation

Participation in sensory analysis or consumer preference studies should be voluntary, and participants should not be coerced or pressured to take part (Stone et al., 2020). Coerced or pressured participation may introduce bias into the research results, as participants may feel compelled to provide responses that do not accurately reflect their true opinions or experiences. Participants should be able to choose whether or not to participate in the research. When participation is voluntary, participants are more likely to feel comfortable and satisfied with their involvement in the research process (Hansen & Umbreit, 2018). This can contribute to a positive research experience and encourage future participation in similar studies.

5.3 Confidentiality and Anonymity

Researchers should safeguard the confidentiality of participants' personal information and guarantee that data is anonymized, to prevent the identification of individual participants (McKibbin et al., 2021). Ensuring confidentiality and anonymity is an ethical obligation for researchers conducting studies involving human participants. It demonstrates respect for participants' autonomy, dignity, and rights to privacy. Maintaining confidentiality and anonymity helps preserve the integrity and validity of research data by minimizing the risk of bias or distortion that may result from participants' concerns about privacy breaches (Liu & Wei, 2023). Many research ethics guidelines and regulations require researchers to protect participant confidentiality and anonymity. Adhering to these standards ensures compliance with legal and regulatory requirements.

5.4 Minimization of Harm

Researchers should take precautions to minimize any physical or psychological damage that participants may encounter throughout the study, such as by using appropriate sampling sizes and avoiding overly sensitive topics (Robinson, 2014).

Ensuring the well-being of participants is paramount. Minimizing harm reduces the risk of any physical or psychological discomfort, distress, or adverse effects that participants may experience because of their involvement in the research (Butler et al., 2019). Researchers have an ethical obligation to prioritize the safety and welfare of participants. Minimizing harm demonstrates a commitment to ethical research conduct and upholds the principles of beneficence and nonmaleficence.

5.5 *Transparency and Disclosure*

Researchers should disclose any potential conflicts of interest and be transparent about the methods, procedures, and findings of the study. Transparency encourages stakeholder engagement and participation in the research process by providing opportunities for stakeholders to review, critique, and contribute to the research design and implementation (Boaz et al., 2018). Openness fosters collaboration and partnership between researchers and stakeholders. Transparency enhances public confidence and trust in research institutions and practices. Openness about research methods, procedures, and findings promotes public understanding and acceptance of research outcomes, contributing to public trust in scientific research (Humphreys et al., 2021).

5.6 *Institutional Review*

An institutional review board or ethics committee should assess and approve studies involving human subjects to guarantee compliance with ethical principles and legislation. (Nichols, 2016). Institutional Review Boards (IRBs) or Ethics Committees play a critical role in ensuring that research involving human participants adheres to ethical standards and guidelines (Resnik, 2021). They provide oversight and guidance to researchers to ensure that research is performed in an honest and accountable way. IRBs uphold the integrity and credibility of research by ensuring that research studies are methodologically sound, scientifically rigorous, and conducted with integrity (Pease, 2018). They review research protocols to ensure that research methods are appropriate, valid, and ethical. Institutional Review processes enhance public trust and confidence in research institutions and practices by ensuring that research involving human participants is conducted ethically, responsibly, and transparently (Jao et al., 2015). IRBs provide assurance to participants, researchers, and the public that research studies are conducted with integrity and respect for participants' rights and welfare.

6 Conclusion and Future Perspective

In conclusion, the integration of AI techniques in sensory and consumer studies, though currently at a basic level, holds significant potential for sustainability in the food industry. This integration can facilitate the development of consumer products tailored to specific sensory qualities, thereby addressing consumer preferences effectively. Future research endeavors should adopt a comparative approach, exploring multiple protein sources and product combinations. Understanding consumer behavior, including acceptance and rejection of novel foods, necessitates comprehensive measurement tools and interdisciplinary research efforts. Research on children's food acceptance behaviors underscores the importance of early familiarization with novel foods, while acknowledging accessibility barriers across diverse populations. Overcoming neophobia and disgust associated with unfamiliar foods remains a crucial challenge, particularly in contexts where food resources are limited. Leveraging digital technologies, such as cloud computing and blockchain, can enhance data acquisition and analysis efficiency throughout the food production chain, benefiting consumers in terms of consistency, safety, and quality. Addressing research gaps, particularly in experimental study designs, is essential for advancing sensory and consumer science towards sustainability goals. The discipline can contribute to promoting dietary shifts, reducing food waste, and enhancing food-related well-being. Emphasizing sustainability in future research agendas will enable sensory consumer science to play a pivotal role in addressing global food challenges. Looking ahead, sensory food science will continue to be indispensable for understanding consumer preferences and industry needs. To ensure the field's progress, investments in training, basic research, and interdisciplinary collaboration are imperative. By addressing these challenges and opportunities, sensory consumer science can remain at the forefront of driving innovation and addressing sustainability needs in the food industry.

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Chapter 15

Food and Dairy Product Shelf-Life Extension



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1 Introduction

Shelf life, as defined by Vasile and Baican (2021), is “the period during which a food retains acceptable characteristics of flavor, colour, aroma, texture, nutritional value, and safety, under defined environmental conditions”. Food wastage is a significant concern contributing to the loss of nearly 1.05 billion food products globally. By the time it reaches the consumption stage, as much as 19% of the food is estimated to be disposed off by retailers, food services, and households (UNEP Food Waste Index Report, 2024). Additionally, Dilucia et al. (2020) mentioned that such losses may occur due to microbial contamination, inadequate packaging, or improper food handling practices. Most commonly, perishable foods are quite susceptible to microbial attack due to higher moisture content in them. The elevated levels of moisture result in higher values of water activity, hence more chances of the product being spoilt (Kumar et al., 2021). With the growing population (expected 10 billion by 2050), the need to provide reliable access to safe food also increases. Since the goal is to seek sustainable solutions and ensure food security by 2030, it is crucial to expand food supply whilst reducing food loss and wastage (UN SDG, Mc Carthy et al., 2018). Henceforth, there is a growing challenge to balance the food waste and shelf life for each type of product (Spada et al., 2018).

Food technocrats, scientists and researchers are exploring new techniques for extending the shelf life of food such as pulsed light, ozonation, cold plasma, electron beam irradiation, high hydrostatic pressure, nanotechnology, intelligent packaging and edible films and coatings. These methods provide extremely favorable outcomes beyond well-known traditional conventional methods including drying,

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freezing, chilling, curing, heating, boiling, sugaring, salting, canning, pickling, and fermentation. Key reason involved in the adaptation of stated novel technologies is the loss of nutritional, textural, and sensorial attributes resulted from the application of traditional methods of preservation. Rendueles et al. (2010) & Knorr et al. (2001) concluded that shelf life or the safe duration of the food products got enhanced by the application of promising novel means like high hydrostatic pressure (HPP) and using electric field by employing pulsed electric field (PEF). Several authors (Rehman et al., 2020; Gemechu, 2015; Raheem, 2013) concluded bio preservation as a potent technique to inhibit microbes and improve shelf stability. Rehman et al. (2020) reported that such improvement in shelf life can be obtained by altering properties like pH, water activity and redox potential. It is done by including natural antimicrobial compounds in the food products thereby inhibiting microbes. As a matter of fact, Gemechu, T. (2015) reported lactic acid bacteria (LAB) to have a widespread utility in the field of food preservation. According to Gram Lone et al. (2002), food can undergo morphological changes and lose nutrients while it is transported because of the influence of external substances like bacteria, chemicals, and enzymes. As a key to this wastage problem, improvement in packaging material offers a significant solution to the food industry (Raheem, 2013). Specifically, intelligent and active packaging systems serve as one of the most prominent developments by food packaging industry worldwide. These refer to the voluntary interactions between food and its environment (Siracusa & Lotti, 2019). Intelligent packaging is quite an advancement over the historical developments in food packaging systems. It serves as a beneficial technique to ensure enhanced shelf life of the product whilst focusing on food safety and stability. This type of packaging generally uses bioactive substances like antioxidants, antimicrobials, and moisture absorbers to perform its active function (Vasile, 2018). The purpose is also to indicate the freshness and overall quality of the product throughout the food supply chain (Siracusa & Lotti, 2019). Active packaging systems can be utilized in several ways and could be identified via large number of researches carried over a long period of time. These studies highlighted that beneficiary effects of active packaging can be obtained by incorporating them to the food packaging materials via processes like integration, coating, immobilization, or surface modification (Bastarrachea et al., 2015; Anwar & Warsiki, 2018). Furthermore, it is claimed that these packaging systems are primarily used to detect alterations and record any changes made in the packaging material, environment, or the food itself (Anwar & Warsiki, 2018; Siracusa & Lotti, 2019). Fadiji et al. (2023) concluded various product parameters to select the most appropriate antimicrobial packaging system. Some of the parameters involve nature, expected shelf life, requirements for food storage, and legal requirements to decide the method selection. In this context, antimicrobial packaging is one of a kind that can be opted by subsuming suitable deliverables into the active coatings and films. Besides this, antimicrobial sachets inside the packaging material or films are also added for an effective application.

For the purpose of agri-food, The Organization for Economic Co-operation and Development (OECD) defines “green growth” as “the pursuit of economic growth and development, while preventing environmental degradation, biodiversity loss,

and unsustainable natural resource use.” Researches have also laid emphasis on green technology as a potent application for improving shelf life of food commodities. Thus, more focus was done to explore the potential of edible films and coatings and nanotechnology in improving the shelf life of food. In line with this, several researchers have paid attention to the green technologies for not only preserving the food in a better manner but at the same time utilizing efforts to extend the shelf of commodities. By regulating lipid oxidation, enzymatic breakdown, and microbial development, active packaging is known to improve the quality of food. Khan et al. (2021) concluded that active films and edible coatings offer quite a sustainable alternate for extending longevity of food products. Such stability is generally based on the principle of retarding parameters like moisture, aroma, or gases, in food commodities. This is achieved by incorporating an active compound like an antioxidant or antimicrobial into the film or coating thereby also slowing down the kinetics of decay for minimally processed fruits and vegetables. Besides these active compounds, protein-based coatings and films also exhibit ability to further lower down the respiration rate in food products to a great extent. As a result of their superior gas barrier and mechanical quality, shelf life of commodities were enhanced (Khan et al., 2021). Besides the widespread application of films and coatings, nanotechnology forms the latest approach among researchers. Because of their exceptional physiochemical, functional, and antibacterial capabilities (Baranwal et al., 2018), these have been employed as biosensors and packaging materials from farm to fork with the objective of improving product quality and safety. Considering the criticality of shelf- life extension for food products in order to avoid any infirmity or ill effects that may occur as a result of food spoilage, this chapter will primarily track the potential of various innovative techniques such as edible films, coatings, pulsed light, ozonation, high hydrostatic pressure (HHP), electron beam irradiation, cold plasma, nanotechnology, bio-preservation, & intelligent packaging. The idea is also to emphasize on the selected literatures focusing on improving the condition of food products confined to the last decade.

2 Fruits and Vegetables

It is established beyond doubt that most of the fruits and vegetables possess an extremely perishable nature and hence exhibit a comparatively shorter shelf life (Khatodiyia and Malik, 2022). Due to this, it is crucial to maintain their storage conditions and hence these cannot be stored at ordinary temperatures for a longer period of time. Certainly, fruit and vegetable commodities also undergo postharvest changes making this food group more prone to the post-harvest losses and hence a problem in food supply chain. Consequently, they also exhibit high susceptibility to microbial contamination. In an effort to combine convenience with superior quality, minimally processed foods are also being studied for their capacity to hold their freshness over extended periods of time (Kumar et al., 2020). Various techniques have been in use to bolster the shelf life of fresh/pre-processed/processed fruits and

vegetables with usage of some like pulsed light, ozonation, electron beam irradiation, high hydrostatic pressure, cold plasma, nanotechnology, bio-preservation, intelligent packaging and edible coatings and films. Recent data of applicability of these techniques in extending shelf life is presented in Table 15.1.

Pulsed light, a non-thermal process has been demonstrated to be useful in maintaining the nutritive and sensory qualities of fruits and vegetables in addition to effectively inactivating bacteria. Primarily, this non-thermal process is carried out to prevent bacterial cell from replicating and hence retarding its growth. This inhibition can be achieved by photochemical influence on the genetic and structural changes in microbes like bacteria, viruses, and other pathogens (Ma et al., 2017). Besides chemical influence, photothermal processes are also utilized to facilitate microbial cell disruption, thereby maintain the product characteristics. According to Charles et al. (2013), on keeping mangoes for 7 days in a storage area at 6 °C, PL helped fresh-cut mangoes retain their firmness, color, and carotenoid content. After a storage period of 3 days, the control group showed significant losses in terms of both firmness and color change. Furthermore, in terms of carotenoid concentration, even after 7 days of observation the reference sample exhibited only a value of 2 mg/g on dry matter basis. Conversely, fresh-cut mangoes when treated with PL showed a value of 9 mg/g on dry matter basis. However, their investigation also reported a rise in polyphenol oxidase activity and the maintenance of nutritional values, such as phenol, and total ascorbic acid concentrations, in comparison to those of the control sample. Similarly, it was shown that fresh-cut avocado treated with 6 J/cm² PL dose maintained its chlorophyll a and b content and reduced the growth of microorganism such as yeasts and molds (MY) (Aguilo-Aguayo et al., 2014). However, because of the temperature rise or thermal damage from using high levels, this treatment causes browning. Gómez et al. (2012) looked at the impact of PL in conjunction with anti-browning pretreatment to combat the fast browning of fresh-cut apples. On dipping fresh-cut apples into a mixed solution of 1% (w/v) ascorbic acid and 0.1% (w/v) calcium chloride, browning could be minimized together with an application of energy density up to 71.6 J/cm².

Variety of food produce including fruits and vegetables, have had their shelf span extended by using ozone technology (Varga & Szigeti, 2016). Ozone based technology is widely used as an alternative to other methods of treatment including chemical ones (Nickhil et al., 2021, 2022). As a part of this process, ozone refers to a highly effective antimicrobial agent during which free radicals are produced further causing pesticide residues to break down molecularly. Additionally, it may include antimicrobial characteristics that help preserve the quality of products that are stored against pests, insects, bacteria, virus, protozoa and fungi (Pandiselvam et al., 2019; Ziyaina & Rasco, 2021). The oxidative reaction mediated by unsaturated lipids in the cell envelope broke down the cell wall, allowing chemicals inside the cell to seep out. Following the process, Deng et al. (2020) concluded that such reactions ultimately result in the lysis of microbial cells, which in turn caused cell death. In another case, dehydration and treatment of Pignola grapes with ozone at treatment value of 1.5 g/h applied for a long duration of 18 h successfully retarded the colony count by 50%. Ozone treatment helps in maintain the original product parameters

Table 15.1 Shelf-life extension of fruits and vegetables

Fruits and Vegetables	Technique and its formulation	Outcomes	References
Apple	Coating: Beta-Cyclodextrin with essential oil of palmarosa or star anise	Inhibited <i>Penicillium expansum</i> Decline in ethylene production, respiration rate Firmness loss reduced	Da Rocha Neto et al. (2019)
	Coating: 1% chitosan, 2% chitosan, caseinate/chitosan 2:1 combined with anti-browning agent composed of 1% citric acid, 1% ascorbic acid (L-form), along with 1% calcium chloride	Effectively reduced respiration rate Improved shelf life from a period of 7 days to 11 days at 5 °C temperature	Volpe and Torrieri (2017)
	Coating: 4% Sodium caseinate +2% chitosan +1% citric acid, ascorbic acid and CaCl ₂ with modified atmosphere packaging at varying temperature (5 °C and 10 °C)	At 5 °C, shelf-life got increased from 7 days to 11 days Hardness value improved to >95 N Respiration rate declined by 50% at 5% oxygen and temperature of 5 °C	Volpe et al. (2019)
Fresh-cut/ Unspoilt apple	Coating: Nanofibers applied by dipping: whey protein isolate, Glycerol, trehalose	Phenolic content retained and impeding weight loss Coating enhanced the shelf-life by slowing down the senescence process at 4 °C as compared to the standard sample of apple pieces after a term of 10 days Restricted Browning No change in consumer acceptance.	Feng et al. (2018)
	Coating: Corn zein, Polyethylene glycol 400	Films showed antioxidant characteristics. Delayed the browning, maintained freshness. Weight loss in apple slices prevented on storage period of 24 h at 20 °C.	Vimala Bharathi et al. (2020)
	PEF combined with coating: 14 Jcm ⁻² of pulsed light in combination with 0.5% (w/v) gellan-gum based edible coating	Reduced softening and browning Effectively retarded microbial growth Maintenance of sensory characteristics Conferred prebiotic potential	Moreira et al. (2015)
	PEF: Pulsed light (17.5, 52.5, 105.0 and 157.5 Jcm ⁻²)	Efficient in maintaining color No remarkable alteration in firmness 17.5 Jcm ⁻² Effective in declining viable count and bacterial load	Ignat et al. (2014)
Apricot	Coating: Aloe vera gel or basil seed mucilage	Reduced weight loss Maintain firmness and bioactive compounds. Production of ethylene and respiration rate reduced	Nourozi and Sayyari (2020)
Hass' avocado	Coating: <i>Meyerozyma caribbica</i> in Sodium alginate, Glycerol	Anthraxnose induced by <i>Colletotrichum gloeosporioides</i> effectively controlled throughout postharvest stage During storage, weight loss declined in the course of 10 and 20 days at 6 °C Decline in weight also observed during fruit ripening at 25 °C.	Iniguez-Moreno et al. (2020)

(continued)

Table 15.1 (continued)

Fruits and Vegetables	Technique and its formulation	Outcomes	References
Fresh-cut avocado, mushroom & watermelon	PEF combined with coating: 180–1100 nm, 12 J/cm ² pulse light merged with dipping in 2% malic acid (w/v)	Storage enabled effective microbial reduction Achieved beyond 5 log depletion of bacteria <i>Listeria innocua</i> and <i>Escherichia coli</i> Effective in extending shelf-life upto 14 days of storage time	Ramos-Villarroel et al. (2015)
Banana	Coating: Oleic acid in Cellulose nanofibers, Sucrose ester fatty acid polymer matrix	Together, the coating reduced ethylene and carbon dioxide formation Reduced breakdown of chlorophyll in banana peels Efficiently declined weight loss Maintained the fruit firmness, thus enhanced marketability and storage characteristics within provided ambient conditions (20 °C for 10 days).	Deng et al. (2017)
	Coating: Pullulan	Significant improvement in weight loss vitamin-C (ascorbic acid) retained Reduced browning index Decrease in TSS content Drop in peel to pulp ratio Enhanced firmness, total and residual sugar content when compared to uncoated or control fruits, shelf-life of banana extended upto 20 days (25 °C).	Ganduri (2020)
Blueberries	Coating: Cyclo-lipopeptides produced by <i>Bacillus subtilis</i> in Sodium alginate, Calcium chloride	Exhibits antifungal activity Ability to maintain product freshness Provided an easy-to-clean, and multifunctional coating film for berries	Xu et al. (2020)
	Coating: Gum arabic, Glycerol, Baobab fruit extracts	Better retention of bioactive compounds with enhanced total soluble solids Minimize the polyphenol oxidase and peroxidase enzymes, delayed microbial deterioration upto 21 days of storage (4 °C and 95% relative humidity)	Tahir et al. (2020)
	Cold plasma: for 10 min	Decline of Fungi and bacteria species by rate of 25.8% and 93.0%, respectively Reduction in decay rate by almost 17.7% after 20 days	Dong and Yang (2019)
Aronia (Rosaceae family) berry puree	HHP: Pressure: 400 and 600 MPa, Duration: 2.5–5.0 min	Dropped microbial count by 1log CFU/g Aerobic bacterial count declined to less than 2 log CFU/g.	Yuan et al. (2018)
Dates	Coating: Chitosan (polysaccharide), gelatin or guar gum. Also contained Glycerol Olive oil + ascorbic acid	Controlled and maintained Vitamin-C, total polyphenols, total carotenoids upto 40 days of storage. No significant change in overall acceptability. Chitosan + ascorbic acid+olive oil reduced the microbial load on dates after 5 weeks of storage	Abu-Shama et al. (2020)
Cloudy haw thorn berry juice	HHP: Pressure: 300–600 MPa, Duration: 30 min (65 °C)	Inhibited microbial expansion including TAB, LAB, yeast and moulds Improved product shelf life beyond 150 days.	Lou et al. (2022)

(continued)

Table 15.1 (continued)

Fruits and Vegetables	Technique and its formulation	Outcomes	References
Fresh-cut dragon	Cold plasma: Treated with green tea followed by plasma for 60 s at 40 W	Decreased microbial load Treatment effective in providing up to 15 days of life	Matan et al. (2015)
Figs	Coating: Sodium alginate + calcium chloride + chitosan Lecithin + glycerol Olive oil	Coated figs stored at 6 °C for 15 days revealed higher acceptability on comparison with fresh figs. Delayed ripening process Enhanced retention of polyphenolic content	Reyes-Avalos et al. (2019)
Grapes	Coating: Chitosan/ alginate beads merged with essential oils (clove, lavender, vanillin)	Food quality maintenance observed Controlled growth of <i>Botrytis cinerea</i>	Sangsuwan and Sutthasupa (2019)
	Coating: Caseinate (Na) + 2% potato starch alongside bacterium <i>L. plantarum</i> (5×10^7 CFU/ml)	Comparatively elevated values for weight loss (~3%) Similarly, inflated estimate of maturity index (67) Alteration observed in treated samples with casein coating (subsumed with probiotics)	Marin et al. (2019)
	Coating: Xanthan gum + calcium chloride Glycerol + Tween 20 Ascorbic acid	Xanthan gum with modified acid maintained structural integrity up to 21 days of storage. Suppressed polyphenol oxidase, ascorbic oxidase, polymethyl esterase activities for 21 repository days	Golly et al. (2019)
	Coating: Chitosan/ Gelatin/silver nanoparticles films, chitosan–1.8%(w/v), silver nanoparticles–0.1%(w/w)	Shelf-life extended upto 14-days	Kumar et al. (2018)
	Coating: CS/TiO ₂ films, CS–2.5%(w/v) TiO ₂ –10%(w/w)	Chitosan film lasted for 15-days, whereas nano-composite films upto 22 days	Zhang et al. (2017)
	Coating: Xanthan gum, Calcium chloride, glycerol	Decline in weight loss Increased phytochemical content Suppression of enzyme activities including polyphenol oxidase, ascorbic acid oxidase, polymethyl esterase Structural integrity of the grapes was preserved at 4 °C. Even in the course of 21 days	Golly et al. (2019)
Guava	Coating: 1% Sodium caseinate + 5% arabic gum Additionally, two concentrations i.e. 1–2% cinnamon and lemon grass oils used	2% EO concentration showed changes Elevated pulp firmness value of 10.01 received for treated fruit samples Toxic effects resulted in extreme enzyme activity (~7 units/100 mg protein)	Murmu and Mishra (2017)
	Coating: Bee wax with Hydroxypropyl methylcellulose, stearic acid, glycerol	Mass loss got reduced Green color retained Fruit firmness improved during storage of 8 days at 21 °C	Formiga et al. (2019)
	Coating: CS/PVP/SA, wherein CS–1.0%(w/v) PVP–1.0%(w/v) SA–2 and 4 mM	Admixture enhanced antioxidant properties Browning restricted	Lo'ay and Taher (2018)
	Coating: Chitosan 1–3%(w/v)	Prolonged quality after harvesting Delayed ripening at ambient storage	Batista Silva et al. (2018)

(continued)

Table 15.1 (continued)

Fruits and Vegetables	Technique and its formulation	Outcomes	References
Indian jujube fruit	Coating: Carnauba wax as principle material alongside oleic acid, myristic acid with Glycerol monolaurate, & ammonia	Weight loss, ethylene creation got reduced Respiratory activity inhibited Inhibited the enzyme activity Chlorophyll content and ascorbic acid preserved, resulting in a delay in skin color changes Delayed the softening process of flesh Provided better sensory quality even after 12 days	Chen et al. (2019b)
Kiwi	Coating: Chitosan hydrochloride	Inhibited <i>Botrytis cinerea</i> , <i>Pectobacterium carotovorum</i> subsp. <i>Carotovorum</i> Improved <i>in vivo</i> antimicrobial properties 20–25 days	Fortunati et al. (2017)
Persian lime	Coating: Limonene in Soy protein isolate, Glycerol	Lowered the risk of contracting <i>Penicillium italicum</i> disease Color in coated limes retained as compared to the control or uncoated sample Reduced moisture loss Also directed the release of active agent during storage period of 13 days at 13 °C	González-Estrada et al. (2017)
Mango	Coating: Aloe vera gel with polysaccharide Chitosan, Tween 80, and glycerol	Postharvest spoilage delayed Quality parameters retained TSS improved Weight loss reduced Maintained originality of peel color Retarding respiration rate and ethylene formation Improved ascorbic acid and antioxidant activity	Shah and Hashmi (2020)
Fresh-cut melon	Coating: Lemon extract in Soy protein isolated	Inhibition and reduction of microbial count including total plate count, yeast and mold Product color and sensory characteristics preserved Vitamin C/ ascorbic acid content retained Retarded respiration rate and water loss Protected melon samples from withering, even beyond 12 days (4 °C).	Yousuf et al. (2020)
Mandarin	Coating: Neem extract in guar gum	Inhibited spoilage Improved organoleptic properties after cold storage Reduced weight loss Acidity retained TSS, and ascorbic acid content got better	Xu et al. (2020)
	Coating: Carboxymethyl cellulose, chitosan, Beewax	Carboxymethyl cellulose 2 g/L was the most effective coating. Preserved soluble solids concentration, titratable acidity, vitamin-C, sensory attributes. Retarded methylesterase and cellulase activity thus delayed fruit softening	Baswal et al. (2020)
Valencia oranges	Coating: Shellac with ethanol	Weight loss Product quality and flavor preserved Product firmness reduced Coatings dried quickly which was odorless and non-sticky and turned fruit glossy. Nil visible cracks	Khorram et al. (2017)

(continued)

Table 15.1 (continued)

Fruits and Vegetables	Technique and its formulation	Outcomes	References
Tangerine fruit	Coating: Chitosan (CS)/montmorillonite(MMT), CS-1.0%(w/v) MMT-0.5,1and2%(w/w)	Good oxygen barrier properties of coating Enhanced structural stability. Enhanced shelf-life	Xu et al. (2018)
Papaya	Active packaging: Oregano, cinnamon and lemon grass essential oil sachet	Cinnamon most effective, reduced growth of <i>Alternaria alternata</i> , <i>Fusarium semitectum</i> , <i>Lasiodiplodia theobromae</i> and <i>Rhizopus stolonifer</i>	Espitia et al. (2012)
	Coating: Mentha EO with Chitosan, acetic acid, Tween 80, glycerol	The formation of anthracnose lesions deduced after 10 days at 25 °C.	dos Passos Braga et al. (2019)
	Coating: CS/Pullulan, CS-0.5%(w/v) Pullulan-0.5%(w/v)	Extended shelflifeandmaintainedthepost-harvest qualityof freshpapaya	Zhang et al. (2019)
	Coating: Aloe vera+ agar gel, Ascorbic acid + citric acid	Reduced respiration rate Improved shelf duration up to 2 week period	Parven et al. (2020)
Peaches	Coating: Chitosan blended with Chlorogenic acid	Maintained firmness, soluble solids, titratable, ascorbic acid Inhibited weight loss, decay index and respiration rate.	Jiao et al. (2019)
Pear	Coating: Nanoparticles applied by spraying: Eugenol in Bovine casein	Fully stamped out anthracnose disease after 8 storage days at ambient temperature of 25 °C	Xue et al. (2019)
	Coating: Cassava starch reinforced by starch nanocrystals Glycerol	Coating with 6% starch nanocrystals exhibited best mechanical properties. Retained the color, texture, total phenolic content, soluble solids and titratable acidity. Water vapor barrier improved	Dai et al. (2020)
Green bartlett pear	Coating: Oleic acid with Cellulose nanocrystal, chitosan, acetic acid	Decline in ethylene formation Decreased superficial scald of 'Bartlett' pears during the cold storage (−1.1 °C for 6 months).	Jung et al. (2020)
Pistachio kernels	Coating: Salvia officinalis L. extract in Whey protein concentrate, Glycerol	Microbial inhibition especially <i>Aspergillus flavus</i> Retarded aflatoxin formation on storing for 9 days at 20 °C.	Tavakolipour et al. (2020)
Plums	Coating: CS (1.0%(w/v) / Heat-treatment	Maintained phytochemicalprofiles ofplumfruitsduring storage	Chang et al. (2019)
	Coating: Origanum heracleoticum L. EO in Hydroxypropyl methylcellulose	Product firmness maintained Surface color retained Respiration rate reduced Ethylene production declined Weight loss observed Total cell count reduced in coated plums after 2 weeks at 23 °C.	Choi et al. (2016)
Raspberries	Active packaging: Nanoparticles applied by dipping: Propolis extract in Gelatin from porcine skin, zein corn, & Glycerol	Extract release monitored <i>Penicillium digitatum</i> and <i>Botrytis cinerea</i> hampered Extract efficiency improved over time	Moreno et al. (2020)

Table 15.1 (continued)

Fruits and Vegetables	Technique and its formulation	Outcomes	References
Strawberries	Active packaging: LDPE combined with silver nanoparticles	Enhanced storage life Improved fruit quality Controlled microbial load such as Molds and yeasts, and <i>E. coli</i>	Motlagh et al. (2020)
	Coating: <i>Mentha spicata</i> EO in Carboxymethyl cellulose, Glycerol, Tween 80 matrix	Shelf-life extended for a minimum period of 12 days Inhibition of titratable acidity Retarding microbial spoilage specially <i>Listeria monocytogenes</i> . Deduced weight loss Water vapor resistance exhibited positive influence in coated strawberry Obstruction in pH Respiratory activity discouraged	Shahbazi (2018)
	Coating: CMC, Glycerol matrix	Ascorbic acid concentration preserved Weight loss and decay reduced Total phenolic content maintained in strawberries throughout the storage period of 16 days at 4 °C.	Khodaei et al. (2021)
	Coating: Aloe vera gel in Banana starch, chitosan, Sorbitol	Shelf life enhanced to 15 days Drop in fungal and structural decay Water vapor loss from the fruit reduced	Pinzon et al. (2020)
	Electrospinning coating: Carboxymethyl chitosan, polyoxyethylene oxide	Reduced weight loss, prevention of diseases and rot, Improved fruit appearance at room temperature or ambient conditions for 9 days	Yue et al. (2018)
	Electrostatic spraying coating: Chitosan, Acetic acid, glycerol	Contrary to the uncoated treatment, the fresh strawberries showed enhanced shelf-life during cold storage for 15 days at low temperature of 4 °C The coating inhibited the physiological and biochemical changes of fresh samples	Jiang et al. (2020)
	Coating: Nanofillers: Nanoparticles applied by dipping: Bee wax, Xanthan gum, polyvinyl alcohol, propilenglycol	Fungal growth and decay rates reduced Weight loss declined Physiological damage was prevented even after a period of 21 days at 4 °C.	Zambrano-Zaragoza et al. (2020)
	Active packaging: Polylactic acid /carbon nanotubes /chitosan composite fibers-Carbon nanotubes	The activity of bacterial species like <i>Staphylococcus aureus</i> , <i>Escherichia coli</i> , <i>Botrytis cinerea</i> and <i>Rhizopus spp.</i> inhibited.	Liu et al. (2019)
	Coating: Fucoidan from <i>Laminaria japonica</i> seaweed	Inhibited degradation of total phenolic content and ascorbic acid	Luo et al. (2020)
	Coating: CS-chlorophyllin(Chl) coating, CS–1.0%(w/v) Chl-0.05%(w/w)	Enhanced post-harvest life of strawberries upto three days	Luksiene and Buchovec (2019)
	Coating: Chitosan, Glycerol with addition of ascorbic acid or acetic acid, sea buckthorn or grape seed essential oil	Preserved ascorbic acid, total phenolic content and anti-oxidant activity Provided mechanical protection Enhanced shelf-life upto 1 week	Pavinatto et al. (2019)
	Coating: Chitosan, <i>Palmaria palmata</i> seaweed extracts	Nutritional loss prevented Respiration rate reduced and microbial growth inhibited Anthocyanin content of the strawberry improved Enhanced ascorbic acid of the sample	Rico et al. (2019)
	Coating: Maltodextrin, whey protein isolate, polyglycerol poliricinateate, Water in olive oil emulsion, pomegranate seed and grape seed oil	Dip coating was more effective than electrospray of coating. Decline the moisture loss. Electrospray coating enhanced firmness, uniform coating and acceptability.	Cakmak et al. (2019)

Table 15.1 (continued)

Fruits and Vegetables	Technique and its formulation	Outcomes	References
Fresh-cut cabbage	Ozonation: 2 ppm of aqueous ozone treatment merged with 0.4% of Na ₂ SiO ₃ acid for 120 s	Improved product appeal Prolonged shelf life upto 12 days Product texture refined	Nie et al. (2020)
Fresh-cut carrot	Coating: Biosecur F440D, essential oils mixture in High methylester pectin, Sunflower lecithin, sucrose monopalmitate	Shelf stability observed Stabilization of compounds like polyphenolics and terpenics observed during the storage period Exhibited antimicrobial activity against two bacterial species <i>Listeria monocytogenes</i> and <i>Penicillium chrysogenum</i> .	Ben-Fadhel et al. (2020)
	Film: CS/Polyurethane/nanoZnO films, CS/PU ratio-0.25:0.75 ZnONPs–1.0, 3.0 and 5.0% (w/w)	Carrot pieces wrapped in composite films showed extended shelf-life upto 9 days	Saral et al. (2019)
Fresh-cut lettuce	Active packaging: Polyvinyl alcohol encapsulated with oregano EO	Maintenance of texture and color Significant inhibitory effects observed against <i>Dickeya chrysanthemi</i> , MY, and MAB	Chang et al. (2017)
Fresh-cut mushroom	PEF: Pulsed light: 4.8 J cm ⁻²	Efficient action against aerobic mesophilic and psychrophilic microorganisms No effect on product sensory characteristics Antioxidant property retained MY reduced	Oms-Oliu et al. (2010)
Chillies	Film: Starch-based films incorporated with lemongrass essential oil	EO effectively inhibited the growth of microbes	Perdana et al. (2021)
Okra	Coating: CS/nanoZnO coatings on polyethylene films, CS-2.0% (w/v)	Enhanced shelf-life of okra from 5 days to 12 days at room temperature	Al-Naamani et al. (2017)
Cucumber	Coating: Carnauba wax with coconut & oregano based oils	Weight loss declined Microbial load reduced (mesophilic bacteria, molds, and yeasts) after 15 days of storage at 10 °C in comparison to uncoated fruit.	Gutiérrez-Pacheco et al. (2020)
Tomatoes	Coating: PV alcohol film added with oregano EO	Packed produce quality preserved from microbial load such as <i>Salmonella enterica</i> , MY, and MAB	Kwon et al. (2017)
	Coating: CS/TiO ₂ films, CS-2.0% (w/v) TiO ₂ –1.0% (w/w)	Fruit ripening procedure slowed down Impeding the softening process in tomatoes	Kaewklin et al. (2018)
Cherry tomatoes	Electrospinning coating: Corn zein, Ethyl alcohol, titanium oxide	Ethylene concentration reduced as a result of photocatalytic activity Further, hinder of the ripening process observed even after a period of 22 days	Bohmer-Maas et al. (2020)
	Coating: Tea tree oil with β-cyclodextrin, and ethanol	Artificially induced bacterial infections looked upon Product duration lengthened up to 1 week	Yue et al. (2020)
Fresh-cut spinach	Ozonated water: pH of 0.4, 0.8 and 1.2 mg/L Duration of 1 s, 15 s or 30 s	Substantially decreased the yellow process Shelf life improved by 3 days	Papachristodoulou et al. (2018)
Bell pepper	Coating: Byrsonima crassifolia extract (L.) Kunth in Chitosan, canola oil, Glycerol	Carotenoid content increased Improved antioxidant capacity Weight loss reduced Color change after 21 days of storage Microbiological activity was reduced by 85%.	González-Saucedo et al. (2019)
Tomato puree	Antimicrobial additive: Benzoic acid, Sodium metabisulphite, TBHQ, Ethyl-N-lauroyl-L-arginine together with essential oils	Bactericidal materials were advantageous	Gherardi et al. (2016)

whilst inactivating the microbial load (Botondi et al., 2015). Moving forward in this line, Dilmacunal et al. (2014) opined a decline in the yeast, coliform and aerobic bacteria count after an extensive ozone treatment at 1.4 mg/l for distinct time variations of 1, 5 and 10 min on cabbage. In another instance, Nie et al. (2020) conducted a study and reported the usage of sodium metasilicate along with ozone to achieve the desired results. During the process, aqueous solution of ozone was used at 2 ppm concentration. In addition to this, 0.4% of sodium metasilicate was employed for 120 s which directed the results in a positive direction. The same study concluded that the texture and visual or outer appearance of the fresh-cut cabbage was improved by the treatment. As established, the antimicrobial based treatment also improved the shelf life of the product upto 12 days of time. Lung et al. (2015) demonstrated that reducing harmful bacteria and eliminating microbial contamination can be accomplished by electron beam irradiation, or EBI. The fundamental mechanism of EBI-induced inactivation of microorganisms is ascertained to the changes in the structure of enzymes. The beams dive deep into the system of enzymes resulting in their denaturation. This extensive action is accompanied by degradation of cell membrane proteins hence causing disruption of the entire DNA structure and enzyme functionality. Such changes ultimately result in the cell's inability to replicate and carry out other vital functions. Mushrooms have an incredibly limited shelf life and are highly perishable. The primary causes of this include changes in texture, weight loss, and enzymatic browning. The EBI treated sample showed the best total antioxidant capacity at a dose of 2 kGy. Additionally, the samples were able to exhibit the lowest electrolyte leakage, and the highest whiteness opposing to the reference or untreated samples. Nevertheless, Mami et al. (2013) reported a significant observation in terms of a substantial drop in ascorbic acid (vitamin C) content of the samples. Though due to safety concern of these beams, the US FDA currently restricts the maximum irradiation level for fresh produce like fruits and vegetables to a limit of 1.0 kGy (Shahbaz et al., 2015). The same study also notified fresh lettuce and spinach as exceptions, that can be generally irradiated up to a level of 4.5 kGy.

Hydrostatic pressure or HHP process works at mild temperatures and pressures between 100 and 1000 MPa for 10–20 min, is used to preserve liquid foods such as juices, milk etc. (Putnik et al., 2019). According to Morales et al. (2019), adiabatic heating occurs when high pressure is applied, resulting in a 3 °C rise in water temperature for each 100 MPa. Studies based on inactivation of microorganisms by HPP in a variety of goods, including dairy, seafood, meat products, eggs, and drinks, have been conducted. Because HPP alters the cell membrane structure, it is capable of reducing microbial load and further initiates a few chemical reactions that stop microorganisms from growing (Niakousari et al., 2018). Various experiments were conducted to examine the relation between processing treatment and antioxidant capacity of cantaloupe melon puree. These are extensively rich in various bioactive compounds hence form a suitable and interesting part of research for authors. Most of these studies reported that hydrostatic pressure processing did not show any appreciable change between the treated and control samples. Additionally, even after a storage period of 10 days, the treated samples showed steady antioxidant levels (Mukhopadhyay et al., 2017). As per the findings of Nayak et al. (2017),

samples treated with apple juice had the same organoleptic characteristics and a lower microbial count than the untreated ones. At a temperature of 4 °C, the shelf life extended to 60 days whilst keeping the parallel quality standards of the sample. According to Chang et al. (2017) on treatment with HPP-600, white grape juice demonstrated lower PPO and POD activities along with similar pH and titratable acidity characteristics to fresh juice.

Cold plasma (CP) has gained attention due to its innovative yet sustainable nature of action. It is a non-thermal method having good potential to preserve or decontaminate perishable produce like fruits and vegetables, thereby inhibiting negative reactions and concluding a positive response. The process, being advantageous in improving the shelf life of food products becomes crucial to understand the practicality of the technology. As indicated by its name, plasma, refers to the fourth state of matter. Fernandez et al. (2012) describes it as a quasi-neutral ionized plasma which is made up of distinct particles like photons, free electrons, positive or negative ions, excited or non-excited atoms, and molecules. Further, the most employed gases for this process are air, oxygen, and nitrogen. Besides these, a compound mix of noble gases like helium, argon, and neon can also be used for CP. The method is utilized for its distinct mechanism of action. The three possible mechanisms of the method include, firstly, the direct chemical interaction between charged particles and reactive species and cell membranes; secondly, Damage to cellular components and other membranes by the action of UV; and lastly UV-induced breaking of DNA strands (Niemira, 2014). The microbiological decontamination of strawberries, lettuce, potatoes, cherry tomatoes, cabbage, and milk has been effectively achieved with the execution of cold plasma treatment, indicating high potential of this innovative sterilization technique (Ma et al., 2017).

Microorganisms such as bacteriophages, bacteriocins and bio protectives form the biopreservation methods that have also been applied. These are sustainable methods and are known to effectively work in upgrading the durability, storability, and stability of fruits and vegetables. In their individual host bacterial cells, bacteriophages have the ability to selectively and efficiently replicate (Meireles et al., 2016). As a result, they do not harm people, animals and plants. Various food borne outbreaks have significantly highlighted the major pathogens which are serious to human health. These were identified to be *Salmonella spp.*, *L. monocytogenes*, and *E. coli O157:H7*. Therefore, a method that could effectively work against the microbial action, thereby reducing the widespread outbreaks was recorded. As concluded by Hudson et al. (2013), bacteriophage showed promising results against the action of these three foodborne pathogens. *Salmonella* levels on keeping fresh-cut honeydew melon at distinct temperatures of 5, 10, and 20 °C were found to be significantly lower. However, no comparable outcomes were observed on fresh apples at any of these distinct temperatures mentioned above. Subsequently, it was constructed that *L. monocytogenes* levels were substantially reduced on freshly cut melon contrary to the freshly cut samples of apple (Leverentz et al., 2003). Despite its inability to eradicate all foodborne pathogens, bacteriophages are recommended as an innovative yet environmentally acceptable alternate to chemical and synthetic sanitizers for purifying commodities. Antimicrobial peptides or proteins that have

the ability to inhibit certain bacteria that cause sickness and spoilage are known as bacteriocins (Balciunas et al., 2013). Because lactic acid bacteria (LAB) create bacteriocins, which are usually thought to be helpful to human health and food production, LAB-produced bacteriocins are currently the subject of a significant deal of interest (Oliveira et al., 2014). As of right now, just two bacteriocins are utilized in food preservation on a commercial basis. Both nisin and carnocyclin A, which are found in ready-to-eat beef products, are produced by *Lactococcus lactis* and *Carnobacterium maltaromaticum* UAL307 (O'Connor et al., 2015). The preservation method for minimally processed papaya was documented by Narsaiah et al. (2015). The study very well focused on the beneficial effects of alginate coatings. These are known to maintain the original product characteristics and delay ripening in fruits like papaya. The study also reported that the alginate coatings when incorporated by bacteriocins could significantly enhance the stability of papaya fruit. This experiment emerged as a profitable way to enhance the shelf life up to a period of 21 days for papaya, in comparison to 15 days for the control sample. The experiment concluded that samples subjected to such alginate coatings showed sustained or slightly altered physical and chemical properties. The incorporation of bacteriocin owed to a significant suppression of microbial growth in the sample fruit. The total plate count in the control sample was 10^7 CFU/g. After a storage period of 21 days, the total plate count in samples were found significantly lower and valued to 10^3 CFU/g. Additionally, the coated samples' hardness and weight loss were 8.7 and 7.4 times lower, respectively, than the control. By adding additional helpful microbes that are competitive, it is possible to stop the proliferation of unwanted microflora (Meireles et al., 2016). Taking into consideration the regulatory framework of bacteria, US FDA grants a GRAS status to the lactic acid bacteria (LAB). Such lactobacillus species are continuously studied by various scientists. For instance, the B2 strain emerging from species *Lactobacillus plantarum* and PBCC11.5 strain extracted from *Lactobacillus fermentum* reportedly prevented growth in terms of number of bacteria *Lactobacillus monocytogenes* in cantaloupes (Russo et al., 2015). Similarly, Siroli et al. (2015) outlined a positive application on shelf life of fresh-cut apples and lettuce. The study made use of CIT3 and V7B3 strains from *Lactobacillus plantarum* collated with natural antimicrobial compounds for test samples. For apples, 2-(E)-hexenal/hexanal and 2-(E)-hexenal/citral were used whereas thyme was used for lamb's lettuce. The experiment concluded that they were able to extend the shelf life of samples (both apple and lettuce) by 8 to 10 days as compared to the standard sample.

López-Gálvez et al. (2015) reported antimicrobial and anti-browning effects of modified atmosphere packaging using fresh cut lettuce refrigerated at 7 °C for a period of six days. Therefore, MAP has been extensively and successfully applied to improve the shelf life of fresh and fresh-cut products. As indicated earlier, the use of several inert or noble gases, like helium (He), argon (Ar), and nitrous oxide (N₂O), has received special attention recently. These gases being denser than nitrogen, may enhance the diffusivity of oxygen, ethylene, and carbon dioxide from plant tissues. Alternatively, they may also prevent respiration by influencing the activity of mitochondrial cytochrome oxidase C. However, few studies like those

conducted by Char et al. (2012) and González-Buesa et al. (2014) reported that modification of enzymes does not directly correlates with the alteration in metabolism of plant tissues. Rocculi et al. (2004), stored the sliced apples at a specific time temperature combination of 12 days and a lower temperature of 5 °C. It was found that the proportion of browning areas in control sample was 60%. Subsequently, proportions of 15% and 25% were found in samples subjected to higher modified atmosphere conditions consisting of N₂O and Ar (90% N₂O, 5% CO₂, 5% O₂, and 65% N₂O, 25% Ar, 5% CO₂, 5% O₂) respectively. As reported by Pinela et al. (2016), MAP combined with noble gases was considered a beneficial and best utilized method in maintaining the overall postharvest quality of fresh-cut watercress. The study highlighted the efficacy of argon-based packaging as compared to other gases.

A new area of research called nanotechnology may provide new protocols and materials for the purpose of enhancing the stability and longevity of foods. This demands for investigation and significant creation of materials with one or more lengths between one and one hundred nm (Mihindukulasuriya & Lim, 2014). Due to their potent antibacterial capabilities against a wide range of microbes, silver nanoparticles and ZnO are well recognized as promising antimicrobial materials (Li et al., 2011). In addition to ZnO and silver nanoparticles, other materials at a similar nanoscale have also grabbed the attention of various researchers. Recently, the application of such materials including those of chitosan-based nanoparticles, nano clays, and food packaging materials combined with metal oxide nanomaterials in freshly produced fruits and vegetables is well studied. These materials, either alone or in combination with other techniques find various applications in food industry. Shapi'i et al. (2020) reported that 15–20% w/w starch film antimicrobial packaging that used chitosan nanoparticles demonstrated the ability to suppress the development of bacteria, including *Salmonella typhimurium*, *E. coli*, *S. aureus*, and *B. cereus* in cherry tomatoes. Because of its natural antibacterial activity, capacity to form films, and biodegradability, chitosan is particularly becoming more and more vital for food packaging industry in terms of creating films and coatings (Kumar et al., 2019). Sufficient amount of studies have shown that adding nanomaterials and/or natural antimicrobials to chitosan-based composites can significantly extend their shelf life and conserve the quality of postharvest product (Xing et al., 2019). Recently, there has been a rise in interest in the use of nanoemulsions and coatings based on them because fresh product now has a protective environment surrounding it. Using 0.05% oregano oil nanoemulsions, Bhargava et al. (2015) observed reduction in number of *Salmonella Typhimurium*, *Escherichia coli*, and *Listeria monocytogenes* in fresh-cut lettuce by up to 3.44, 2.31, and 3.05 log CFU/g, respectively. Similar to this, when compared to traditional emulsions, nanoemulsion-based coatings had positive and better results. Essential oils are widely employed as antimicrobial compounds to prevent deterioration in food. One such case containing lemongrass essential oil (LEO) aided in the quicker and more thorough halting of *Escherichia coli* growth in freshly cut apples in the course of their storage time (Salvia-Trujillo et al., 2015). To bring in a collated effort, Table 15.1 displays recent uses of nanotechnology in commodities such as fruits and vegetables.

Antimicrobial agents may be included in food packaging as an efficient way of reducing microbial impact, increasing product quality, and prolonging shelf life. Giannakourou and Tsironi (2021) and Jung and Zhao (2016) have stated that three types of antimicrobial packaging viz., sachets, films and edible coatings rooted in as favourable means when used on fresh and lightly processed fruits and vegetables. These antimicrobial substances may be both natural or manufactured active substances to prevent microbial growth including some of these like plant extracts, essential oils, chitosan, and organic acids and their salts. Essential oil (EO) sachets of oregano, cinnamon, and lemongrass were found to be effective against various phytopathogenic fungus, including *Fusarium semitectum*, *Alternaria alternata*, *Lasiodiplodia theobromae*, and *Rhizopus stolonifer* (Espitia et al., 2012). Shemesh et al. (2016) concluded that polyamide based antimicrobial packaging film when incorporated with carvacrol essential oil could exhibit remarkable antifungal activity against *Penicillium digitatum*, *Penicillium expansum*, *Alternaria alternata*, and *Botrytis cinerea*, along with exceptional efficacy in mitigating degradation and prolonging the shelf life of grapes, lychee and cherry tomatoes. In another case, highlighting the significant effects of essential oils, the use of polyvinyl alcohol film along with oregano EO in cherry tomatoes, provided a growth curbing effect for mold, yeast and bacteria like *Salmonella enterica* and mesophilic aerobic ones. It was observed that even after 7 days of storage, films with 2% and 3% EO could thereby retain the original physical characteristics of tomato (Chang et al., 2017).

Fruits and vegetables keep on respiring even after harvesting. This ability of such raw commodities to continuously transpire is one of the major grounds responsible for their comparatively shorter shelf life. Henceforth, natural process of respiration is also responsible for their degradation in quality aspects. Fruit ripening is a highly intricate process that involves significant alterations in physiological and biochemical parameters, encompassing ethylene formation, enzymatic cell wall breakdown, alteration in sugar content, level of aromatic compounds and respiratory properties therein (Lee & Hwang, 2017). Encasing or coating edible film derived from biopolymers is a cheap, easy, and efficient way to prevent moisture loss, which lowers deterioration and respiration rate (Kumar et al., 2019). Perdana et al. (2021) observed the potential of starch or chitosan flour when merged with lemongrass essential oil. As already discussed, essential oils are a great way to provide antimicrobial effect on the packaging films. Therefore, the study could effectively report the action of EO based film on microbial growth such yeast, molds, and both Gram-positive and Gram-negative bacteria. The films could inhibit the action of these microorganisms. Further, the resultant layer also significantly reduced water loss and postponed ripening. Active coating should ideally operate as a barrier to slow the loss of water vapor and desired flavor volatiles, while also modifying the atmosphere surrounding perishable fruit and vegetable by limiting the interchange of CO₂ and O₂. Therefore, this altered environment may decrease the rate of ethylene production and respiration while delaying the action of ethylene (Colak et al., 2015; Ranjbaryan & Pourfathi, 2019). Additionally, by adding gloss, masking scars, preventing decay, and preventing the onset of physiological disorders, edible coatings enhance the appearance of horticulture produce (Ncama et al., 2018). Ozdemir et al.

(2004) began experimenting on cherries and found that a milk protein based approach would be beneficial for maintain the shelf life of the fruit. On moving forward with the steps, the application of a caseinate (preferably sodium) based edible coating along with milk protein concentrate successfully preserved the water content and prevented any loss during storage period having specific conditions at 4 °C for up to 63 days. The favourable outcome of caseinate coatings led to a wide adoption of such topics for researches. One such approach in 2017 also mentioned that edible caseinate coatings tend to adhere at fruit surfaces in a smooth manner. Additionally, these coatings are effective in reducing oxidative stress, and exhibit good consumer acceptance upon fruit ripening (Murmu & Mishra, 2017). Nevertheless, it has been noted in the literature that caseinate cannot increase shelf life of fruits and vegetables. Ramirez et al. (2015) found that edible coatings containing 2% sodium caseinate did not possess any effect on quality traits of fresh cut nectarine stored at lower temperature range of 3 ± 1 °C for 1 week. Correa-Betanzo et al.'s (2011) finding regarding berry cacti verified this outcome. Caseinate based coatings can also be utilized by incorporating compounds like sorbitol and glycerol. Their effects were noted by keeping fruits treated with edible coating made up of compounds including sodium caseinate, sorbitol and glycerol in a clam shell box. These boxes were kept at 5 ± 1 °C for 15 days and various reactions or changes were noted. The fruits' ability to function as antioxidants was unaffected by the edible sodium caseinate covering. Blending casein with other biopolymers is a viable strategy that may improve coating qualities and hence increase shelf life. According to Volpe and Torrieri (2017), a coating made of a chitosan and sodium caseinate combination was capable of lowering the respiration rate and maintain product's color at the same time in minimally processed apples.

Sodium caseinate has been shown by Valentino et al. (2020) to be an effective substrate for chemicals that promote dispersion. In this investigation, the 4% sodium caseinate solution was supplemented with 1.5% rosemary essential oil and $0.50 \mu\text{g mL}^{-1}$ gallic acid, an antioxidant component. In general, adding essential oils to casein-based coating materials to a certain degree improves sensory qualities and lowers microbiological contamination, enhancing the shelf life of foods. Edible coating on guava was incorporated based on 1% sodium caseinate, 5% Arabic gum, and 1–2% lemon and cinnamon EO. The coating combination was used to conclude various changes observed in the samples. These had an impact on the fruit firmness and enzyme activity of polyphenol peroxidase (PPO). Since the experiment intimated a significant observation on PPO activity, it was added that the reduced enzyme activity was also responsible for a reduced browning effect on the fruit sample. Moreover, the coating-containing samples also had the highest overall acceptability score alongside higher DPPH radical scavenging activity. As a result of reduced enzymatic activity, a comparatively slower rise in total and reducing sugar in guava was observed. Similarly, when guava samples were packed with edible coatings consisting of 2.5% tulsi extract and 1% sodium caseinate, the samples showed nil mold growth and pulp hardness. Additionally, the coating medium also enabled the retention of guava peel color along with fruit firmness similar to the one found in ripened guava (Raghav et al., 2016). Adding to the positive set of

changes, the retention of phenolic and flavonoid content in guava was noted to maximum extent. EO widens its application to other vegetables like button mushrooms as well. In a study, it was concluded that after a term of 16 cold storage days, these mushrooms retained their quality due to the integration of essential oils with them. Forming a major part of this experiment, the button mushrooms were fumigated with clove, thyme, and cinnamaldehyde EOs which were proven to give beneficial quality results (Gao et al., 2014). Three apple varieties that had been infected with the postharvest diseases *Penicillium expansum*, *Botrytis cinerea*, and *Neofabra alba* were treated with clove oil and garlic extracts and it was found that fruit treated directly with antimicrobials had longer shelf life (Daniel et al., 2015).

Consequently, Guerreiro et al. (2015) examined the impact of incorporating cinnamon leaf oil into pectin based edible coating. The experiment involving EO, concluded that table grapes maintained at 10 °C completely inhibited fungal deterioration caused by *Botrytis cinerea* for a period of 15 days. Using an edible coating, cauliflower florets were treated with an antibacterial composition made of components such as lactic acid, citrus extract, and lemongrass EO. This type of essential oil is highly effective in retarding bacterial load. Moreover, the said coating completely restricted the growth of *Listeria innocua* that had been injected onto the florets after they were stored at 4 °C for 1 week (Boumail et al., 2016). Table 15.1 summarizes the studies conducted by several groups and their findings based on preserving post-harvest quality and decline in decay in fresh fruits and vegetables.

3 Dairy Products

Dairy products possess limited shelf life and hence furnish a competent environment for sustaining the development of various microorganisms including spoilage causing bacteria like pathogens (Malik and Sharma, 2019). Thus, purifying milk and keeping it away from microbial actions is a necessary step to enhance its shelf life and prevent any deterioration so as to make it fit for human consumption. Currently, thermal treatments are the sole methods used worldwide. HTST pasteurization and UHT sterilization are the two main process types used. However, as much as these thermal treatments are beneficial for milk, they may produce certain undesirable changes characteristic to the milk. Some of these changes could be physical, chemical and sensory changes, such as browning and development of cooked flavor in dairy products. Further, depending on the extent and intensity of thermal conditions, these processes may also aid in vitamin loss, or the loss of essential amino acids in the product (Fracassetti et al., 2018). Therefore, new technologies must be focused on reducing these negative impacts and satisfying consumer demand for milk that has the best qualities possible (Limbo et al., 2020). One of FAO's strategies is holding the food business accountable for producing sustainable and healthier goods. Table 15.2 provides an overview of the efficacy and applicability of numerous innovative processing techniques that have been studied in various dairy sectors using different techniques. Based on the most recent scientific

Table 15.2 Shelf-life extension of milk and milk products

Milk and Milk Products	Technique and processing parameters	Outcomes	References
Milk	Cold plasma: 15 kHz (plasma generation) Processing variables-voltage groups (0, 40, 50, 60, 70 & 80 V for 120 s) & time groups (70 V for 0, 15, 30, 60, 90 & 120 s)	Plasma at 70 & 80 V for 120 s and 70 V at 90 & 120 s were equally effective as ancient thermal treatments	Wu et al. (2021)
	Cold plasma: Encapsulated dielectric barrier discharge plasma Involved conditions of 15 kHz for 5 & 10 min in ambient air	<i>E. coli</i> growth reduced by 2.43 log cfu/ml Sample disclosed of 10 min Declined <i>L. monocytogenes</i> expansion by 2.40 log cfu/mL <i>Salmonella typhimurium</i> by 2.46 log cfu/ml	Kim et al. (2015)
	Cold plasma: Linear micro discharge jet generated using He gas, 13.56 MHz frequency and treatment from 1 to 12 min	Free radicals made <i>Prototheca zopfii</i> more sensitive to cold plasma compared to antifungal agents	Tyczkowska-Sieron et al. (2018)
	Cold plasma: Argon gas plasma at 2, 3 & 4 kHz frequency for 2 min & 4 kHz for 30–120 s	Significantly retarded microbial count Came out as a better treatment in terms of maintaining microbial quality compared to pasteurization processing	Ponraj et al. (2017)
	Ohmic heating: 50 Hz, 10 V/cm, 67 °C	Inactivated <i>S. aureus</i> Exponential inactivation phase started above 50 °C Negligible changes in pH and colour value	Shao et al. (2021)
	HHP: Pressure: 400–600 MPa, Duration: 1–5.0 min	Microorganism proliferation restricted by 5logCFU/ml. Decreased the <i>Enterobacteriaceae</i> , <i>pseudomonas spp.</i> , lactic acid, and total viable counts Increased longevity by 7 days in comparison to milk treated with pasteurization	Stratakos et al. (2019)
	HHP: Pressure: 400–600 MPa, Time: 1–5.0 min	Decline in <i>S. aureus</i> count by 7 log CFU/ml of goat milk	Razali et al. (2021)
	HPP: 600 MPa for 5 min, 40 °C	No pathogens detected Total bacterial count decreased by 2 log	Liu et al. (2020)
	Microwave heating: 2455 MHz; power between 0 and 1800 W; ramp time (2.9–5.5 min); holding time (6.6–23.4 s); final temperature (60–80 °C).	Heating at 75 °C/20 s found favourable Duration of 3.3 min provided a 5 log reduction for <i>E. coli</i> Thermal inactivation of <i>S. aureus</i> at 70 °C/20 s, 4.4 min.	Thum et al. (2020)
	PEF: 20 Hz; 25.7 ± 02 kV/cm for 34 µs; preheating at 55 °C	Bacterial count reduced by 1.14 log After 21-days, bacteria in PEF-induced milk was lower than that of LTLT or HTST Elevated lipolytic activity observed	Sharma et al. (2018)
Non-fat dry milk powder	Cold plasma: Cold atmospheric plasma (4.4 kV for 0–120 s) generated using N ₂ gas. Treatment for 0–120 s with refrained humidity at ~35%	The flow rate and treatment time influenced the inactivation of species <i>Cronobacter sakazakii</i>	Chen et al. (2019a)

(continued)

Table 15.2 (continued)

Milk and Milk Products	Technique and processing parameters	Outcomes	References
Cheese	Coating: Sodium caseinate (2.5%) and chitosan (2%) (alone or in combination)	Film forming solution (10–12 mm) and films (4.2 cm ²) hampered sample microflora.	Moreira et al. (2011)
	HHP: Pressure: 500 MPa, Time: 15 min, Temperature: >28 °C	Increased yield Improved product sustenance Enhanced characteristics.	Kapoor et al. (2021)
	Intelligent packaging: Sorbates	Combination of antimicrobial agent with LDPE material	Gómez-Estaca et al. (2010)
	Coating: Cinnamaldehyde in Wheat protein-based materials	Inhibited <i>P. expansum</i> , and <i>A. niger</i>	Balaguer et al. (2013)
	Film: nanoparticles based on nisin-loaded poly- γ -glutamic acid/chitosan contained in PEO nanofibers	Bactericidal against <i>Listeria monocytogenes</i> Negligible effects on sensorial parameters	Cui et al. (2016)
	Cold plasma: Dielectric barrier discharge plasma for process at 15 kHz & atmospheric gas, Duration of 0, 2.5, 5 & 10 min	On treating for 4, 10 & 75 s, microbial species like <i>E. coli</i> , <i>L. monocytogenes</i> & <i>S. typhimurium</i> were completely inactivated. Colony decline by 3.2 & 2.1 log cfu/g Completely inactivated <i>E. coli</i> , <i>L. monocytogenes</i> & <i>S. typhimurium</i> after treated for 10 min	Yong et al. (2015a)
	Cold plasma: Dielectric barrier discharge plasma at 3.5 kV and a bipolar 50 kHz (low frequency range) square wave with a 50% duty cycle	For <i>E. coli</i> : Count declined from 0.09 to 1.47 log with He Similarly, He/O ₂ mixture declined microbial count from 0.05 log to 1.98 log. For <i>S. aureus</i> : Count declined from 0.05 to 0.45 log with He Count declined from 0.08 to 0.91 log with He/O ₂ mixture	Lee et al. (2012)
	Cold plasma: Dielectric barrier discharge plasma at 15 kHz with post plasma treatment exposure for 1, 3 & 5 min	Completely inactivated <i>E. coli</i> , <i>S. typhimurium</i> & <i>L. monocytogenes</i> when treated for 90, 60 s & 10 min. Significant reduction in colonies by 2.88, 3.11 & 2.26 log cfu/g was noted for 15 min. Post storage duration further showed a substantial decline in colony count	Yong et al. (2015b)
	Cold plasma: Atmospheric pressure plasma powered by 13.56 MHz using helium gas (75, 100, 125 & 150 W for 60, 90 & 120 s)	Plasma applied at higher power (120 s at 150 W) levels lowered the <i>L. monocytogenes</i> by 8 log cycle. Full degradation of viable cells for 7 days	Song et al. (2009)
	Film: Pullulan based nanofibers Consisted of effective bacteriocin like nisin, along with amaranth protein isolate	Completely disabled microbial activity of <i>Salmonella Typhimurium</i> , <i>Listeria monocytogenes</i> , and <i>Leuconostoc mesenteroides</i> after 142 h, 120 h, and 170 h respectively	Soto et al. (2019)

(continued)

Table 15.2 (continued)

Milk and Milk Products	Technique and processing parameters	Outcomes	References
Cheddar cheese	Film: LDPE and cellulose films coated with peptide of <i>Bacillus licheniformis</i> Me1	Bio-preservative addition in activated film growths limited pathogen	Nithya et al. (2013)
	Film: Linalool in low-density polyethylene (LDPE) films	Inhibited <i>L. innocua</i> , <i>E. coli</i>	Rupika et al. (2005)
	Film: Linalool, Carvacrol, Thymol in Starch-based films	Inhibited <i>S. cerevisiae</i> , <i>S. aureus</i>	Kuorwel et al. (2010, 2011)
	Film: Carvacrol in LDPE and nylon films	Inhibited <i>E. coli</i>	Rardniyom (2009)
	Coating: Starch films containing sodium benzoate (1-SB), citric acid (2-CA), and both (3-CASB)	Reduced microbial (<i>L. innocua</i>) growth on test sample surface	De Moraes et al. (2020)
Mozzarella cheese	Coating: Polyethylene (PE) films containing linalool or thymol	Antimicrobial activity of the film protected against <i>E. coli</i> , <i>S. aureus</i> , <i>L. innocua</i> , and <i>Saccharomyces cerevisiae</i>	Chang et al. (2021a)
	Film: Cellulose acetate films incorporated with pink pepper	Bioactivefilms decreases microbial growth	Da Silva Dannenberg et al. (2017)
	Intelligent packaging: Sachets from microcellular foam starch consisting of rosemary and thyme oil	The growth of LAB and TAB inhibited by the action of volatile oils	Han (2014)
	Film: hydroxy propyl methyl cellulose collated with nisin	Nisin exhibited microbicidal activity against <i>Staphylococcus aureus</i> , <i>Listeria innocua</i> , and <i>Salmonella enterica</i> Films with 10% wt. were more effective in inhibiting microorganisms during storage period of 8 days	Freitas et al. (2020)
Ultra-filtrated cheese	Film: Organoclay nanoparticles incorporated into LDPE films	Increased shelf-life of ultrafiltered cheese quality without toxicity	Peighambardoust et al. (2016)
	Film: Low density polyethylene films incorporated with nanoparticles	Prime sterilizing effect with LDPE films containing Cu-ZnO without silver particles	Beigmohammadi et al. (2016)
	Film: bilayer film based on chitosan, cellulose, and nisin/ Cellulosic paper coated with chitosan-zinc oxide nanocomposite containing nisin	Nisin based films reduced the presence of <i>L. monocytogenes</i> Treatment with 1000 µg/mL completely inhibited <i>Listeria monocytogenes</i> after 14 days storage at 4 °C	Divsalar et al. (2018)
Minas Frescal cheese	Film: Nano based composite films collated with Starch/halloysite/nisin	Acts as a lucrative barrier for avoiding cheese contamination from pathogens such as <i>L. monocytogenes</i> , <i>S. aureus</i> , and <i>Clostridium perfringens</i>	Meira et al. (2016)

(continued)

Table 15.2 (continued)

Milk and Milk Products	Technique and processing parameters	Outcomes	References
Port Salut cheese	Film: NI & NA	Hindered microbial expansion especially MY Maintaining the sustenance of psychrotrophic bacteria. Preventing spoilage from <i>Listeria innocua</i> and <i>Saccharomyces cerevisiae</i>	Resa et al. (2016)
Kashar cheese	Film: Zein and zein–wax coating with lysozyme, catechin, and gallic acid	Out of all, lysozyme-based proved to be beneficial Hindered the growth of <i>L. monocytogenes</i>	Unalan et al. (2013)
	Film: Alginate and zein films containing natamycin (NA)	Inclusion of NA enhanced the antifungal property of the film	Kucuk et al. (2020)
	Film: whey protein isolate films subsumed with antibacterial agent like nisin	Exhibited antimicrobial activity opposed to <i>Salmonella Enteritidis</i> and <i>Listeria monocytogenes</i> . Inactivated the species	Seydim et al. (2020)
Modeled cheese	Film: Cinnamaldehyde in Polypropylene films	Inhibited the growth of vast microbes <i>A. flavus</i> , <i>P. commune</i> , <i>P. expansum</i> , <i>P. nalgiovense</i> , <i>P. roqueforti</i> , <i>P. islandicum</i>	Ben Arfa et al. (2007), Lopez et al. (2007)
Gouda cheese	Coating: tapioca starch & glycerol, along with NI and NA	Negligible effects during ripening process Physicochemical parameters of the product retained Provided extensive barrier against outer contamination	Berti et al. (2019)
Khoa	Vacuum packaging: Bio preservatives (nisin NI and natamycin NA)	Steady till 5 month term at subzero (-18 ± 2 °C)	Bhardwaj and Kumar (2020)
	MAP: Headspace composition of 10% CO ₂ and 90% N ₂ with benzoic acid	Product with preservative, stable upto 12 days Product without preservative, stable upto 8 days	Chowdhury et al. (2017)

literature, it was analyzed that the most suitable methods or the novel techniques for dairy products were ohmic heating, microwave, high pressure processing, pulsed electric fields, microfiltration, and edible films and coatings. Not only dairy, but these methods also proved to be suitable for other food products.

Research on the efficiency of ohmic heating (OH)-induced microbial inactivation in milk showed a higher incidence of microbial mortality compared to traditional pasteurization (Shao et al., 2021). Thermal inactivation is considered to be the primary and most important mechanism of microbial destruction. Kim and Kang (2015) were able to inactivate three main food borne pathogens vis *Escherichia coli* O157:H7, *Salmonella typhimurium*, and *Listeria monocytogenes*. The study subjected skimmed milk to a constant time temperature combination via pasteurization procedure and discovered that ohmic heating was more successful than traditional mechanism of destroying spoilage causing microbes. Nonetheless, a number of

investigations also revealed few non-thermal adverse effect that the electrical field had on microorganisms. According to Kubo et al. (2020), this event, called electroporation, suggests the proliferation of pores inside the microbial cell membrane, thereby resulting in permeability changes. These structural alterations often result in exudation of intracellular materials, ultimately resulting in microbial cell death. This technique is most frequently used in case of products like fruit juices rather than milk or dairy items. Numerous investigations have shown that microwave heating can inactivate bacteria such *Bacillus subtilis*, *Staphylococcus aureus*, *Salmonella spp.*, and *Escherichia coli*, as well as the toxins that *Escherichia coli* produces in dairy products. The penetration depths ranging from typical bands with 8 to 22 cm and from 2 to 8 cm, respectively, are 915 ± 25 MHz and 2450 ± 50 MHz. This technology can be used for heating food. Martins et al. (2019) explained that electricity is usually transformed into electromagnetic radiation, which further collides with the ingredients inside food to produce heat. Such heat, produced as a result of collision with the food matrix, results in heating up of food. It has been demonstrated that High pressure processing or HPP treatment (treatment conditions with 600 MPa for 3–5 min or 500 MPa for 15 min) effectively inactivated harmful bacteria in milk, making it a viable substitute for pasteurization (Liu et al., 2020). However, according to Shabbir et al. (2020), it is said to result in permanent alterations to proteins' secondary, tertiary, and quaternary structures. Due to this, its application is only limited to whey proteins and colostrum.

Bermudez-Aguirre et al. (2011) revealed the outcome of PEF treatment in raw skimmed milk. During the experiment it was found that the mesophilic bacteria were rendered inactive up to a cell count of 10^3 CFU/mL by employing PEF treatment with specific controls ($E = 46.15$ kVcm $^{-1}$; $t = 60$ μ s; $T = 20$ – 40 °C). Reference to various published literatures, it could be established, that as an alternative to sole processing with PEF or thermal pasteurization, collation of PEF processing when appropriately paired with thermal pasteurization can be considered a possible method for pasteurizing milk that delivers better bacteriological quality. In an experiment, 3.6 log of *Bacillus* spores were inactivated by a combination of PEF, nisin addition and thermal treatment. The hurdle combination was employed at control levels of $E = 40$ kV/cm; $N = 144$ pulses; $t = 300$ μ s for PEF and temperature of 65 °C alongside 50 IU/mL nisin value (Bermúdez-Aguirre et al., 2012). Another great example by Yeom et al. (2004) reported that the shelf life of flavoured yogurt-based goods tripled by using a combination of PEF ($E = 30$ kVcm $^{-1}$; $t = 32$ μ s) and heat processing ($T = 60$ °C; $t = 30$ s). When compared to untreated sample, the stability got extended to 90 days (about 3 months) at refrigerated conditions of 4 °C. Researches generally showed that PEF treatment combined with preheating greatly extends milk's refrigerated storage shelf life, making this technique comparable to thermal pasteurization.

Antimicrobial packaging promises to improve microbiological safety and hence serves as a potent method to preserve dairy products. Among large number of these items, cheese received much attention for incorporation of antimicrobial agents (Karaman et al., 2015). Packaging films like polypropylene and polyethylene terephthalate were tested by Otero et al. (2014) for their antimicrobial activity when

coated with essential oil obtained from *Origanum vulgare* and Ethyl Lauroyl Arginate HCl against two strains of pathogenic bacteria *E.coli*. Another study by Incoronato et al. (2011) worked upon Fior di Latte cheese and investigated the efficacy of packaging consisting of silver nanoparticles. The films were successful in retarding microbial growth and preserving the sensory quality of cheese. Furthermore, the functional dairy microbiota of product was also preserved. A study very well focused on mozzarella cheese and investigated the microbicidal efficacy of a film obtained from chicken bone gelatine (CBG). The film was prepared by inculcating cinnamon bark oil (CBO) as an active ingredient. The prime objective of the experiment was to design the films' ability in retarding microbial growth and investigate the antibacterial property against bacterial species like *L. monocytogenes* and *E. coli*. The results concluded a great reduction in number of *L. monocytogenes* when the film was employed over mozzarella cheese. Another recent instance by Motelica et al. (2021) emphasized on improving packaging of cheese sample. The researchers utilized a combination of nanoparticles along with well-known essential oils to exhibit their antimicrobial activity and resultantly positive response. The study gave positive results and concluded that the alginate-based films, formed with silver nanoparticles and lemon grass EO, were able to restrict microbes. As a result of such inhibition, the shelf life of cheese got enhanced by up to 2 weeks. Not only this, the films had high antibacterial properties and hence showed action against gram positive bacteria like *B.cereus* and *S.aureus*, and two of the gram negative bacteria, *E.coli* and *S. typhi*. Out of the four pathogens, the films exhibited the best results against *B.cereus*. Fajardo et al. (2010) also researched on Saloio cheese packaging. The study concluded an improved stability and extended shelf life on employing chitosan and natamycin based packaging films.

One such emerging option is active and intelligent packaging of dairy produce including milk. These provide real-time monitoring of food safety thereby reducing food wastage. Shikonin-based films made from carrageenan/gelatin showed promising efficacy against spoilage causing bacteria such as *L. monocytogenes* and *E. coli* bacteria. This film not only proved to be effective against microorganism action, but also exhibited pH-dependent color variations. These variations helped in identifying the film stability based on pH value. For instance, the film appeared red at pH 2–7, turned into purplish at pH 9, and blue at pH 10–12. Further, these films were able to maintain good color retention even after a period of 3 months. Immersing the film in fresh, decaying, or rotten milk for 10 min caused the color to change from purple to reddish-pink. Simultaneously, a co-relation was developed between red chromatic shift index, pH result, and extent of milk deterioration (Roy & Rhim, 2020). Similar to freshness indicators, Gao et al. (2022) utilized the idea to create a similar indicator packaging film to check milk freshness. This film was prepared by integrating gelatin, anthocyanins extracted from blueberry, and Fe²⁺ into a corn protein matrix via electrostatic spinning. The film tone transitioned drastically and hence became an indicator to determine the freshness of milk. It could be understood when the milk got altered from purple black indicating highly fresh milk, to royal purple which gives a state of spoiled milk, and finally purplered milk which is completely unfit for consumption or spoiled milk.

Lactococcus lactis subsp. *lactis* is known to produce nisin, a natural polypeptide found in vegetable and milk products, which can also be used in antimicrobial packaging. Nisin is effective against both Gram-positive and Gram-negative bacteria, specifically *Listeria monocytogenes*, *Brochothrix thermosphacta*, *Micrococcus avium*, *Lactobacillus helveticus*, and *Pediococcus pentosaceus* (Sobrinho-Lopez & MartínBelloso, 2008). Nisin may bind to a wide range of molecules due to its high surface activity. This binding feature makes it useful for adsorption on solid surfaces as well as helpful in killing bacterial cells that adhere to them (Jin et al., 2009). Lee et al. (2001) used a vinyl acetate-ethylene copolymer binder to coat paper with a 3 mm-thick nisin (bacteriocin) alongside α -tocopherol coating (with nil adjuvant effect) at 3% concentrated value. This quantity was sufficient to provide antioxidative and antimicrobial properties for cream packaging to show efficacy resistant to lipid oxidation and microbial growth, especially *M. flavus* load. Antimicrobial films were produced by incorporating natamycin (NA), nisin (NI), or a combination of the two (NA/NI) into cellulose polymer. These were tested against yeasts, molds, psychotropic bacteria, and *Staphylococcus* sp. on mozzarella cheese slices. By the ninth storage day, the yeast and mold count on cheese surrounded by NA films decreased by 2 log 10 units compared to cheese having standard films. NI film had little effect on *Staphylococcus* sp. but was effective against psychotropic bacteria during cheese storage for six days. Incorporating antimicrobial chemicals reduced film elongation and resistance, resulting in alterations in molecular conformations. Time-dependent natamycin diffusion was observed however when it comes to cheese, no nisin diffusion was marked from the packaging films to the sample product. Furthermore, no repercussions noted with NI-NA consolidate inclusion in films. Another attempt by Sobrinho-Lopez and MartínBelloso (2008) studied the application of a nisin containing cellulose-based packaging. The effect was observed on Cheddar cheese slice subjected to modified atmosphere conditions. The results indicated a considerable increase in shelf life of cheese, probably because of a notable decline in the microbiological counts of harmful bacteria *L. innocua* and *S. aureus*.

Essential oils are well researched as potential microbial inhibitors. These compounds are often incorporated into the films in combination with either polysaccharide, protein, or lipid-based films. Out of these, cinnamaldehyde, being the primary ingredient in essential oils, have great possibility for its use as an antibacterial agent in active food packaging (Sanla-Ead et al., 2012).

Dating back to 2013, Balaguer et al. created the first antimicrobial film for cheese spread using wheat protein-based polymers. These were the carriers of cinnamaldehyde and exhibited action against *Aspergillus niger* and *Penicillium expansum*. The same study stipulated that 10 days of in-vitro storage could completely inhibit the fungal species. This inhibition was made possible in the presence of 3% cinnamaldehyde containing gluten films on cheese samples. Further, when these were subjected to packaging with 5% cinnamaldehyde containing gluten films, no fungal activity was observed even beyond 26 days for storage at 48 °C. Contrary to the EO based packaging, the control cheese samples showed fungal growth after 16 storage days.

Another investigation reported by Kuorwel et al. (2010) showed inhibitory action of phenolic compounds like linalool, carvacrol, and thymol against bacterial species *Saccharomyces cerevisiae*. This was observed in a starch-based film coating on the Cheddar cheese and in vitro. Another important study by Chung et al. (2003) reported a decline by more than 2 logs cell count of *Pseudomonas* spp. in chitosan-based films and despite the fact that controlled cell counts decreased by roughly 1 log over the testing time period of 2-weeks, the significance is questioned. Duan et al. (2007) tested *Candida inconspicua*, and the results revealed negligible inhibition. On testing against molds, the films showed less than a 2-log drop but were nonetheless classified as “complete inhibition”. Torlak and Nizamlioglu (2011) studied the antibacterial effects of 2% wt/vol chitosan coated polypropylene films on bacteria inoculated with Kashar cheese slices. Chitosan-coated polypropylene films showed considerable lower values of *L. monocytogenes*, *S. aureus*, and *E. coli*O157:H7 even after 2 week of storage at 48 °C in efficient vacuum based food packaging. These findings suggest that using chitosan films to wrap cheese in maturation chambers can prevent mold and harmful bacteria from growing on the surface.

Similar to other agents being discussed, lauramide arginine ethyl ester (LAE) is also known to possess notable antimicrobial properties primarily due to its chemical structure and surfactant properties. Muriel-Galet et al. (2012) developed antimicrobial films containing LAE in ethylene vinyl alcohol (EVOH) copolymers with distinct percentage of ethylene contents (29% and 44%). The findings demonstrated that the viable counts reduced with the application of 0.25% and 1% LAE. The concentration of LAE determined the extent of microbial inhibition. On increasing the values up to 5% and 10% LAE, the films provided total growth inhibition. Further, to determine the effectiveness of the films, these were applied to an infant formula milk inoculated with *Listeria monocytogenes* and *Saccharomyces enterica* kept for a storage period of 6 days at low temperature of 4 °C. It was presumed that the utilization of films with 10% LAE when used in sensitive products like infant formula, further consisting of *L. monocytogenes* declined approximately 4 log, and when applied with *S. enterica*, the reduction was 3.74 log and 3.95log with (EVOH-29) 5% and 10% respectively. Additionally, the reduction was 1log and 3.27log with (EVOH-44) 5% and 10% respectively.

Natamycin is considered an antifungal agent occurring naturally during fermentation by the bacterium *Streptomyces natalensis*. Various research and experiments have been undertaken to focus on different sets of products with an aim to identify potent applications of natamycin in active packaging. De Oliveira et al. (2007) evaluated films with different natamycin concentrations in Gorgonzola cheese. This was performed to assess the film performance on cheese surface against *Penicillium roqueforti*. The study concluded that the films with 2% and 4% showed significant inhibition in fungal growth. Similarly, active coating of CMC with different concentrations of natamycin was assessed in cheese by Azhdari and Moradi (2022).

Cocoa flavanols have gained popularity due to their antioxidant properties and potential health benefits. Novel EVOH films with flavonoid-rich cocoa were created. Films applied to infant milk formula inoculated with *L. monocytogenes*

inhibited bacterial growth by 1.5 log units on the first day and 0.52 and 0.76 log units by the sixth day, respectively. Furthermore, it was also observed that direct addition of cocoa had no effect (Katz et al., 2011). Study by Calatayud et al. (2013) reported that the release of components from cocoa extract was highly influenced by both temperature and antioxidant content present in the film.

Another research by Divsalar et al. (2018) used chitosan, cellulose, and nisin to create a bilayer film with antibacterial qualities. After a 2 weeks period at 4 °C, the films containing 1000 µg/mL could completely eliminate the growth of *Listeria monocytogenes* from the surface of ultra-filtered (UF) cheese. Cui et al. (2017) created nanoparticles based on nisin-loaded poly-γ-glutamic acid or chitosan. These were packed in PEO nanofibers and assessed against the anti-*Listeria* activity of the particles on cheese. The findings demonstrated that the prepared nanofibers had strong antibacterial activity against *Listeria monocytogenes* while having negligible changes on the sensory aspect of cheese sample. Seydim et al. (2020) prepared films which could inactivate the growth of *Salmonella* Enteritidis and *Listeria monocytogenes* in cheese. The efficacy was observed with whey protein isolate films comprising nisin and subsequently used on kasar based cheese slices inoculated by bacterial species including *Listeria monocytogenes*, *Salmonella* Enteritidis, *Escherichia coli* 0157:H7, *Staphylococcus aureus*, and *Penicillium* spp. Berti et al. (2019) worked upon Gouda cheese. The samples were covered with a tapioca starch and glycerol based edible coating, comprising additional components like nisin and natamycin. Considering the fusion of spoilage causing bacteria such as *Listeria innocua* and *Saccharomyces cerevisiae*, the research concluded that the films provided better protection against external contamination. Surprisingly, the coatings did not affect the physico-chemical parameters of cheese samples. Surprisingly, the growth of *Lactobacilli* development during the ripening process remains unaffected as well. By combining nisin with hydroxypropyl methylcellulose. Additionally, bacteriocins have also been an area of interest. Here, using bacteriocins in direct contact with food in packaging improves the product's safety and quality. Since food deterioration may occur because of microbial growth, such usage of bacteriocins also enables an extension in the shelf duration of foods (Batiha et al., 2021).

Pseudomonas observed with coliform populations reduced in mozzarella cheese when the samples were held for eight days at 4 °C, demonstrating the antibacterial activity of lysozyme active together with EDTA. Another similar instance by (eDel Nobel, 2012) presented a positive response in Burrata cheese packaged under modified atmosphere conditions. When applied to Kashar cheese, chitosan-coated polypropylene films worked as an antagonist against spoilage microflora for the course of the 14-day vacuum-sealed storage period. This resulted in a significant decrease in the number of microorganisms in comparison to the controlled cheese. Antibacterial peptides from *Bacillus licheniformis* applied as a film on another dairy product like paneer significantly decreased the population of *L. monocytogenes* (Nithya et al., 2013). *P. roquefortii* in Gorgonzola cheese was satisfactorily inhibited by a film containing 2 and 4% natamycin (Seydim et al., 2020). After a week of storage at 4 °C, nisin-coated sodium caseinate film significantly contracted the number of *L. innocua* in small red Baybel cheese (Cao-Hoang et al., 2010). By

slowing down the growth of *L. monocytogenes* in ricotta cheese, the shelf life of cheese was extended. This was possible by employing nisin added through edible coatings of sodium caseinate and galactomannans (Martins et al., 2010). The growth of *A. niger* and *Penicillium roquefortii* were also suppressed by natamycin, which was applied to kashar cheese as part of novel yet sustainable methods including edible coating system (Ture et al., 2011). During the stipulated storage period, natamycin-coated semihard cheese retarded the growth of microorganisms especially yeasts and molds (Fajardo et al., 2010). Min et al. (2010) reported that Turkey-bologna kept at 4 °C inhibited *L. monocytogenes* by treatment with an edible gelatin coating system. Similar inhibition was observed when nisin was applied by edible coatings to fresh beef and ricotta cheese (Martins et al., 2010). During the course of product storage, the counts of mold, yeast, and aerobic mesophiles were significantly reduced by the lemongrass EO-sachets. Thyme essential oil sachets along with a combination of thyme and rosemary essential oils (EO) showed significant anti-listerial activity in shredded mozzarella cheese stored at low temperature, as well as a decrease in total aerobes and lactics (Han et al. 2015). When placed on cottage cheese, AITC sachets greatly suppressed the formation of mold and yeast. Pereira de Abreu et al. (2012) observed a 4-log decrease in *Staphylococcus spp.* in mozzarella cheese as a result of AITC sachets. Food-borne pathogens in milk were effectively inhibited by thymol encapsulated in sodium caseinate (Pan et al., 2014). It was discovered that nisin-loaded chitosan nanoparticles were useful for preserving cheese (Zohri et al., 2013). It is also said that the findings of thymol as a nano-dispersed system were much better than those of the traditional application. In low-fat milk and apple cider, thymol was added as a nano-based complex involving whey protein isolate and maltodextrin, which efficiently suppressed the food-borne pathogens (Shah et al., 2012). The use of nano-emulsified thymol was shown to have a remarkable anti-listerial effect in milk, to the extent that, 48 h after application, the population of bacteria was minimal (Xue et al., 2017). Chen et al. (2015) employed spray drying to create a co-encapsulated system that included thymol and eugenol in zein/casein nanoparticles. After being rehydrated and added to milk whey, this nanoparticle system demonstrated antimicrobial or bacteriostatic activity against toxic bacterial species such as *Escherichia coli* and *Listeria monocytogenes*.

4 Meat and Meat Products

Meat, being a perishable commodity, provides an eminent medium for life sustenance of spoilage causing bacteria. Over the time, it has been observed that microbial growth fosters pathogen development and unpleasant organoleptic changes in packaged meats. Owing to their high water activity, both red and white meats have great potential for bacterial growth (Bader et al., 2021). Therefore, their perishable nature necessitates the efficacy of antimicrobial packaging in such a way that it monitors and controls the appropriate microbial count in meat products (Talebi

et al., 2018). Mizielińska et al. (2018) highlighted that incorporating lactic acid bacteria into biopolymer films form a lucrative yet novel approach in active packaging systems. At the same time, Barcenilla et al. (2022) clarified that these bacteria are widely utilized for both vacuum and modified atmosphere packaging due to their resistance to carbon dioxide. Some of the well-known antimicrobial agents for active packaging of meat includes biopolymers like chitosan, organic acids and/or their related acid anhydrides and alcohols. Besides these, Mizielińska et al. (2018) also mentioned that bacteriocins have a great potential to restrict food borne pathogens. The same study also reported nisin, pediocin, efficient chelators, and lysozyme as effective antimicrobial agents. When it comes to essential oils, their extensive odor on application to meat limits their use as an antimicrobial agent (Fang et al., 2017). Trbojevich et al. (2020) provided new insights into the silver-based packaging to prevent beef spoilage. Soysal et al. (2015) conducted research using antimicrobial agents that provide a significant medium of action. These agents include nisin (an effective bacteriocin), chitosan (a polysaccharide), potassium sorbate (PS) (a chemical salt), and silver substituted zeolite (AgZeo). Their effect was investigated after incorporating them into LDPE films and results indicated a lower count of mold, yeasts, total coliform, and aerobic mesophilic bacteria (APC) in chicken drumsticks. Out of all agents, chitosan-based films were reported to be the most successful in improving the shelf stability of the product at 5 °C for 6 days by reducing APC, mold and yeast count. Besides chitosan, the sequence of activity follows the order nisin, Ag Zeo, and then potassium sorbate.

Additionally, Mehdizadeh et al. (2020) concluded a shorter shelf life for fresh meat at 4 °C (3–5 days). There have been studies on anthocyanins to investigate their effectiveness in active and intelligent packaging. One such study by Hao et al. used anthocyanins from black rice bran (BRBAs) and prepared a film along with oregano essential oil (OEO). Essential oils have been the centre of attention quite lately and hence numerous research have been carried out due to their potent application in active packaging systems. Moreover, the study reported that CS-OEO-BRBA film reduced the bacterial spoilage in pork, restricted the emergence of any objectionable odor and improved the sensory index of pork. Further, it also restricted the rise of pH thereby improving the quality attribute of the pork as well. The results continued to display that the film turned from red to bottle green in color at the end of 12th day indicating the loss of commercial value of pork (Hao et al., 2023). Another study focused on developing a film, and as a result of the experiment, the researchers were able to obtain an active and intelligent film which could potentially keep a check on pork originality and freshness. Here, the TVB-N value of 15.16 ± 1.15 mg/100 g was obtained on the first day, indicating that pork is unfit. A slight shift in the color of meat could be observed from blue to navy blue, however it was not significant enough to assess the nature of meat. Therefore, when the color changed drastically to green and subsequently the TVB-N value increased to 24.32 ± 1.02 mg/100 g on the second day, it could be said that the pork has now been severely spoiled (Wang et al., 2023). The films are also employed to delay the microbial growth in meat products.

Kaewprachu et al. (2018) experimented using minced hog flesh as the test sample. Nisin and catechin were incorporated into a gelatin-based film to study the shelf life of test sample. The concept of the paper was based on the efficacy of gelatin-based film in improving shelf life of the hog flesh. The results of the study highlighted that the films could retard microbial growth and lipid oxidation. Cao et al. (2019) worked on fresh pork loin by employing MAP with a combination of coatings including nisin, gallic acid, & chitosan. The test was performed to determine the preservative effect during cold storage of pork. According to the findings, the best solution was to use a coating made of chitosan, nisin, and gallic acid, primarily, because it had the lowest TBARS (thiobarbituric acid reactive substances) value, preserved better product color, and had synergistic bactericidal effects. The findings also concluded a lower lipid and protein oxidation. Another experiment employed a coating on Yao meat to study the longevity of the food sample. This experiment as conducted by Liu et al. (2020), attempted to create a nano based emulsion comprising of antibacterial agent like nisin, an effective essential oil suitably extracted from star anise, and polylysine. The nano emulsion was employed over the sample, Yao meat. It was concluded that the coating maintained color and odor of the meat and showed no substantial effect on the moisture content of food up to a period of 20 days. Moreover, the longevity of the meat sample was improved and resulted in an increased shelf life by 8 days. There have been instances involving novel techniques like high-pressure processing along with utilizing active films to study the efficacy over a wide range of food products. One such research was opted by Martillanes et al. (2021) wherein dry-cured Iberian ham was utilized to study the potential of proposed combination of HPP and chitosan-based film. The said ham, inoculated with *Listeria monocytogenes* reported a lower bacterial count post application of the film containing nisin and/or rice bran. The results were quite positive and the correlation of HPP with the films concluded a reduced bacterial count by 6log CFU/g. Yang et al. (2020) tested on a RTE ham by utilizing nanotechnology-based agents. The experiment made use of cellulose nanofibrils and/or nisin nano-hybrid films. As a result, the films were capable of inhibiting *Listeria* spp. completely when they were stored at 4 °C for a week. Several researches considered sausage subjects as the cornerstone of their experiments. Another classic example worth mentioning is that of a collagen casting inculcated with a known bacteriocin, that is, nisin and applied to Vienna sausage by Batpho et al. (2017). The study showed results at two different temperatures. The shelf duration of sausage increased for 90 days (about 3 months) at 4 °C and up to 49 days at 10 °C. Another remarkable investigation by Pattanayaing et al. (2015) reported the effect on pullulan films on turkey breast slices. The films had lauric arginate along with nisin, either alone or blended to form a constructive pair with each other. They were quite effective against the bacteria *Salmonella typhimurium* and *Salmonella enteritidis* and happened to reduce their load during the testing period. During cold storage, it is notable that the films could also reduce *Staphylococcus aureus* and *Listeria monocytogenes* load on ham surfaces. Morsy et al. (2018) could successfully inhibit the growth of *Escherichia coli* O157:H7, *Listeria monocytogenes*, and *Bacillus cereus* by using distinct yet valuable combinations of lysozyme (L, 500 U/mL),

EDTA nanoparticles (E, 5 mM), ZnO nanoparticles (Z, 12 mM), and nisin (N, 1000 IU/mL). When the effects on packaged minced beef were assessed, the greatest collective actions were determined by LNZ, and LNEZ at 4 °C for 15 days. Similarly, Gedarawatte et al. (2022) applied cellulose nanocrystals and nisin based nano coatings on beef and reported no changes in sensorial and physicochemical properties. Reduced bacterial growth was observed when nisin was accompanied by cellulose nanocrystals and the results were more preferable when compared to nanocrystals alone. Another significant work by Lin et al. (2022) prepared edible nano particles using agents like *Lycium barbarum* polysaccharides along with nisin and rosemary essential oil. The study reported their favorable preservative effect on beef color and texture. Fish subjects have also been of quite interest to researchers. For instance, study on yellow croaker with a combination of chitosan and nisin was conducted by Guohua et al. (2016) during the storage period of 8 days at 4 °C. As discussed in previous sections as well, this study also concluded better quality parameters when nisin was present. These improvements include moisture loss control, controlled viable count, restricted spoilage, reduced TVB-N value, and maintaining sensorial acceptability. Kakatkar et al. (2017) tested a coating on seer fish steaks using a gel dispersion, nisin, and gamma irradiation. The study concluded that the afore-mentioned combination could upgrade the shelf-life of samples during cold storage term. An increase in storage period from 7 to 34–42 days was observed. Also, nisin and curcumin proved to be an effective material in improving the shelf life of products like fish. It was proved by Meral et al. (2019) wherein such nano mats were used as coatings on fish fillets which exhibited adequate sensorial characteristics even by the end of tenth day of their storage period. This was contrary to the sensory attributes of the control samples which were acceptable only up to their fourth day of storage. With this, it was noted that the shelf-life of samples treated with applicable coatings were significantly enhanced by 12 long days. A new packaging material was created by Oner et al. (2021). The study mixed nisin-loaded PVA-based nanofibers with polyethylene (PE) and the resultant material provided better sensory attributes compared to the control ones. Further, it could be noted that the development of LAB and total mesophilic bacteria reduced by 38% and 31% in fish fillets, respectively. Cen et al. (2021) studied the outcome and hence the resultant action of preservatives on shrimp quality (*Penaeus vannamei* species). The distinct preservatives used as a part of this study includes chitosan, sodium alginate, and nisin, all applied during cold storage of the product. The results concluded lower values for marked parameters such as pH, TVB-N, TVC (total viable count), together with freshness indicator contrary to the untreated or reference samples. Moreover, this experiment conducted could substantially reduce the microbial count thereby resulting in a longer product life. EDTA is an economical alternative due to its potential to hinder bacterial growth, especially gram-negative bacteria. Chang et al. (2021b) added nisin and EDTA to a chitosan-PLA composite film and performed an experiment to determine its application in fish fillets. This resulted in a substantial reduction in microbial load. Out of the microorganisms, coliforms and mesophile count got decreased substantially. Such experiments also aid in preventing any further microbial spoilage thereby preventing food from deterioration.

Besides the major outcomes, the total volatile basic nitrogen content also got reduced at distinct temperatures of 4 °C and 25 °C.

Plant-based alternatives have gained wider attention because of their sustainable and eco-friendly nature. Besides being an extensive source of protein for human diets, these alternatives have found their place in packaging industry as well. Therefore, their increased demand eventually led to the progress of plant-based packaging films employing good source proteins like soy proteins. In this regard, Emiroglu et al. (2010) demonstrated the efficacy of a rich protein source, soy-protein, based films associated with thyme and essential oils (majorly oregano based) in beef patties. The results reported that 1.5% concentration of oregano EO was able to possess antimicrobial action against pseudomonas species and various other microflora species. Calo et al. (2015) mentioned that on application of Limonene on chicken, preferably its legs and thighs, the growth of a pathogenic bacteria like *Campylobacter jejuni* was completely inhibited. When applied to ground pork, Saturejahorvatii essential oil containing p-cymene and thymol, inhibited *L. monocytogenes*, increasing its keeping quality (Bukvicki et al., 2014). Pisoschi et al. (2018) discovered that employing a combination of multifunctional protein like lactoferrin along with a significant antimicrobial compound such as nisin potentially safeguards the product quality and improves the overall characteristics of Turkish meatballs. While the combination ensures food safety, it is also proven to reduce the spoilage-causing bacteria from foods. Gyawali and Ibrahim (2014) significantly reported that on storing chicken breasts at 4 °C for 72 h, carvacrol films could inhibit the growth of *E. coli*, *S. enterica*, and *L. monocytogenes*. Modified atmosphere packaging (MAP) has been put forth to limit the oxygen to facilitate shelf-life extension. In line with this, Irkin and Esmer (2010) conducted a study to highlight the action of bay essential oil in combination with MAP. The study could well establish the fact that excluding oxygen as a part of MAP controlled the growth of bacterial species such as *L. monocytogenes* and *E. coli* in ground chicken meat. Since it has already being shown beyond doubt the ability of MAP to improve the product stability, this experiment is one such instance which also reported an increase in shelf life of the food subject. Huang et al. (2019) employed nisin and EDTA in both forms i.e. alone or in combination resulting in shelf stable fresh chicken for straight 24 days under MAP conditions at 4 °C. The keeping quality of the shrimp meat was improved with the help of garlic oil based chitosan coating (Asik & Candogan, 2014). Similarly, incorporating lactoperoxidase in chitosan-based coatings positively influenced the shelf life of trout fillets at 4 °C for 16 days (Jasour et al., 2015). Besides, Pan et al. (2014) constituted whey protein isolates and oregano EO to test the efficacy of edible coatings in improving shelf life of chicken breasts. When under refrigeration, the coatings maintained the microbial counts below the acceptable limits from 6 to 13 days of storage. When incorporated into the film, Carocho et al. (2015) showed the effect of antimicrobial agent against bacteria. They implied cellulose based films with pediocin, which are proteinaceous antimicrobials in general, and studied their effect in sliced ham for 15 days of storage at a temperature of 12 °C. They concluded that the film with pediocin could inhibit the microbial growth (especially *L. innocua*) as compared

to the films without pediocin. Kuorwel et al. (2011) explored the antibacterial properties of nisin using various types of films on food products like hot dogs, boiler drumstick, ground beef and oysters. It was concluded that the films could significantly diminish the bacterial load in meats like oysters and beef. At the same time, nisin could inhibit definite microorganisms, especially bacterial species in different food commodities mentioned above. For instance, the study concluded a hinderance in the growth of *L. monocytogenes* in hot dog samples. Similarly, *S. typhimurium* was restricted when tested on boiler drumstick skin. Further, another literature by Unalan et al. (2011) utilized zein films in combination with lysozyme and di-sodium EDTA and successfully established the antimicrobial action of the films against pathogens in beef patties. Other studies highlighting the antimicrobial effect of various essential oils have centered out various products to perform upon. Another remarkable example include *Pimpinella affinis* in silver fillets as reported by Ariaii et al. (2015). Following this, oregano essential oil in rainbow trout was studied to understand the efficacy of EO in improving food product stability (Hosseini et al., 2016), and horsemint in carp fillets sets an example for novel method of preservation (Heydari et al., 2015). Chitosan coatings constituted with lysozyme brought a four-fold reduction in the proliferation of *S. enteritidis*. Shivangi et al. (2021) observed the reduction throughout a 4-week storage period at 10 °C in hard-boiled eggs. The shelf life of trout fillets enhanced by executing nano emulsions with sunflower as base containing *Zataria multiflora* essential oil. Shadman et al. (2017) reported further inhibition of lipid oxidation in fillets. There is extensive research put forward on the triumph of edible coatings as an exceptional delivery medium. These studies highlighted the positive outcome of such use and elucidated the role of antimicrobials in food preservation as a lucrative step (Table 15.3).

5 Other Food Products

Although consumers enjoy seafoods, certain biochemical reactions may occur as a result of microbial growth thereby inducing spoilage during storage. Bacterial spoilage of aquatic products can be induced as a result of degradation of proteins like trimethylamine and dimethylamine. Consequently, such reactions lead to an increase in pH thereby becoming an important quality parameter. Subsequently, alteration in pH value also brings about a series of reactions in the product. Hematian et al. (2023) mentioned that the changes in pH can also cause modification in the molecular structures and conformation of anthocyanins within the packaging films thereby inducing a change in the color of the film. These natural pigments have gained wide interest as freshness indicators and are highly correlated with several factors. The study concluded that the color of active and intelligent films was highly dependent on several factors. These factors are large in number but not limited lipid peroxide value, colony count, and salt volatility. Besides the major factors, other components crucial to monitor the color of the film and hence the end product includes nitrogen content and pH value of the product. Smart pH-responsive films have also been

Table 15.3 Shelf-life extension of meat and meat based processed products

Meat and Meat based products	Shelf-life extension techniques	Formulation parameters	Outcomes	References
Bacon	Cold plasma	Atmospheric pressure plasma treatment at 100 W for 1.5 min	Microbial load reduced resulting in better food safety and shelf stability	Kim et al. (2011)
Meat	Bioactive packaging films	Chitosan-nano Zinc oxide(ZnO) antimicrobial flexible pouches Chitosan—2% (w/v) Zinc acetate dihydrate (1–2 g)	Inhibited microbial growth for a period of 6 days in raw meat stored at 4 °C	Rahman et al. (2017)
	Bioactive packaging films	Chitosan –nanocellulose (NC) films chitosan—1% (w/v) NC—0.18% (w/w)	Nanocomposite films decreased LAB count in test sample on storing up to 6-days	Dehnad et al. (2014)
	HPP	At 20 °C, 600 MPa for 3 min	No microbial concern, food safety ensured Improved shelf life for 98 days of storage at 4 °C	Hayman et al. (2004)
Chicken meat films	Bioactive packaging films	Chitosan films incorporating peanut skin (PS) and pink pepper residue (PPR) extract chitosan—2% (w/v) PS—0.84% and PPR1.90% (v/v)	Enhanced shelf-life Retarding microbial growth Quality of chicken also improved by reduced lipid oxidation	Serrano-Leon et al. (2018)
Pork	Bioactive packaging films	Lysozyme	Could assemble chitosan organic rectorite layer by layer	Huang et al. (2012)
		Nisin, EDTA, and PBAT/TPS blends	Prevented lipid breakdown Bacterial proliferation inhibited Increased stability of meat redness Delayed discoloration in meat	Liu et al. (2020)
	Edible film	Gelatin-based films formed by incorporating nisin and catechin	Reduced microbial load and restricted proliferation Prevented lipid oxidation	Cao et al. (2019)

(continued)

Table 15.3 (continued)

Meat and Meat based products	Shelf-life extension techniques	Formulation parameters	Outcomes	References
Pork loin	Edible coating	Coatings-nisin/gallic acid/chitosan	Product color and visual appearance retained Reduced fat and protein oxidation Lowest TBARS value observed Coating gave a collective bactericidal effect	Leelaphiwat et al. (2022)
Pork meat patties	Bioactive packaging film	Chitosan film incorporated with tea polyphenol (TP) chitosan—2% (w/v) TP—30% (w/w)	Improved product shelf-life by retarding microbial growth throughout 6-days	Qin et al. (2013)
Pork sausages	Bioactive packaging film	Chitosan film incorporating green tea extract (GTE), CS—2% (w/v) GTE—20% (w/w)	Maintained the sausage quality Enhanced product shelf-life	Siripatrawan and Noipha (2012)
Chicken drumsticks	Intelligent packaging	Nisin, Chitosan, Potassium sorbate, Silver substituted zerolite	Beneficial multilayer with active functioning (LDPE/polyamide)	Soysal et al. (2015)
Beef	Coating	Nanocoating based on bacterial cellulose nanocrystals with and without nisin incorporation	Maintained sensorial and physicochemical properties. Inhibited microbial growth	Lin et al. (2022)
Minced beef	Bioactive packaging film	Combinations of lysozyme 500 U/mL (L), nisin 1000 IU/mL (N), EDTA nanoparticles 5 mM (E), and ZnO nanoparticles 12 mM (Z)	Collective microbicidal effect noticed for LNZ and LNEZ, 15 days of storage at 4 °C Efficiently retarded <i>Escherichia coli</i> O157:H7, <i>Listeria monocytogenes</i> , and <i>Bacillus cereus</i>	Gedarawatte et al. (2022)
	Bioactive packaging film	Kombucha Tea Extract of 1 to 3% (w/w) added to form a combined Chitosan based film	Beef quality retained Microbial growth hindered Broadened the product life by 3 days	Ashrafi et al. (2018)

(continued)

Table 15.3 (continued)

Meat and Meat based products	Shelf-life extension techniques	Formulation parameters	Outcomes	References
Sliced ham	Bioactive packaging film	Poly(hydroxybutyrate) (PHB)/poly(caprolactone) /nisin film	Quite efficient opposed to <i>Lactobacillus plantarum</i> CRL691 Product life significantly improved	Martillanes et al. (2021)
Dry-cured Iberian ham	Bioactive packaging film combined with (HPP)	HPP employed Chitosan-based films prepared with nisin and/or rice bran	Microbial count for <i>L. monocytogenes</i> reduced by 6 log CFU/g	Yang et al. (2020)
Ready-to-eat (RTE) ham	Bioactive packaging film	Cellulose nanofibrils/nisin nanohybrid films	Absolute hinderance of <i>Listeria monocytogenes</i> for 1 week at 4 °C	Batpho et al. (2017)
Yao meat	Bioactive packaging film	Nanoemulsion incorporated with nisin, star anise EO, and polylysine	Product characteristics like color and odor maintained Nil effect on moisture content for about 20 days Prolonged life by 8 days	Correa et al. (2017)

produced to monitor such quality changes in aquatic products. Shikonin is a natural pigment extracted from *Lithospermum erythrorhizon* root. Several studies have indicated its antioxidant and antibacterial activity. One such instance reported by Ezati et al., highlighted the antioxidant effect of Shikonin as a result of its release from complex films. Additionally, the said film also exhibited an inhibitory effect on bacteria *Listeria monocytogenes*. It could be seen that the growth of bacteria reduced to three-fold after 12 h in shikonin-induced films as compared to the pure films. When it comes to aquatic products, preserving their color is of utmost importance. More importantly, microbial activity is considered as one of the major reasons for spoilage of sea foods like shrimp, especially when stored at lower temperatures. It is when active films or coatings come to the rescue and proved to be an effective method maintaining shrimp quality during its storage period (Wu et al., 2024).

Seafoods often come into the talk of foodborne outbreaks. Although they are rarely reported in India (only 37 outbreaks in the last 30 years), United States reported quite a significant portion of outbreaks. Meat based foods were largely

responsible for about 500–1500 outbreaks in the US. In India, majority cases were due to bacteria, predominantly *Salmonella* spp. followed by *Vibrio* spp. and *Staphylococcus aureus*. Besides microbial growth, oxidation of food also affects the shelf life of the product. For instance, meat and fish are comminuted products and are highly perishable in nature (Khatodiya and Malik, 2022). Foodborne pathogens can easily incorporate into the inner muscle layers of such foods making it relatively more difficult to remove them after. These cases significantly question the health and well-being of humans. Therefore, the incorporation of various antimicrobial and antioxidant agents into the packaging films is a promising solution to these concerns whilst minimizing the use of synthetic preservatives as well. At low temperatures of 4 °C, fish may also be susceptible to microbial spoilage. Kanatt (2020) was able to develop an active film with *Amaranthus* leaf extract that could possibly inhibit the growth of *S. aureus* and reduce the total bacterial count. The leaf extract-induced films were successful in increasing the shelf stability of fish by nine days. Further, it was also reported that any change in color from red to yellow in the fish would resultantly mean that it is spoilt and not fit for further consumption. Besides fish, for meat products like pork, chicken, etc. several studies including those by Qin et al. (2013) along with another worthwhile study by Serrano-León et al. (2018) reported fabrication of chitosan-based films. These films when incorporated with acetic acid, were found to be more effective than LDPE films in maintaining the freshness of the chilled meat. They effectively restricted microbial growth and the results of the same study indicated that it was due to the antibacterial nature of the films. Green tea extracts are known for their ability to prevent lipid oxidation in foods. Consequently, these are quite suitable when combined with chitosan-based film to boost the shelf duration of products like pork sausage (Siripatrawan & Noipha, 2012). The cited study concluded that the pork covered in chitosan-based films showed lower changes in terms of characteristics like color, texture, TBA value and other sensory aspects. They further suggested that such films can be a suitable option for extending the duration of pork sausages.

Saeed et al. (2022) investigated the effectiveness of different essential oils in rice-based foods. These essential oils were collected from various sources and were utilized in the experiment to determine the efficacy against bacterium *Bacillus cereus*. These oils were extracted from sources oregano, thyme, and basil which gave positive results. Considering the fact that breads are quite susceptible to mold spoilage, a study concluded that sachets containing oregano essential oil were proven to reduce the formation of fungi on bread surfaces (Passarinho et al., 2014). AITC sachets could exhibit an inhibitory effect on *Aspergillus flavus*-induced post-harvest sporulation in peanuts. A five-fold decrease in the microorganism's population was seen even after 60 days of storage, suggesting that peanuts were safe for consumption.

As concluded by Li et al. (2015) and many other remarkable experiments, ozone treatment is quite successful for eliminating different types of microbial agents. Apart from microbes, the ozone process is known to inhibit the action of mycotoxins, aflatoxins, and other pests as observed during grain preservation (Table 15.4).

Table 15.4 Shelf-life extension of other food products

Cereal Commodity	Shelf-life extension technique	Agents or components	Outcomes	Reference
Salmon	Bioactive packaging film	CS film with grape seed extract (GSE) and carvacrol microcapsules (CM), CS—2.0% (w/v)	Refrigerated sample showed better shelf-life by 4–7 days	Alves et al. (2018)
Yellow croaker	Coating	Chitosan base incorporated with nisin	Nisin's presence resulted in better characteristics Total viable count controlled Original color retention Sensorial parameters maintained originality	Guohua et al. (2016)
Fish fillets	Additives	Nanomats containing nisin and curcumin	Sensory qualities maintained up to 10 days of storage Product durability enhanced upto 12 days	Meral et al. (2019)
	Smart packaging	Nisin-loaded PVA-based nanofibers with PE	Slowed down total mesophilic bacteria by 31% Slowed down LAB count by 38% Improved sensory aspects	Oner et al. (2021)
	Bioactive packaging film	Chitosan-poly(lactic acid) composite added with nisin and EDTA	Decline spoilage bacteria Coliform and mesophile count reduced Further restricted total volatile N ₂ content through storage at 25°C and 4°C	Chang et al. (2021a, b)
Grass carp fillets	Bioactive packaging film	Chitosan film containing thinned young apple polyphenols (YAP) Concentration values used: Chitosan—2% (w/v) YAP-1.0% (w/w)	Enhanced shelf-life of sample during cold storage conditions.	Sun et al. (2018)

(continued)

Table 15.4 (continued)

Cereal Commodity	Shelf-life extension technique	Agents or components	Outcomes	Reference
Minced trout fillet	Bioactive packaging film	Chitosan–gelatin (GL) film used grape seed extract (GSE) along with <i>Ziziphora clinopodioides</i> essential oil (ZEO) Chitosan/GL- 60:40, GSE—1 or 2% (w/w), ZEO—1 or 2% (w/w)	Refrigerated temperature enabled a prolonged fish life upto 11-days	Kakaei and Shahbazi (2016)
Hake fillets and sole	Bioactive packaging film	Chitosan—3% (w/v)	Fish quality enhanced when stored at refrigerated temperature	Fernandez-Saiz et al. (2013)
Seer fish steaks	Edible coatings	Gel dispersion of seer fish Formed with nisin and γ -irradiation	Cold storage gave positive results Improved product duration from 7 days to a range of 34–42 days	Kakatkar et al. (2017)
Japanese sea bass (<i>Lateolabrax japonicus</i>) fillets	Edible coating	Chitosan coating inculcated using citric acid (CA) or licorice extract (LE), Conc. Utilized as CS—1.5% (w/v) CA—0.5% (w/v) or LE—1.0% (w/v)	Microorganism growth inhibited Lipid oxidation retarded	Qiu et al. (2014)
Fish balls	Coating	Zein incorporated nisin (54.4 AU/cm ²) or nisin/EDTA 568 μ g/cm ²	Decline in microbial count for species <i>Escherichia coli</i> , <i>Enterobacter aerogenes</i> , and <i>Citrobacter freundii</i> observed from 3.19 ± 0.03 log CFU/g. Opposing, the reference sample valued at 6.08 ± 0.23 log CFU/g	Lin et al. (2011)
Sea bass (<i>Dicentrarchus labrax</i>) fillets	Edible coating	Chitosan and alginate together with resveratrol powder Chitosan—1% (w/v), Alginate—1.5% (w/v)	Hindered microbial growth Fillet oxidation prevented	Martinez et al. (2018)

(continued)

Table 15.4 (continued)

Cereal Commodity	Shelf-life extension technique	Agents or components	Outcomes	Reference
Bigeye snapper and tiger prawn slices	Bioactive packaging film	Thermoplastic starch/PBAT (Polybutylene-adipate-co-terephthalate) film coated with Gelatin with lauric arginate (LA) Gelatin, LA with nisin	Nisin assisted in hindering bacterial growth For <i>Salmonella Typhimurium</i> ATCC 14,028 combined with <i>Vibrio parahaemolyticus</i> , inhibition for 28 days at 4 °C For <i>Salmonella Typhimurium</i> alone, 60 days at –20 °C Consider <i>Vibrio parahaemolyticus</i> stopped after 14 days (bigeye snapper) <i>Vibrio parahaemolyticus</i> stopped for 21 days (tiger prawn)	Pattanayaifying et al. (2019)
Cereal	Anti-microbial agent in active packaging	Zein/Alginate with titanium dioxide nanoparticles and betanin	Synergistic effect of titanium dioxide nano particles and betanin as antimicrobial activity against food borne pathogens. Approved <i>in-vitro</i> cell cytotoxicity assay	Amjadi et al. (2020)
Fresh pasta	Modified atmosphere packaging and anti-microbial agent (Potassium sorbate)	Multilayer film made of polyethylene Terephthalate (PET), Ethylene-Vinyl Alcohol (EVOH) and polyethylene (PE), Carbon-dioxide: Nitrogen 22:78% (Modified atmosphere packaging)	Combination of filtered air with anti-microbial agent extended the shelf-life from 20 days (air packing) to beyond 40 days when stored at 8 °C	Lucera et al. (2014)

(continued)

Table 15.4 (continued)

Cereal Commodity	Shelf-life extension technique	Agents or components	Outcomes	Reference
Fresh pasta filled with cheese	Modified atmosphere packaging	Tray: EVOH/PS/PE (Ethylene-vinyl alcohol polymer/Polystyrene/Polyethylene) wrapped in film: EVOH/OPET/PE (Ethylene-vinyl alcohol polymer/oriented PET/Polyethylene), Carbondioxide:Nitrogen 50:50% Modified atmosphere packaging	Widened shelf life from 7–14 days (air packing) to more than 42 days at 4 °C	Sanguinetti et al. (2011)
Sliced wheat bread	Active packaging	PET-SiOx (silicon and its suboxides)/ (Low density polyethylene) LDPE, Ethanol emitter + oxygen absorber	Shelf life extended from 4 days (simple packing) to more than 30 days at 20 °C	Latou et al. (2010)
Bread	Active packaging with antimicrobial agent (Thymol)	Poly lactic acid-Poly butylene-succinate-co-adipate (PLA-PBSA) bag, Thymol	Product life enhanced from period of three days up to 7–9 days at 25 °C	Suwanamornlert et al. (2020)
Sliced bread	Active packaging	Poly(butylene adipate-co-terephthalate)PBAT-(Poly lactic acid) PLA bag, Trans-cinnamaldehyde	Product longevity got enhanced from 3 days to more than 21 days at 30 °C	Srisa and Harnkarnsujarit (2020)
Part-baked flat bread (Sangak)	Modified packaging	Polyamide/Polyethylene PA/PE, CO ₂ 100% MAP	Increased product durability from 9 days to 21 days at 25 °C	Khoshakhlagh et al. (2014)

6 Conclusion

Fresh fruits, vegetables, dairy products, meat, poultry, seafood and other processed product with high water activity are prone to microbial and enzymatic spoilage. In view to enhance the shelf-life and reduce food loss, shift has been observed from traditional preservation methods to novel green preservation techniques and are widely employed. These novel techniques include HPP, PEF, ozonation, cold plasma, intelligent packaging, edible films, coatings and nanotechnology. More emphasis is being laid on the utilization of edible coatings, films and nanotechnology because of their environment friendly nature, retention of nutrients, sensorial and textural characteristics along with bioactive components with upgraded shelf life of food products. Out of a large bunch of novel techniques, PEF technology

outlines as an attractive alternative due to its ability to eliminate the spoilage and pathogenic bacteria in dairy products. Contrary to the conventional thermal treatment, the safety and shelf life of liquid dairy commodities were significantly improved. PEF gained much attention due to its negligible effects on the original product characteristics including sensorial properties and functionality of milk combined with its nutritional properties during processing operations. On the other hand, when it comes to HPP, it performs a dual function. At the forefront, HPP inactivates the microbial load in a food product. On the sidelines, the process is known to enhance and extract a number of viable and functional compounds such as phenolics, antioxidants, and bioactive compounds from distinct sources. Such functions are prevalent as a part of its potential application in distinct domains including those in pharmaceutical, food, nutraceutical, and other related sectors. Besides PEF and HPP, being extremely attractive alternates for novel processing, ozone treatment is also known to demonstrate great efficacy in maintaining food safety. Lastly, these methods come with a bunch of benefits and limitations. For example, while Cold plasma is known for ensuring safety of marine foods by inhibiting microbial load, at the same time it also possesses certain barriers extending to lipid and protein oxidation that can eventually change the sensory attribute of a food. Not only this, but it can also adversely affect the appearance leading to discoloration in sea foods. Edible coatings, films, active packaging systems with essential oils and selective nanoparticles have not only improved the shelf-life of food products but also improved their bioactive component profile alongside ensuring maximum nutrient retention in them. Nevertheless, in the lines of complementing such novel techniques, plasma activated water ice might also come out as an effective way to enhance the shelf life of fresh commodities soon.

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Chapter 16

Regulatory Compliance and Food Safety Standards



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1 Introduction: Regulatory Compliance and Food Safety

The chapter outlines to evaluate regulatory compliance and food safety in which compliance generally refers like GFSI, HACCP, SQF, BRC, and ISO/FSSC 22000 of the topics covered in this chapter. Compliance has become significant to our contemporary markets, societies, and modes of governance across a variety of public and private domains. The goal of regulatory compliance is for businesses to make sure they understand and abide by pertinent laws, policies, and regulations. Organizations are putting in place more standardized and efficient a result of the expanding number of regulations and the need for operational transparency sets of compliance controls. This method is employed to guarantee that all essential governance needs may be satisfied without needlessly expending extra work and resources. Food regulatory compliance helps industries meet customer requirements, attract new clients and deliver wholesome food to regional and international markets. It is responsible for risk management, safeguarding customers, compliance with complex legislation, and quality and safety throughout diverse supply chains. Implementing food safety management programs can help companies improve their complying with regulatory systems at the national and international levels, such CODEX. These programs also promote a stronger food safety culture and better practices across different regions and geographies (Jairath & Purohit, 2013).

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The safety of food is a shared objective between government and industry. In order to achieve this goal, they must each fulfill their distinct but complementary roles. Industry bears the primary responsibility for ensuring the safety of food, while government's role is to verify that industry is fulfilling its duty. In addition to these fundamental responsibilities, there are many other activities where the two entities interact. These interactions are discussed, and measures are recommended to improve the relationship between government and industry, thereby enhancing customer assurance regarding the security of the food supply (Tompkin, 2001).

Agriculture market is the main economic activity in the majority of developing nations, which benefit due to the seasonal output and comparative advantage of reduced labor costs. These advantages can be taken advantage of to open up new doors for these nations' producers in terms of reducing poverty and improving livelihoods of commodities on the market, causing prices to decline. Many farmers are consequently driven out of business as a result of a variety of problems, including reduced costs in export markets as a result of unavailable stock being delayed, quality degradation during transportation, and other problems with food safety, of which pesticide residue is one that has become more prominent recently. It can be challenging for small-scale, marginal farmers in developing nations to compete with major commercial agribusinesses unless they get government backing in the form of institutional and technical support. Governments have started programs to inform farmers and offer handholding maintain for the acceptance of post-harvest and pre-harvest technology in several developing nations, including India (Fox & Vorley, 2012). In addition to increasing stakeholder capacity and developing specialized infrastructure through their own development programs, developed nations also help underdeveloped nations strengthen their supply chains (Grain, 2010; Valente, 2003). Sanitary and Phytosanitary (SPS) Agreement related issue have become a source of tension and friction in international trade negotiations. An important first step toward improving the global trade architecture and establishing more orderly and transparent circumstances for the global food trade is the SPS Agreement and the associated WTO dispute resolution process (Athukorala & Jayasuriya, 2003). The chapter also highlights the impact of international standards systems on food safety initiatives by governments, intergovernmental organizations, and other interested parties.

2 Trusting Consumers: Consumer Attitudes Toward Issues in Food Safety

Customers who trusts the government analysis is less likely to worry about food safety and product quality, including health issues and food borne illnesses. The level of trust consumers have in the food chain actors significantly affects their perception of food risks and behavior's involved in the food chain. This trust, or lack thereof, can significantly affect consumer behavior. It is interesting to note that

customers who were more trusting were found to be less likely to agree with the idea that buyers should be able to evaluate food purchases independently, even if the product included safety information on the label. This implies that trust can be important in how individuals perceive the need for independent evaluation of food products (Lobb, 2005).

According to Kennedy (1988), asserts that trust is a key factor in food safety issues since customers are unable to assess the risks associated with food directly. The degree to which consumers trust government institutions and the food business, both of which are in charge of guaranteeing food safety, is closely correlated with their attitudes toward food safety (Wilcock et al., 2004). According to published research, the most prevalent sociodemographic factors affecting consumer behaviors, knowledge, and risk perceptions regarding food safety are age, size of household, income, and education. These factors are age, education, income, the presence of an allergy in the home, the presence of a child under the age of five, marital status, the number of children, occupation, sector, and location were found to be significant sociodemographic factors in differentiating the consumer food safety segments. Food preparation, consumption, and buying decisions made by consumers will be greatly influenced by these factors. Two significant elements influencing consumer attitudes toward food safety include adopting a risk-based perspective on food dangers and fostering greater customer trust in food chain actor. Facts regarding the composition of the food safety system and the extent of the government's authority to ensure a safe food supply should be part of communication and education campaigns (Verma et al., 2023; Mostafa et al., 2024).

Customer views on the quality of the food supplies and the correlation between food safety concerns and particular product categories, legal concerns, the ranking of financing areas for food safety, and an assessment of consumer attitudes and actions surrounding particular food safety issues. Chemical, microbiological, and regulatory concerns rose in tandem with the general degree of worry over food safety. Compared to earlier research, there was more concern about microbiological problems. Merely 15% of the respondents believed that they had become ill from a foodborne illness in the previous year; more than 40% considered restaurant food to be the cause, and more than 25% said it was an occurrence at their place of worship or education. There were noticeably more worries about sugar, salt, and cholesterol than in earlier research. Although consumers gave money for regulatory problems like hiring more inspectors low importance, they were particularly worried about the monitoring of imported commodities and restaurant sanitation. It's interesting to see that while a majority of consumers have faith in the safety of genetically modified, irradiated, or hormone/antibiotic-treated foods that have been approved by the FDA, there is still a significant portion of the population that is hesitant to buy them. In fact, nearly one-third of consumers wouldn't purchase these types of foods, and over 20% have reduced their consumption of certain foods due to concerns about GMOs, irradiation, and hormone or antibiotic treatment of animals. Despite growing concerns of consumers regarding regulatory and microbiological risks, funding for more inspectors for foodservice and manufacturing facilities has not been prioritized. It is important for organizations to prioritize safety and compliance with

regulations regarding their opinions, between 70% and 80% of consumers would think it is safe to eat irradiated foods, foods with genetically modified organisms, and goods originating from animals given antibiotics or hormone treatments if the FDA declared them to be safe. But 18–28% of them have cut back on their intake of these foods. Furthermore, 33–40% of consumers are willing to pay extra for goods that are guaranteed to be free of radiation, genetically modified organisms, and animal byproducts (Bolek, 2020; Brewer & Rojas, 2008).

3 Food Safety Management Systems

Ensuring food safety remains a challenging issue in both wealthy and developing nations. Access to safe and healthy food is a fundamental necessity for people worldwide to maintain their overall health and well-being. For any nation, food safety is a top social and health concern. From lethal cancer to diarrhoea, unsafe food is the source of many ailments. Globally, food-borne illnesses and viruses have wreaked damage on the medical and financial fields. Food borne illnesses brought on by tainted and unclean food pose a threat to public health. Food-borne illnesses are a major global health burden and cause a high death rate (Henson & Caswell, 1999).

According to World Health Organization (WHO) data from 2017, food-borne illnesses account for one-third of all fatalities worldwide. According to a WHO research, children under the age of five are among those impacted, while making up only 9% of the global population. Unsafe food affects not only children but also older adults and pregnant women. This is now the worst problem that has happened in a long time. Every nation is battling to create a better, more wholesome future. Throughout history, food safety has been a major global concern. In many countries even today, providing safe and sanitary food is a difficulty. Given that India is the most populous country, it is almost a mission to provide everyone with access to safe and hygienic food. While there are sophisticated regulations in wealthy countries to ensure food safety, it can be difficult to implement these requirements in less developed and underdeveloped countries (Beliaev et al., 2019).

Although food contamination can be prevented from spreading to spread diseases, the large number of persons involved in the preparation and supply chain make this impossible to do. People are becoming more conscious about their cleanliness and health these days. They also have greater understanding of their right to safe food and are more concerned about what they eat, which has made the government and regulatory bodies more proactive in promoting a healthy future. Overview placed third in terms of financial significance in international trade, the food industry is estimated to be worth \$3.4 trillion US in 2022. The global revenue in the food market was forecast to continuously increase between 2023 and 2030 by in total 5.1 trillion U.S. dollars (Research & Market, 2023).

This kind of business is also distinguished by a particular kind of risk, which is linked to food safety and whose loss or absence may have detrimental effects on

customers, including death, and the collapse of the food firm. The food dangers of today are linked to the product's loss of one of its essential qualities. The facts compiled and published in research studies by the FAO and WHO as well as other scientific publications demonstrate the inextricable link between security and internationally traded goods. The discovery of melamine in milk is one instance of such an incidence from recent years (China, 2008), the maximum allowable level of lead found in pasta (India, 2015), various spices, including turmeric powder (Asian countries, 2013–2017), and other foods. According to WHO, 1 in 10 people fall ill and 420,000 lives are lost every year due to consuming low-quality food. Children and those living in low-income areas are particularly vulnerable to food-related illnesses and risks (Fung et al., 2018).

Food Safety Management System to ensure the safety and quality of food products as they move through the production and supply chain. Quality management systems suggest that organizations set quality objectives and implement a quality policy for food quality assurance, with a focus on continuous improvement. This helps to control and coordinate quality, ensuring that organizations are meeting their quality goals. Theoretically, it is based on the analysis and organization of scientific publications and normative documents. It is established that different quality management and safety systems are used in international practice, including, HACCP (Hazard Analysis Critical Control Points), ISO 22000 Food safety management systems—requirements for any organization in food chain, and others. Prerequisite programs (PRPs) are the fundamental setups and practices required to uphold a sanitary environment at every stage of the food chain, guaranteeing the safe production, handling, and distribution of food suitable for human consumption. Depending on the organization's type of business and its position in the food chain, different PRPs are needed. Alongside PRPs, other phrases that are frequently used interchangeably are good manufacturing practice (GMP), good distribution practice (GDP), and good agriculture practice (GAP). There are four types of good practices: good trading, good production, good sanitary, and good veterinary (GVP, GHP, and GTP). These programs include basic food handling practices, like food hygiene and minimum food operations (Panghal et al., 2018).

4 Food Safety Rules and FDA Regulations

Food safety rules are a collection of laws and policies that ensure the food's quality and safety. The purpose of these rules is to reduce the possibility of food contamination and stop foodborne illnesses. They are implemented by food safety authorities in different countries.

- ***Hazard Analysis and Critical Control Points (HACCP)***: HACCP is an organized technique for identifying and reducing possible risks in food production operations. By identifying crucial control points in the production process and putting preventive measures in place, HACCP helps to guarantee the safety and

quality of food. It is widely applied in the food industry to prevent food contamination and decrease the danger of foodborne illnesses.

- **Good manufacturing practices (GMPs):** GMPs are rules that specify requirements for sanitation, equipment upkeep, and personal hygiene. They provide a hygienic and clean atmosphere for the production of food. These laws are crucial to the food sector as they help to ensure the quality and safety of the goods that are manufactured.
- **Food labeling requirements:** It is mandatory for food products to be labeled with specific information such as the nutritional data, an ingredient list, name of the product, and allergy information. This labeling is necessary to inform consumers about what they are purchasing and to help those with allergies or dietary restrictions make informed choices.
- **Import/export regulations:** distinct nations have distinct import and export policies. Food imports are guaranteed to adhere to the same safety requirements as those produced domestically thanks to these restrictions.
- **Inspections:** To make sure that food manufacturing facilities are adhering to food safety rules, government organizations in charge of food safety conduct inspections of the facilities.
- **Foodborne illness reporting requirements:** Foodborne illness outbreaks are required in many countries to be reported to the government agencies in responsibility of regulating food security. This aids these groups in recognizing possible risks and preparing for any future epidemics (Kamboj et al., 2020).

Challenges in Food Safety Regulations Rapid technology improvements, worldwide supply chains, climate change, and food fraud present a number of issues for food safety legislation. Food processing, genetic engineering, and nanotechnology are examples of technological developments that bring additional complexity and demand constant upgrades. There are moments when tracking down components and spotting contamination is challenging due to worldwide supply systems. Furthermore, continuous problem is the detection of new contaminants and diseases. New contaminants are emerging as a result of fast changing global trade patterns, climatic upheavals, and agricultural practices. The regulatory authorities need to stay up to date with these advancements in order to prevent epidemics and protect public health by proactively updating standards and surveillance systems. Furthermore, it is crucial to acknowledge the contribution of technology progress in augmenting food safety.

Additionally, it is critical to acknowledge how technical developments contribute to improved food safety. The efficient implementation of food safety laws can occasionally be seriously hampered by a lack of resources. Lack of funding, personnel, and technology may also make food safety-related inspections less frequent and thorough. This problem is made worse by the need for real-time monitoring and fast response times in the event of potential epidemics. Novel approaches can greatly aid in risk assessment and mitigation, from enhanced monitoring systems to the use of data analytics. An innovative food safety regulatory system should place a high

priority on funding this kind of research and encouraging the application of cutting-edge technologies (Singh & Puniya, 2024).

Food and Drug Administration (FDA) FDA is one of the important US based government agency organization assigned the duty of ensuring the efficacy and safety of a broad range of supplies; include food, medication, and medical equipment.

- **Background and Histories:** The main objective of the FDA's historic history, which began in 1906 when it was founded, was to safeguard the public against tainted and dangerous foods and medications. The agency's regulatory purview has been broadened throughout time to cover other goods, including tobacco, nutritional supplements, and cosmetics.
- **FDA's Mission:** The FDA is responsible for regulating the manufacturing, promotion, sale, and labeling of pharmaceuticals, food items, medical equipment, and other goods. To protect and improve public health, its goal is to guarantee the security, safety, and effectiveness of these items. The FDA has the power to seize illegal products, issue warning letters, and enforce regulations.
- **The FDA's Organizational Structure:** A commissioner overseeing the agency is chosen by the Senate and given approval by the President. It is divided into several offices and centers, each with a different mission statement and set of responsibilities.
- **FDA's Role in Food Safety:** Assuring the safety of the food supply in the US is a major responsibility of the FDA. It creates guidelines for food safety, monitors food imports, and inspects food establishments. The Centers for Devices and Radiological Health, Biologics Evaluation and Research, Food Safety and Applied Nutrition, and Drug Evaluation and Research are some of the centers that make up the organization. Apart from regulating food safety, the FDA is accountable for shielding customers against deceptive or false product advertising. In addition to having the authority to take businesses that make erroneous or unfounded claims to court, it controls how products are labeled and promoted. The authority to recall food goods exists if they are discovered to be contaminated or hazardous.
- **FDA-Industry Relationship:** The relationship between the FDA and the industry is crucial to ensure the safety and efficacy of goods. The FDA works closely with businesses to expedite the approval process for new products and provide guidance on meeting regulatory standards.
- **Public Health Emergencies:** The FDA's essential role for public health during periods of pandemics like COVID-19 or foodborne illness outbreaks. Planning and executing strategies to deal with these crises is done in cooperation with a range of stakeholders, including companies, the general public and other governmental entities.
- **World Trade Organization (WTO):** The World Trade Organization (WTO) is a global institution that regulates international trade and enforces food safety agreements such as the Sanitary and Phytosanitary Measures (SPS) Agreement.

- **European Food Safety Authority (EFSA):** An unbiased scientific body called the European Food Safety Authority (EFSA) that carries out risk assessments pertaining to food safety throughout the European Union (EU) and offers trustworthy scientific advice. The EFSA guarantees that pollutants, genetically modified organisms (GMOs), and food additives are safe for human consumption and do not present any health hazards (Oria et al., 2010; Authority et al., 2019; Darrow et al., 2020).

5 Strengthening Food Safety Initiatives: India

Government initiatives and assistance aimed at reducing the expense of adhering to international standards would seem to be necessary for small facilities to remain competitive. The Food Safety and Standard Act (FSSA), passed by the Indian Parliament in 2006, was a result of increased sales of packaged foods in the early 2000s, which highlighted the need for a regulatory body to regulate food quality and standards in India. The Food Safety & Standards Authority of India (FSSAI) was established two years later and has since then established an integrated food safety regulatory framework. In addition to overseeing the production, distribution, storage, and import of food items in order to maintain quality and hygienic conditions, the Food Safety and Standards Authority of India (FSSAI) is an independent statutory agency. The food industry, producers, and retailers in India are selling junk food as desirable health food by means of intense marketing campaigns, Indian prime time commercials, and fraudulent marketing strategies such as celebrity brand endorsements. This shows how inadequately the nation's food safety laws are being applied, particularly when it comes to the marketing of fruits and vegetables. The local government has failed to give access to modern infrastructure, such as scientific ripening chambers for fruits and vegetables, even at contemporary markets (Dhara et al., 2021).

Food safety concerns appear to be disregarded even in India's modern marketplaces, as seen by the absence of scientific ripening chambers that satisfy international safety standards. It is stated that there is an urgent requirement for:

- (i) A special budget for the construction of soft and hard infrastructure.
- (ii) more partnerships between the public and private sectors to carry out risk communication programs, sensitization campaigns, and capacity building for both perishable as well as non-perishable food items.
- (iii) To create a network of authorized laboratories staffed by experts to conduct scientific testing on the majority of perishable agricultural products.
- (iv) Agricultural Produce Marketing Committee (APMCs) to guarantee a premium payment for higher-graded produce to the farmers as an incentive to adhere to and innovate more food safety norms, while providing both traders and farmers with modern infrastructure facilities.
- (v) Investigate novel management models.

For example, the state government may take into consideration a pilot project to lease out the regulated market to private agribusinesses. In turn, the regulatory bodies take on an advisory and regulatory function to ensure that safety standards in that market comply with legal requirements and offer necessary infrastructure which establish a trusting relationship with customers.

- (vi) Gradually implementing a city-wise program to limit the sale of expired food items.
- (vii) Using consumer groups to spread awareness of hazards to food safety and possible safeguards.
- (viii) Mandating record-keeping from implementation authorities in order to track the effectiveness of food surveillance and law enforcement operations.
- (ix) Encouraging the prescriptive sale of controlled chemicals at registered locations.
- (x) Establishing a committee to develop a place of good and hygienic and practices for all activities carried out in the fruit and vegetable market.
- (xi) To prevent contamination in fields, farmers should be educated proper personal hygiene practices as well as safe pesticide application techniques and efficient spray technology.
- (xii) Integrate India's small farmers and traders into networks for food safety and quality by growing the number of supermarkets; this could help with both the traceability problem.
- (xiii) This method for learning to increase awareness also if the aforementioned proposals were put into practice, agribusiness would be encouraged in both domestic and foreign markets.

Specifically, their responsibilities include creating standards for food safety and enforcing them in order to keep an eye on any threats to food safety. Consumers face two primary categories of food-related dangers. The first has to do with cleanliness and is particular to foods that are dangerous for people to eat. The second concerns food standards and includes labeling related to composition (e.g., misleading the consumer due to contents not meeting compositional criteria), safety (e.g., erroneous use by dates), and nutrition (e.g., consumers are misled about fat content) (Jairath & Purohit, 2013). Thus, risks related to food safety include those that directly impact human health as well as those associated with "food fraud incidents," which involve dishonesty or malicious intent (Gizaw, 2019). Consequently, food regulators have a wide variety of responsibilities, which include everything from planning extensive product recalls to enforcing food standards in restaurants. Whatever its function, food regulation plays a critical role in guaranteeing public safety and fostering and preserving public confidence in food. Food safety laws must be upheld, and food scares must be avoided, by the food sector. In order for regulation to be effective in the food business, trust must be the foundation of the relationship between regulators and industry participants. High levels of trust between a firm and its major stakeholders are critical to its success, as research has demonstrated in a number of scenarios (Baba & Esfandiari, 2023).

It is evident that these food producers are spending more money on advertising their products than on ensuring their quality. This raises questions about the quality and safety of packaged foods, which are getting progressively worse. It is a warning that the makers of these food products may not be prioritizing the safety and well-being of their consumers. In 2015, a major food safety concern arose in India when Nestle's "Maggi" noodles, a popular instant food product, were found to be unsafe and in violation of laws and guidelines. Food Sentry, a global food sourcing monitoring program, has identified India as the worst food offender despite the existence of food quality rules.

India has been facing food contamination and adulteration challenges for a long time, which is unfortunate. The 1998 dropsy outbreak is a tragic example of such incidents. It was caused by consuming tainted mustard oil and resulted in the loss of over sixty lives. There have been other instances of foodborne illnesses caused by contaminated soft drinks, unsafe food, and adulterated chocolates as well. These occurrences are alarming and raise concerns about the safety and quality of food products. It is expected that government agencies and regulatory bodies take responsibility for ensuring the safety of food products. In India, various departments and ministries have passed legislation to ensure that citizens have access to safe, nourishing food. Prior to 2006, different parliamentary acts were in place to govern food-related matters, including the "Edible Oils Packaging (Regulation) Order 1988," "Vegetable Oil Products (Control) Order 1947," "Meat Food Products Order 1973," "Fruit Products Order 1955," and "Prevention of Food Adulteration Act 1954 (Dudeja & Singh, 2017; Kaur et al., 2021).

The FSSAI is an independent organization that was founded by the Indian government's Ministry of Health and Family Welfare. FSSAI is responsible for regulating and overseeing food safety in India in order to safeguard and promote public health. As a result, the Food Safety and Standards Act, 2006 has granted FSSAI the legal authority to oversee and regulate the food safety standards in India.

- Drafting legislation to establish guidelines for food safety
- Establishing standards for food testing laboratory accreditation
- Offering the Central Government scientific counsel and technical assistance
- Helping to develop international food technical standards
- Gathering and compiling information on emerging risks, food consumption contamination, etc.
- Raising awareness and disseminating information about food safety and nutrition in India. In addition to the framework mentioned above, the Food Safety and Standards Authority (FSSAI) have established specific rules for food safety research and standards development (Jairath & Purohit, 2013).

Developing and implementing food safety regulations is a laborious task. The procedure is founded on the most recent advancements in the field of food science, patterns of consumption, novel food goods and additives, modifications to processing technology, and the detection of fresh hazards or alternative regulatory alternatives. The regulations that govern food additives and standards, packaging, labeling, and residues; these regulations were all passed in 2011 have established food safety

standards that take into account the most recent scientific advancements in food technology (Singh et al., 2013). The following food products must adhere to criteria set by the FSSAI:

- Fruits and vegetable products
- Dairy products and analogues
- Cereal and cereal products
- Fats, oils and fat emulsions
- Fish and fish products
- Meat and meat products
- Irradiation of food
- Sweetening agents including honey
- Sweets & confectionery
- Beverages, (other than dairy and fruits & vegetables based)
- Salt, spices, condiments and related products
- Proprietary food (Ajay, 2018)

The consumers' views on food safety are influenced by various factors such as the type of food they consume, their culture, lifestyle, and demographics. In India, over the past few decades, there has been a significant shift in food habits and lifestyle, which has affected the way consumers perceive food safety. With population growth, urbanization, globalization, and more people joining the workforce, Foods that are packed and ready to consume are in more demand.. However, there has also been a noticeable change in the mindset of Indian consumers as they have become more health-conscious and aware of fitness. There is a growing concern among consumers in India regarding food safety. Nowadays, people are more conscious of the food they consume and are placing greater importance on the quality and hygiene of their meals. Consumers are also demanding more transparency in terms of nutritional information and pricing. It seems that people are becoming increasingly aware of the government's role in ensuring food safety and are unwilling to accept a lower-than-expected level of food quality (Dhara et al., 2021; Goswami & Mulherkar, 2012).

6 Global Food Safety Initiative (GFSI)

Established in 2000, the Global Food Safety Initiative (GFSI) as a result of multiple high-profile outbreaks of foodborne illness that led to a historic decline in consumer trust in the food supply. Since then, more than 15,000 foreign manufacturers of food and beverages have complied with the food safety criteria set forth by GFSI. The Consumer Goods Forum, a worldwide network of over 400 of the largest retailers in the world of consumer goods, as well as their manufacturers and suppliers from 150 countries, is in charge of overseeing the day-to-day operations of GFSI. The GFSI's guideline paper has been updated for over 15 years by food safety specialists from food producers, retailers, and consumer organizations. Currently, private, third-party food security inspection systems that want to be certified as equivalent use this

report as a standard. Food producers select a benchmarked program to undergo auditing against, and if they clear the audit, they receive certification against that program. In order to verify their food safety management systems to the benchmarked GFSI standards, almost 150 nations with 100,000 food production facilities receive assistance from independent auditors. Additional contextual information regarding the evolution of global Guidelines for food safety has been providing by Crandall et al. (2017).

7 Hazard Analysis Critical Control Point (HACCP)

The HACCP system was developed in response to NASA's (National Aeronautics and Space Administration) requirement for a safe food supply for its manned space flights. The NASA requested Pillsbury to create and produce the first meals for space travel in the 1960s, which is when the idea originated. HACCP, which stands for Hazard Analysis Critical Control Point, to create for food production administration system that would ensure food safety for astronauts (Bauman, 1995; Mortimore & Wallace, 2013). Subsequently, HACCP has gained recognition on a global scale as a sensible instrument for converting conventional inspection techniques into a contemporary, scientifically grounded food safety framework.

Starting from the earliest point in the process, environment, distribution, the raw material storage, and the environment were all managed by the system to guarantee that no additional testing was needed for monitoring purpose; this control method in conjunction with record keeping was used. In addition to improving resource efficiency and problem-solving speed, it improves food safety. Producing consistently safe food—that is, a product devoid of chemical, physical, or microbiological risks—is the main goal of a HACCP program.

1. To take a measure that will successfully shield food from dangers and contaminations.
2. To achieve a more cost-effective production method by making efficient use of labor and resources.
3. To ensure adequate food safety and quality in order to raise practitioners' level of hygiene management.

As consumers, we have a number of requirements of the food supply, such as that it be pure, healthful, safe, and nourishing. It will also likely be plentiful, reasonably priced, and offer a range of options. Consumers now expect that food shouldn't cause chronic illnesses like cancer and heart disease, and they have been more concerned about food safety in recent years. The terms safe, hazard, and risk in order comprehending the meaning of "food safety." Food that is labeled as safe means that eating it will not harm us. However, this is not a particularly satisfying perspective when it comes to food. Some toxicants can still cause harm to us years after the exposure, tobacco-induced malignancies are prime examples of this (Dolan et al., 2010). Food scientists and technologists consider the dangers and hazards

associated with food. Any biological, chemical, physical, or food-related agent that has the potential to have a negative impact on health is referred to as a “hazard” in this context. Several crucial terminologies concerning food safety are: Toxins produced by bacterial, fungal, viral, and parasitic species are known as biological agents. Physical agents include wood, glass shards, seeds, stones, etc. Chemical agents include excessive amounts of taste enhancers, antibiotics, pesticides, other food additives (Kushwah & Kumar, 2017).

The Hazard Analysis tools involved the estimates for the time and expenses. The document, which outlines the nature, duties, procedures, and documentation needed in the performance of such evaluations, was meant to serve as a standard reference and typical guideline for use at petroleum, petrochemical, and chemical facilities regarding several process safety subjects, such as Hazard Analysis (Kletz, 1993; Nolan, 1994).

The concepts of Hazard Analysis development were given by a group of researchers, who also broadened their scope to include a variety of hazard detection and loss prevention issues (Kletz, 1998). Using their significant experience in using the process most effectively, EPSC developed updated Hazard Analysis guidelines in 2000, adjusting the methodology to the advent of new technology (EPSC, 2000). Finally, a British Standard published in 2001, established and defined new requirements for carrying out a HAZOP (Hazard and Operability) study thereby clearly pointing to its continuing importance as the most widely used technique in process plants and other types of facilities (BS-IEC 61882, 2001). In 2004, Macdonald revised his work included instructions on how to conduct a Hazard Analysis and connected it to upcoming research on Safety Integrity Level (SIL) assignments in sequence on HAZOP’s characteristics. The purpose of hazard study techniques and the ensuing steps for delivering risk protection are the main topics of this document. Furthermore, this study offers instructions for the three fundamental processes (identifying hazards, defining risk reduction strategies and assessing risks) are included in process facilities’ overall risk management framework (Kushwah & Kumar, 2017).

There is currently a number of food safety testing methods available. Hazard analysis’s success or failure is dependent on a number of variables. A well-designed hazard analysis is essential to its success and to evaluate whether or not the design is good, testing is necessary. Quality assurance (QA) follows if the test findings are satisfactory (Macdonald, 2004). The staff responsible for hazard analysis must receive quality training in order to maintain quality, which is the parameter that needs constant improvement. Well-defined operations are necessary for various hazard analysis principles. In order to achieve long-term success, it is imperative to have regular maintenance and effective administration. The Plan Do Check Act (PDCA) is essential to HACCP’s success (Pierson, 2012). Furthermore, microbial testing is a crucial tool for ensuring food safety; it has certain drawbacks, including the need for time and the tendency to identify issues only after they arise. The key to preventing food-borne illness is to comprehend the origins of these illnesses as well as how improper handling and storage of food might raise the chance of contracting the illness. It is possible to ensure that these dangers are reduced if these

elements are understood. Reducing microbiological dangers in food is best achieved via prevention (Cuihua, 2013).

One important instrument for reaching a high level of protection and dependability is HACCP (Kushwah & Kumar, 2017).

The following are the major points about HACCP:

- HACCP is a methodical methodology to identify, assessing, and managing food manufacturing processes that are essential to food safety.
- The fundamental goal of the HACCP idea is to ensure invention of safe food items by prevention rather than by quality assessment. It is an analytical tool that enables management to implement and sustain a cost-effective, continuing food safety program.

HACCP Principles: The HACCP system consists of the following seven principles: Principle 1: Conduct a hazard analysis.

Principle 2: Identify the Critical Control Points (CCPs).

Principle 3: Establish critical limits.

Principle 4: Establish monitoring procedures.

Principle 5: Establish corrective action.

Principle 6: Establish procedures for verifications procedures.

Principle 7: Establish record-keeping procedures.

Principle 1: Conduct a hazard analysis: Analyze potential hazards plants are able to recognize the risks to food safety and come up with countermeasures to help manage them risks pertaining to cultivation, harvesting, processing, manufacture, distribution, and marketing, as well as ingredients and raw materials. Each aspect of a particular food's preparation and consumption is evaluated thoroughly. The possible areas contaminated by chemicals, microbes, or physical agents are identified.

Principle 2: Identify the Critical Control Points (CCPs): The CCPs managing each of the hazards mentioned above are those process steps where a breakdown could pose an unacceptable risk to public health. These points must be kept under control to guarantee the product's safety. One example of a critical control point would be the careful monitoring of a product's temperature following processing.

Principle 3: Establish critical limits: The boundaries surrounding each crucial control point need to be established after it has been identified. This could be the adding of a minimum quantity of acid or salt, or it could be the minimum or maximum temperature.

Principle 4: Establish a system to monitor control of the CCP: Specific protocols for monitoring the significant control point or points need to be established. A control point's maximum temperature is not particularly helpful, unless there is a specific protocol in place for collecting information on the critical control point. If a product depends on the addition of acid for safety, then the limits on the pH or the acid content must be defined and monitored.

Principle 5: Establish corrective action: To create an action plan for corrective actions in the event that monitoring shows that the limitations of the critical control point have been exceeded. Corrective measures are meant to make sure that no product that has been tampered with or is harmful to health as a result of the deviation ever reaches the market.

Principle 6: Establish procedures for verifications procedures: The plans accomplish their goals and are successful in guaranteeing the creation of safe goods and necessary for plants to verify their own HACCP programs. HACCP plans will be reviewed by FSIS to ensure compliance with the final rule, but will not be approved in advance. The complete documentation of the HACCP plans is crucial. This covers the strategy in its entirety as well as the maintenance of measurement incentives for each and every important control point.

Principle 7: Establish record-keeping procedures: According to the HACCP regulation every plant must keep a record of its documentation of the monitoring of critical control points, critical limits, and verification processes, hazard analysis, and draw HACCP plan. Finally, it is imperative to set up procedures for verifying that the HACCP plan is being followed and performing as intended.

The Bureau of Indian Standards (BIS) has two distinct certification programs for the food business in India:

1. HACCP Stand-alone Certification against IS 15000:1998 and
2. HACCP based Quality System Certification, which permits the attainment of two certifications with just one audit:
 1. IS/ISO 9000 Quality System Certification and
 2. IS 15000:1998 HACCP Certifications. In addition to BIS, there is also the Food Safety and Standard Authority of India (FSSAI) standard for food safety.

The Food Safety and Standard Act of 2006 allowed for its establishment in 2008 under the Ministry of Health and Family Welfare. HACCP standards are included in ISO 22000 FSMS 2005 at the worldwide level. This standard includes all necessary programs for food safety and is a comprehensive food safety standard with MIS. The HACCP method has been implemented and legitimized in numerous nations' worldwide, yielding positive outcomes in the management of food safety. The HACCP method was primarily implemented in larger food industries in China, but it was also launched there in early 1990. The practices were either inadequately implemented or did not have a sufficiently gratifying result for the catering firms (Cuihua, 2013). While there are many food industries in China, most of them are small-scale and have poor overall cleanliness standards. This reality led to the emergence of countless food hygiene issues (Dunjó et al., 2010; Gaigné & Larue, 2016; Potter & Hotchkiss, 1998). Therefore, it is crucial to implement the HACCP system, an efficient food safety control system, in the food business.

8 Safe Quality Food (SQF)

The Safe Quality Food (SQF) accreditation offers your customers assurance on food safety that is recognized worldwide. Retailers, producers, manufacturers, and processors can all take part in this elite, GFSI-benchmarked certification program. By obtaining SQF certification, businesses can achieve the extra quality management system criteria of the SQF Quality Code and prove the rigor of their HACCP-based food safety plan in accordance with the current SQF Food Safety Code. All facets of the food industry, including primary production, manufacturing, and processing, as well as transportation, storage, distribution, and retailing, can adopt SQF. It is a HACCP-based standard for food safety and quality control. SQF certification has a site- and product-specific scope. The following mandatory SQF system elements must be met in order to receive certification: food safety fundamentals and plans; documentation control and records; management commitment; product development and specification; SQF system verification; product identification, trace; withdrawal and recall; food defense; identity preserved foods; and training. SCS may guide you through a pre-assessment procedure to ease the move to SQF certification. A non-scored simulated audit called a pre-assessment is used to gauge how well-prepared you are for a certification audit. For increased efficiency, businesses can integrate a pre-assessment with their initial audit (Odugbemi, 2017).

9 British Retail Consortium (BRC)

UK retailers formed the British Retail Consortium (BRC) as a trade association in 1992. In order to further the interests of retailers across a range of industries, it provides quality benchmarking, training, expert advice and other services. The development of the Global Food Standard for Food Safety in 1998, which has now evolved into the norm for food safety laws worldwide, is among the BRC's most important accomplishments. Food industry professionals in the British Retail Consortium created the first version of the BRC Global Standard for Food Safety. For food safety, product integrity, quality, and legality, it provides an extensive set of criteria. It covers a range of operational controls related to the production, handling, and preparation of food products. The Global Standard for Food Safety, now in its eighth iteration, has been acknowledged by the Global Food Safety Initiative (GFSI). The objective of this regulatory organization is to enhance food product safety and quality while also harmonizing international food safety systems. Upholding global standards for food safety and quality is greatly aided by the BRC. The group supports food safety, nutrition, product labeling, incident handling, and other related operations for merchants. By offering helpful insights and establishing standards for process controls, it also encourages the production of food in a responsible manner. The BRC Global Standard for Food Safety is its most notable

contribution to the food business. This certification program was started in 1998 and has now grown to over 20,000 industrial facilities across 130 nations. Currently, 90% of the revenue in the British distribution industry and 50% of the turnover in the British retail brand market are attributed to BRC members. Asda Group, Iceland Frozen Foods Plc, Cws Ltd., Somerfield Plc, Safeway Stores Plc, Waitrose Ltd., Spar (U.K.) Ltd., Boots The Chemist, Tesco Stores Ltd., and J Sainsbury Plc collaborated with the BRC to release the Technical Standard and Protocol for Companies Supplying Retailer Branded Food Products in October 1998 (Arfini & Mancini, 2003). “BRC/IOP (Institute of Packaging) Technical Standard and Protocol for Companies Manufacturing and Supplying Food Packaging Materials for Retailer Branded Products” and the “BRC/FDF (Food and Drink Federation) Technical Standard for the Supply of Identity Preserved Non-Genetically Modified Food Ingredients and Products” (BRC/FDF IP Standard), which were directed at food suppliers and food processing businesses that decide to use exclusively non-GMO ingredients in their products. Global Food Safety Initiative has approved this standard as a reference for international food safety standards. Product safety is promoted by the Global Standard for Food Safety by:

- *Encouraging best practices*
- *Improving operational systems across supply chains*
- *Complying with legal, regulatory, quality and safety requirements*

BRC IOP for Food Packaging, BRC Global Food Standard, BRC Storage and Distribution, and BRC Consumer Products. Senior Management Commitment and Continuous Improvement; Food Safety and Quality Management System; Site Standards; Product Control; Process Control; and Personnel are some of the main topics covered by the Standards. One of the BRC standard’s strengths is its extremely thorough explanations of hygiene control and process, which give management and staff a clear idea of what has to be done on a daily basis to support the overall food safety strategy. Detailed descriptions of process and hygiene control are one of the BRC standard’s strong points they, give management and staff a clear understanding of what has to be done daily to support the overall food safety strategy (Odugbemi, 2017).

Furthermore, food safety, quality, and legality are all covered by BRC certification, which is important information for any stakeholder navigating the complexities of food law. The company may decide to carry out a preliminary pre-audit in order to find any requirements gaps after obtaining and approving a proposal for BRC certification from an accredited certifying authority. Alternatively, the formal certification audit may be conducted without delay, during which every aspect of the website and its procedures are evaluated in comparison to the standard’s scope. The company has 28 calendar days to produce documented proof or consent to an on-site review of the corrective activities if the resulting corrective Action Report finds any non-conformity. The issuance of BRC certification is contingent upon an authorized Certification Manager’s review (Sansawat & Victor, 2011).

10 ISO/FSSC 22000 Certification

ISO22000 is the foundation for FSSC 22000 (Food Safety System Certification). In the year 2010, The FSSC 22000 has been acknowledged by the Global Food Safety Initiative (GFSI) as a standard for guaranteeing food safety. Both the American Institution of Baking (AIB) and the European Food and Drink Association endorse the both support the FSSC 22000 standard. The development of FSSC 22000 was aimed at satisfying the demands of the food industry's manufacturers and processors of perishable vegetable and animal food products, as well as those of high shelf life food products and food ingredients like vitamins, bio-cultures, and food additives. Furthermore, where transportation and storage are a component of the work done by enterprises that produce or process food, they are covered by FSSC 22000.

The International Organization for Standardization (ISO) produced the Food Safety Management System (FSMS) standard, ISO 22000. Originally released in 2005, its purpose is to give businesses a framework for handling food safety hazards all the way up the food chain. The Hazard Analysis and Critical Control Point (HACCP) concepts, which are globally accepted techniques for reducing risks to food safety, serve as the foundation for the standard. The introduction of ISO 22000 food safety management systems was intended to guarantee that food manufacturers and sellers followed the strictest safety and quality standards. The goal of the international standard ISO 22000 for food safety management systems is to guarantee the security of food items both during manufacturing and delivery. It outlines the specifications for a food safety system that includes staff monitoring, product traceability, Hazard Analysis and Risk-based preventative controls (HACCP), and other elements. Globally, there is a lot of concern about food safety. It may be defined as the actual understanding that eating food won't hurt or make you sick. Businesses may prove to customers that they are committed to creating safe food and beverages by obtaining ISO 22000 certification (Panghal et al., 2018).

The ISO 22000 Specifications

Food safety: This pertains to the standards and procedures that your business must follow throughout its supply chain in order to keep food fit for human consumption.

Management responsibility: This refers to the responsibilities that your management team has to prioritize, take part in, and bear accountability for the process of assigning resources—such as personnel, buildings, and infrastructure—in order to maximize performance is known as resource management. *Assessment, Evaluation, and Enhancement*—The methods for determining whether your management system is operating as intended and enabling continuous system improvement are outlined in the following paragraphs.

The main advantages of ISO 22000 can be summarized as follows:

- **Improved risk response**—Organizations that have a strong FSMS in place are better able to react quickly and effectively to problems that might jeopardize the safety of their food. By doing this, they may stop possible contamination and other food safety problems in their tracks. Additionally, the organization can

react appropriately to unforeseen events due to the presence of emergency preparedness.

- **Reduced investigation time**—In the unlikely event that contamination does occur, a good FSMS directs organizations in a way that makes it easier to find the source of any food safety violations or security breakdowns. As a consequence, the issue is quickly resolved, and recurrence is avoided.
- **Cost-saving**—The standardization of all Hazard Analysis Critical Control Point (HACCP)-based standards is made possible by ISO 22000.
- **Opportunities for new enterprises**—Enhancing an organization's capacity to collaborate with others by **applying ISO 22000** as a requirement for contracts of cooperation.
- **Employee involvement**—ISO 22000 has a renewed emphasis on employee involvement, which is crucial for promoting a food safety culture throughout the organization (Raspor & Ambrožič, 2011).

11 Codex Alimentarius Commission (CAC)

The World Health Organization (WHO) and the Food and Agriculture Organization of the United Nations (FAO) formed the Codex Alimentarius Commission (CAC) as an international agency to develop and promote global food safety standards. The CAC creates standards and guidelines that national and international governments use as benchmarks for food safety. These guidelines address a number of topics related to food safety, such as pollutants, food additives, food labeling, and food hygiene. The Codex Alimentarius, sometimes known as the “Food Code,” is a set of global norms, regulations, and codes of conduct designed to safeguard consumer health and promote ethical behavior in the food industry. The most recent advances in science and technology serve as the foundation for Codex guidelines. As a fundamental component of global food safety governance, FAO collaborates with WHO to offer scientific advice on food safety in support of Codex Alimentarius' standard-setting efforts. In 1962, the World Health Organization (WHO) and the Food and Agriculture Organization (FAO) together sponsored the creation of the Codex Alimentarius Commission. Presently, Codex has 165 member countries around the world. Fair practices in the food trade and consumer health protection are the two main objectives of the Codex Alimentarius Commission by creating food standards and food guidelines, codes of hygienic procedures these objectives are achieved (WHO/FAO, 1999; Kimbrell, 2000; WHO, 2002; Codex Alimentarius, 2013). There are various committees within Codex Alimentarius that provide recommendations (Panghal et al., 2018).

Committees come in several forms, such as commodity, horizontal, and regional coordinating committees. Codex committees on milk and milk products, fish and fish products, fish additives and pollutants, pesticide residues, food hygiene, veterinary, pharmaceuticals, and food labeling are examples of horizontal committees with a broad scope. Regional coordinating committees for Codex offer assistance in

the creation of commodity standards that may have regional relevance. It also gives regional members the chance to create plans that could help them in other Codex committees. Developing nations can attend the regional meetings and learn about Codex efforts going on in their area (Kimbrell, 2000; WHO, 2002; Codex Alimentarius, 2013). Organizations from the private sector, such as trade associations and consumer advocacy groups, are free to participate in government delegations. In addition, the business sector is permitted to participate in meetings as an international non-governmental organization (INGO) recognized by Codex and to provide feedback during committee sessions (WHO/FAO, 1999; Kimbrell, 2000; WHO, 2002). While public certifications, such the Codex Alimentarius food safety procedure, have been shown to assist producers improve, small-scale farmers may occasionally find it unaffordable and unable to participate in global trade (Lee et al., 2012). The HACCP-based food hygiene system, which include biological, chemical, and allergy hazards during production processes that could result in an unsafe finished food product and adopts a complete preventive approach to food safety, Codex are in good agreement with this system. It can be applied at every point in the food supply chain and is a preventive measure as opposed to a post-preparation inspection (Narula & Dangi, 2014).

12 Implementing Food Safety: Challenges for Developing Nations

It is beneficial for developing country producers to have access to markets and premium prices when food safety issues are implemented throughout the agricultural supply chain. However, it can be difficult to work with small and marginal farmers who lack resources and knowledge in the field. Factors including limited landholdings, ignorance of safety regulations, a shortage of skilled technical labor, poor market infrastructure and connections limitation. In order to fortify the food safety framework throughout these nations' supply chains, robust and policy support are needed. The following are some of the most common challenges to following food safety regulations:

- **Lack of Resources:** Unfortunately, small food manufacturers often face challenges when it comes to meeting regulatory requirements for food safety. Limited resources can make it difficult to invest in equipment, training, or testing that is necessary to ensure compliance. Everyone involved in the food industry must have access to the resources and support they need to prioritize food safety and protect consumers.
- **Changing Regulations:** Regulations about food safety are dynamic, making it difficult for food makers to stay abreast of the most recent needs. To maintain compliance, manufacturers must remain informed about any modifications to legislation. This may necessitate substantial expenditures on research & development.

- **Lack of Communication:** Communication between food manufacturers and regulatory bodies is crucial for ensuring compliance with food safety regulations. Misunderstandings can lead to non-compliance and other serious consequences.
- **Supply Chain Management:** The securities of food producers are accountable for supply chains, which can be complex and difficult to control and requires ongoing testing and monitoring to ensure compliance.
- **Cultural Differences:** When producing food for export, food regarding food safety rules, producers have to navigate cultural variances. The public's health may eventually be at risk when economic pressures force people to make food safety compromises. To cut expenses, producers can be persuaded to utilize less expensive materials or conduct less testing but such actions can have serious consequences.
- **Lack of Data:** To prove compliance with food safety rules, food makers are required to keep correct records. However, if the required data is not available or the record-keeping procedure is ineffective, this could prove difficult.
- **Language Barriers:** For language barriers can present a serious problem for food manufacturers doing business in nations where the official language is not their mother tongue. Understanding regulatory requirements and effectively communicating with regulatory authorities may become challenging as a result (Grace, 2015; Narula & Dangi, 2014).

It might be difficult for small producers to comply with food safety regulations since they may need to spend more money on training and technology. Furthermore, it might be challenging for manufacturers to stay current with the latest requirements due to the constant change in regulations. Developing nations have a lot of things to think about when trying to tap into the global markets. The inadequate logistical networks in developing nations impact the amount and quality of fresh product, making it significantly inaccessible. Produce from isolated places can occasionally be difficult to transport to major markets due to inadequate primary infrastructure, including roads, airports, and railroads. Additionally, there is a deficiency of specialized infrastructure, including ripening chambers, storage warehouses, refrigeration equipment, and machinery for grading and standards. In developing nations like India, a dependable and efficient cold chain system could contribute to a decrease in waste (from the local to the national level), bolstering the country's agricultural industry and enhancing the management of the food supply chain (Joshi et al., 2009).

13 Conclusion

As discussed in this chapter, the national government bears a distinct responsibility to guarantee that the health and interests of consumers come first. Traditionally, a number of central government agencies, including the ministries or departments of

agriculture, health, trade, or commerce, have been in charge of overseeing food safety at the federal level. These duties are assigned to municipalities, local governments, or local authorities at the local level. The FAO and WHO have developed guidelines to help nations build and strengthen national systems for food safety control. These advice national authorities on how stop deceit and fraud, to improve food control systems in order to safeguard public health, stop food adulteration, and ease trade.

A wide range of stakeholders, including food producers, processors, merchants, and public health experts are interested in consumer views on food safety, food handling practices, and new technologies. A global and integrated system for the production and distribution of food has resulted from consumer attitudes around food safety issues and the globalization of food production. These advancements have led to the development of numerous governmental and commercial standards on food safety and quality during the past ten years. Quality assurance in the food industry has become a reality based on requirements of the public sector, private safety and quality standards are emerging and implemented.

This has been the main focus of this chapter, FSSAI the legal authority to oversee and regulate the food safety standards in India. Food safety issues are fast widespread across the globe due to technological up-gradation, triggered by rising consumer awareness and increased international trade. This chapter focuses on the food safety management and the application of the Hazard Analysis Critical Control Point (HACCP) systems approach to food safety management in relation to the production of fruit and vegetables. The role of global institutions and local governments (ISO, WTO, Codex Alimentarius, GFSI, and BRC), which expand private as well as public standards in food safety.

Lastly, the chapter offers crucial policy-level recommendations needed to raise food safety standards in developing countries because of the expanding food trade and rapid globalization. The chapter highlights the effective food safety compliance requires a complex set of factors—well-designed enforcement, competence, good regulation, possibly most importantly and knowledge because of the importance of consumer demand on operators, schemes such as food hygiene ratings can also be used integrating these better with widely used internet search tools (and emphasizing consumer education) could also make them more effective.

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Chapter 17

Novel Extraction Techniques in Food Processing



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1 Introduction

Food is composed of complex structures of biological material. It is a recognized source of macro-components, micronutrients, phytochemicals, and other bioactive components, which provide the energy to regulate human physiological and metabolic activities after consumption. These nutrients play an essential role in conserving body functioning, preventing chronic illnesses, and regulating cognitive function and mood. Modern society is facing nutritional disorders mostly due to people's irrational dietary habits and evolving living conditions (Puri et al., 2023). Nowadays, an increasing health consciousness among consumers is influencing personal decisions and overall food processing. This awareness has various aspects of providing a nutrient-rich, healthy diet. Modern engineering in food processing and nutrition has shifted consumer preferences towards functional-rich foods.

Most health-promoting nutrients are embedded within the matrix structure of food and have lower bioavailability during digestion. The extraction of nutritional components is intended to isolate such nutritional components from biological materials. It is a crucial unit operation in modern food processing operations to extract selective components (Geow et al., 2021). Extraction is mass transfer process where one component selectively migrates from one phase to another. Plant-based foods and other sources are rich sources of macromolecules, antioxidants, phytochemicals, pharmaceuticals, nutritional components, essential oils, aromatic compounds, pigments etc. Also, food industrial wastes have a significant amount of these nutritional components. Therefore, extraction of such nutrient-rich

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components and their utilization in formulated food enhances not only nutritional value and functional properties but also organoleptic characteristics. The extracts are widely utilized for the formulation of functional foods, pharmaceuticals, and cosmetic products (Bitwell et al., 2023; Neog et al., 2023).

Different extraction methods can be used for plant-based food material with the goal of selective separation of targeted compounds at optimum quantity and quality. Before adopting any extraction method, initially, various extraction methods should be applied at diverse operating conditions for knowing yield of extraction and its influencing parameters for efficient extraction. All extraction methods have common aims, viz. (a) to extract targeted nutritional components from the sample, (b) to have the highest yield of extract, and (c) to lower extraction cost and time (Azmir et al., 2013). The concept of extraction involves partitioning a substance between two phases that cannot mix, facilitating the isolation and retrieval of these substances. The substance of interest will be divided between the two phases based on factors such as the distribution coefficient, temperature, and the respective volumes of the phases. Nevertheless, the rate of extraction relies on the migration kinetics, which are influenced by the diffusion rate and temperature within the two different phases. In extraction, the targeted components that are either physically or chemically attached to the solid materials need to be moved into the solvent phase through dissolution. Subsequently, the mixture of solute and solvent diffuses to the surface of the solid and transitions across the interface surrounding the particle into the liquid phase. When the extracting solvent uniformly saturates the solid matrix, the material near the surface will dissolve into the solvent initially, resulting in a porous structure in the remaining solid residue. As the process continues, the solvent gradually enters the outer layer to reach solutes bound deeper within, making it harder to extract them. When solutes strongly stick to the solid material, it requires extra energy to separate them. When the substances remain inside the plant's organic cells, tough extraction conditions are required to break open the cells and make the extraction process possible or easier. During extraction multiple phenomenological process occurs between solid containing targeted component and extracting solvent, which are (a) penetration of solvent into solid matrix (b) diffusion and dissolution of solvent into solute (c) transfer of extract to surface and (d) separation of targeted components.

Conventional extraction techniques, such the Soxhlet solvent extraction method, continue to serve as standards for comparing and assessing the effective yield of an extract in relation to innovative extraction techniques (Azmir et al., 2013). Similarly, other traditional extraction methods are maceration, percolation, decoction or infusion, hydro distillation, etc. These extraction methods require longer processing time and relatively larger amounts of solvent, leading to environment hazards (Waliat et al., 2023).

There is an increasing interest in novel extraction methods that have shorter extraction, lesser utilization of organic solvents and are eco-friendly in nature. Many researchers have worked on different novel extraction techniques to extract

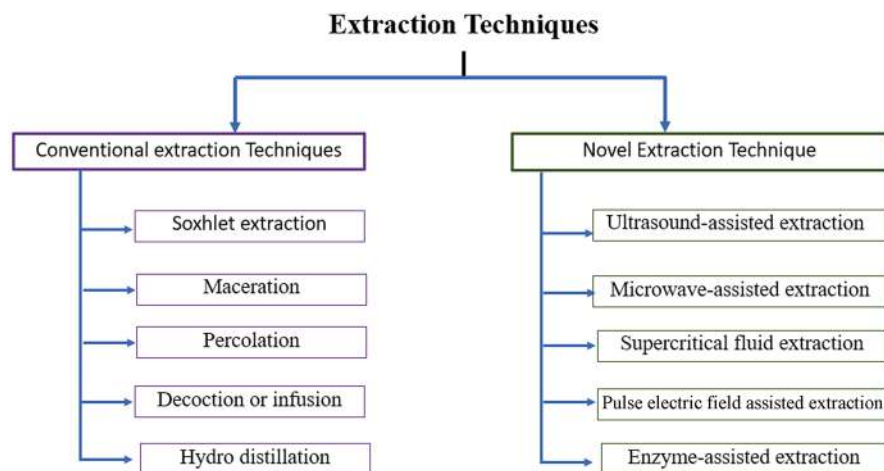


Fig. 17.1 Extraction techniques used in food processing

various plant nutrients, and they have reported these innovative extraction techniques, one or in combination, as the best alternative solution for efficient extraction. Novel extraction techniques, including microwave-assisted extraction (MAE), ultrasound-assisted extraction (UAE), enzyme-assisted extraction (EAE), supercritical fluid extraction, and pulsed electric field-assisted extraction (PAE), are some of the efficient techniques for extraction of nutrient components from food matrixes (Maibam et al., 2023). Different extraction methods are shown in Fig. 17.1. The selection of extraction method depends on various influencing parameters such as plant matrix, the sensitivity of extract, temperature, pressure, the solvent used for extraction, processing time, solid-liquid ratio, area of exposure, etc. (Bitwell et al., 2023). This chapter provides principles and mechanism of extraction, factors affecting extraction, and merits and demerits of extraction methods for future scope.

2 Conventional Extraction Methods

Conventional extraction methods for nutraceuticals involve selecting a solvent and implementing heat and/or mixing. Various conventional methods are applied for the extraction of nutrients, including Soxhlet, hydro distillation, reflux extraction, and maceration with or without heated solvent (Osorio-Tobón, 2020; Ranjha et al., 2021). Soxhlet extraction is considered as standard and reference method among all other extraction methods.

2.1 Soxhlet Extraction

An agricultural chemist named Fraiz Ritter Von Soxhlet from Germany discovered the Soxhlet extraction technique for continuous extraction of fat/lipids by using a hot solvent. It is applied for the isolation of components that are thermally stable and have low to medium volatility. The Soxhlet technique is employed to separate compounds with varied volatility ranging from moderate to low (Rasul, 2018; Waliat et al., 2023). This method requires a high solvent-to-solid ratio (above 20:1) and takes a long treatment time for the complete extraction of the targeted compound from the plant matrix (Bitwell et al., 2023; Osorio-Tobón, 2020).

The thimble is porous in nature, which is made of either sturdy filter paper or cellulose. The powdered plant materials are filled in this thimble and then placed within the compartment of the Soxhlet apparatus. A solvent is poured into the bottom flask. Upon heating, the solvent vaporizes within the thimble containing the sample, condenses in the apparatus's upper condenser, and then drips back down, effectively extracting phytochemicals. Once the liquid reaches the point of overflow, a siphon is activated, pulling the solution from the thimble-holder and transferring it back into the distillation flask along with the extracted solutes. During distillation within the solvent flask, solutes are separated from the solvent, with solutes remaining in the flask while the fresh solvent is continuously circulated back into the bed of plant material. This cycle continues until complete extraction is attained (Azwanida, 2015).

This method yields higher compared to maceration-based extraction and other extraction methods. However, due to the elevated temperature, there's a risk of degradation of thermolabile compound. Significantly, research comparing Soxhlet and maceration extraction techniques demonstrated reduced levels of both polyphenols and alkaloid extracts in the Soxhlet method.

2.2 Maceration

Maceration is one of the oldest extraction methods, in which ground plant materials are soaked in an appropriate solvent for a specific time, from several hours to a day, for equilibrium at room temperature (Azwanida, 2015; Waliat et al., 2023). Extraction is carried out in an enclosed container with a stopper to avoid evaporative solvent losses. This mixture is intermittently agitated to maximum soluble matter dissolved. The sufficient soaking time allows the solvent to diffuse through the cell structure to solubilize the targeted components by molecular diffusion. Finally, the solvent mixture is clarified by filtration; the solid mass is pressed to recover the maximum solvent. Sometimes, to avoid microbial growth, a small quantity of alcohol may be added. The preferable solvents, especially for the isolation of phenolic compounds by maceration extraction, are dichloromethane, ethanol, methanol, water/methanol mixture, and hydrochloric solution (Goti & Dasgupta, 2023; Olejar et al., 2015).

2.3 Percolation

Percolation is especially applied to extract active ingredients for the preparation of fluid extract and tinctures. A cone-shaped vessel, narrow and open at both sides, known as a percolator, is used. The biomass ingredients from which active components are to be extracted are allowed to soak with solvent for an appropriate time duration in a closed container; thereafter, the mixture is packed in the percolator. Additional solvent is poured as required and then allowed to drip slowly through the percolator for more than a day (Rasul, 2018). It is normally continued at a moderate rate. The mixture is pressed to remove efficient extract after the percolation process. The same process is repeated until required amount of extract is obtained. Clarification of extract is done through filtration or by decantation process. Evaporation of solvent is done to obtain the concentrate of extract. This extraction method is specially recommended for extraction from herbs and spices. It is also better suited for the extraction of thermo-sensitive components and more cost-effective than the Soxhlet method. However, it requires special attention on particle size of extract and has low chances of complete extraction of active ingredient (Alara et al., 2021).

2.4 Decoction or Infusion

This method is the oldest method adopted since the time of Ayurveda. This method is especially preferred for the isolation of water-soluble and highly thermal-stable constituents. In this method, biomass (plant materials) is soaked or boiled continuously in water. It is recommended in the Ayurveda method that hard parts of plants, like fibrous plant parts, roots, and barks through which active ingredients are extracted, should be continuously boiled or soaked. In 'infusion' the proper proportion of cold or boiling water is mixed in the pulverized sample succinctly, whereas, in decoction, the plant matrix is allowed to boil in water for a specific time period (Alara et al., 2021; Olejar et al., 2015). This extraction facilitates the retention of the extract's inherent characteristics. However, it is not usable to extract non-water-soluble components.

2.5 Hydro Distillation

Hydro distillation is a typical method for extracting plant components without relying on organic solvents. Hydro-distillation operates similarly to Soxhlet extraction by heating a mixture of sample material and water in a distillation unit to vaporize the mixture. This procedure is typically employed to remove volatile and non-volatile compounds, such as essential oils and aromatic components, from plant

material. High-temperature water aids in the extraction of components by breaking the plant tissues. Vaporization of distillate has condensed, and then separating components are collected by a separator (Waliat et al., 2023). It is an eco-friendly method to extract essential oil from plant material. However, there is a loss of some thermolabile volatile components due to prolonged high-temperature treatment (Rasul, 2018).

3 Novel Extraction Methods

Traditional methods of extracting phytochemicals are criticized for being time-consuming, using too much solvent, and requiring many processes along with high energy. These shortcomings highlight the necessity for improved and sustainable extraction methods (Pawar & Nema, 2023; Wani et al., 2021). Nowadays, to conquer these limitations, innovative and eco-friendly extraction technologies are being encouraged to extract bioactive components. These novel methods are used to save energy and time, reduce solvent usage, improve solvent recovery, and enhance the quality, sensitivity, and efficiency of the extraction process. Commonly used novel extraction methods includes MAE, UAE, EAE, SFE, PAE, etc. (Wen et al., 2020). Every extraction method has a distinct mechanism aimed to improve extraction, based on specific concepts and processing parameters.

3.1 *Ultrasound-Assisted Extraction (UAE)*

Sound waves, characterized by frequencies from 20 kHz to 100 MHz, manifest as mechanical vibrations within solids, liquids, and gases. Unlike electromagnetic waves, which can propagate through a vacuum, sound waves necessitate a medium for transmission and entail cycles of expansion and compression as they traverse through it. Expansion phases cause molecules to separate, while compression phases bring them closer together. In liquids, expansion can induce bubble formation, generating areas of negative pressure (Wani et al., 2021). These bubbles undergo growth and eventual collapse. When near a solid boundary, the collapse of these cavities becomes asymmetrical, resulting in the formation of high-velocity liquid jets. These jets exert a substantial impact on the adjacent solid surface. This phenomenon is referred to as acoustic cavitation, which creates a rupture of the cell. (Wen et al., 2020). The application of ultrasound produces mechanical actions that enhance the infiltration of solvent into cellular substances and enhance mass transfer. Ultrasound disrupts the nature of biological cell walls due to turbulent mixing of solvent and acoustic streaming, thereby aiding the release of inner targeted components. Consequently, the effectiveness of extraction with ultrasound is attributed to its ability to disrupt cells and facilitate efficient mass transfer efficiently. Many researchers found that Ultrasound-assisted extraction methods are effective in extracting the components from plant matrices (Tiwari, 2015).

UAE devices play a vital role in determining the efficient isolation of targeted components. There are two primary devices for ultrasound-assisted extractors, which are ultrasonic baths and closed extractors equipped with an ultrasonic probe transducer. The ultrasonic bath system utilizes transducer arrays to generate sonication, positioned under the bottom, on the sides, or as individual transducer array boxes within the tank. Transducers in this system typically have large surface areas, which aids in inducing vibration and generating sound waves. In the probe-type ultrasound system, a probe with an attached transducer is submerged directly into solvents, enabling efficient transmission of ultrasound energy with minimal loss. Unlike bath-type UAE devices, probes generally have smaller surface areas, potentially resulting in higher ultrasound intensity. Ultrasound intensity significantly affects extraction efficiency, emphasizing the importance of considering probe shape and reactor design when choosing suitable devices (Geow et al., 2021).

The process of ultrasound-assisted extraction (UAE) is subject to the influence of various crucial aspects, which can have a substantial impact on its efficiency and effectiveness. The aforementioned factors encompass (Wen et al., 2020):

Frequency and Intensity of Ultrasound: The impact of ultrasonic wave frequency and intensity in extraction is of utmost importance as it directly affects the disruption of cell walls and the subsequent release of target substances. The selection of appropriate frequencies and intensities is based on the distinct attributes of the sample matrix and the compounds being extracted (Maric et al., 2018; Wen et al., 2020).

Solvent Selection: The selection of a solvent plays a crucial role in the process of Ultrasound-assisted extraction. It influences the solubility and selectivity of target molecules. It is important for the solvent being used to possess favorable interaction with ultrasonic waves and have a significant extraction efficiency, all the while ensuring safety and environmental sustainability.

Temperature: The kinetics of extraction reactions and the stability of heat-sensitive chemicals can be influenced by temperature. The controlling of temperature during ultrasonic-assisted extraction is crucial in order to mitigate thermal degradation of the desired components and uphold the true nature of the final product.

Extraction Time: The extraction efficiency is significantly affected by the duration of ultrasound exposure. Prolonged periods of extraction have the potential to result in increased yields; nevertheless, it also carries the inherent danger of undesired reactions or degradation of sensitive molecules. The optimization of extraction time is crucial in order to attain the highest possible yield while maintaining the purity of the product.

Sample Pre-treatment: Pre-treatment of the sample, such as grinding, drying, or particle size reduction, can enhance the accessibility of target compounds to the solvent and improve extraction efficiency. Proper pre-treatment methods should be selected based on the characteristics of the sample matrix and the desired outcome of extraction.

Ultrasonic Power Density: Ultrasonic power density measures the amount of energy delivered per unit volume of the sample. Efficient cavitation and disruption of cell structures can be achieved by maintaining an optimal power density.

Sample-Solvent Ratio: The concentration gradient and mass transfer kinetics during extraction are influenced by the ratio of sample to solvent. It is crucial to carefully choose a suitable ratio between the sample and solvent in order to optimize the interaction between the solvent and the sample matrix.

Ultrasonic Probe Design and Configuration: The distribution and strength of ultrasound waves within the extraction vessel can be influenced by the design and configuration of the ultrasonic probe or transducer used in UAE. The appropriate choice of probe parameters, including shape, size, and positioning, is crucial for achieving consistent and effective extraction (Geow et al., 2021).

Through meticulous oversight of these important factors, researchers, as well as experts in the food sector, may improve ultrasound-assisted extraction methodologies in order to get optimal levels of yield, purity, and quality for extracted compounds derived from diverse natural origins.

3.2 *Microwave-Assisted Extraction (MAE)*

Microwaves are a form of electromagnetic waves having a frequency range from 0.3 to 300 GHz. These waves easily enter biomaterials and intermingle with polar molecules. The extraction process relies on generating heat through the application of microwaves, where electromagnetic energy is transformed into heat, subsequently leading to ionic conduction and dipole rotation of molecules (Kaderides et al., 2019). During the process of ionic conduction, heat is produced due to the medium's resistance hindering ion flow. Moreover, as ions navigate through fields with alternating signs, their changing direction results in collisions between molecules, generating additional heat. Microwave-assisted extraction (MAE) enables rapid energy transfer to plant matrix as well as solvent, resulting in efficient and uniform heating. Moisture inside the plant matrix absorbs microwave energy and starts water molecules to oscillate back and forth rapidly. This rotation generates friction between molecules, resulting in heat. Such internal superheating promotes cell disruption, facilitating the release of targeted compounds from the plant matrix and enhancing the extraction efficiency. The heating due to microwave energy is closely depends on the dielectric properties of solvent and plant matrix. Influential factors for MAE efficiency are the sample matrix, the moisture content in the sample, microwave power, extraction time, uniform stirring of solvent, nature of the solvent, the ratio of solid to solvent, etc.

Two types of commercial MAE systems are available at present that are closed extraction vessels (controlled pressure and temperature) and focused microwave (atmospheric pressure). Closed MAE systems are mostly preferred for the extraction of thermosensitive components under controlled temperature and pressure. The pressure inside vessels is based on the nature of the solvent, i.e., the boiling point of the solvent and its volume used for extraction. In the focused MAE system, the highest temperature is the solvent's boiling point at atmospheric pressure (Vinatoru et al., 2017).

Various influencing factors are considered for microwave-assisted extraction (MAE), which is used to extract targeted compounds efficiently. These factors include the following (Wen et al., 2020):

Solvent Selection: Selecting the appropriate solvent is crucial among all influencing variables. Solubility, dielectric constant, and dissipation factors emerge as pivotal considerations in solvent selection for extraction purposes. Solvents with higher dielectric constants, such as water and polar solvents, possess the capability to absorb more microwave energy compared to nonpolar solvents. Hence, water and polar solvents are deemed more effective for MAE (Vinatoru et al., 2017).

Microwave Power and Frequency: The power and frequency of microwaves used during the extraction process are significant factors. Elevated amounts of microwave power typically result in accelerated extraction rates; however, an excessive amount of power could lead to the thermal destruction of sensitive compounds. The penetration depth and energy distribution within the sample are further affected by the microwave frequency.

Sample Preparation: Preparing the sample in advance of extraction can increase the target compounds' solvent permeability and improve extraction process. Various techniques, such as grinding, drying, milling, particle size reduction, and soaking, enhance the available surface area for extraction.

Extraction Time and Temperature: Key elements in MAE are the extraction temperature and the length of the microwave exposure. Higher yields could result from longer extraction durations; however, overheating can cause heat-sensitive compounds to degrade thermally. It is essential to find the optimum extraction parameters that provide an equilibrium between target component preservation and extraction efficiency.

Sample-Solvent Ratio: During extraction, the mass transfer kinetics and concentration gradient are influenced by the sample-to-solvent ratio. In order to maximize interaction between the solvent and the sample matrix while limiting excessive dilution or saturation, the proper sample-solvent ratio needs to be selected.

Mixing or agitation: Mass transfer and extraction efficiency can both be increased by agitating the sample-solvent mixture. In order to facilitate the dispersion of targeted compounds, it is essential to stir or mix the extraction mixture to ensure that heat and solvent are distributed uniformly throughout the sample.

Microwave Vessel Design: A vessel's shape, size, agitation speed, and material used must be carefully considered in order to maximize extraction efficiency and avoid overheating or sample deterioration.

3.3 *Supercritical Fluid Extraction (SFE)*

SFE is a versatile technique that has garnered much interest in numerous sectors owing to its capacity to collect valuable substances from a vast diversity of materials effectively. The term “supercritical fluid extraction” refers to an extraction method

that uses supercritical fluids, frequently employing carbon dioxide (CO₂) as the solvent in order to extract compounds from solid or liquid matrices (Uwineza & Waśkiewicz, 2020). In the supercritical state, a material has characteristics that are both a gas and a liquid. It demonstrates high diffusivity and low viscosity, which enable it to function as an efficient solvent for the purpose of extraction. The method entails exposing the solvent CO₂ to high temperature and pressure conditions beyond its critical point, at which it transforms into a supercritical fluid (Budisa & Schulze-Makuch, 2014). The supercritical state of Carbon dioxide is achieved over the temperature of 31.04 °C and pressures over 7.38 MPa (Jiang et al., 2016). Supercritical CO₂ in this condition exhibits improved solvent characteristics, enabling it to infiltrate the solid matrix and dissolve the desired compounds.

Dissolution, mass transfer, and separation are the three crucial tactics that are involved in the extraction process at its inception. Initial steps include the infusion of the supercritical fluid, which is commonly carbon dioxide, into the extraction vessel that is holding the solid or liquid matrix that has to be extracted. Under supercritical conditions, carbon dioxide is able to enter the matrix and dissolve the compounds, which leads to the formation of a solution. Following this, the dissolved compounds get transported away from the matrix through mass transfer processes, which are driven by pressure and temperature gradients. In the final phase, the compounds that have been extracted are separated from the supercritical fluid through a depressurization or temperature reduction process. This process enables the fluid to return to its gaseous form, leaving behind the desired extract (Mendes et al., 2003).

Applications of SFE may be found in a wide variety of sectors, such as the pharmaceutical industry, the nutraceutical industry, the beverage industry, the food industry, and the cosmetics industry.

The SFE method depends on many essential factors, includes:

Pressure plays an essential role in SFE by affecting the density of the solvent and its ability to dissolve substances. Higher pressure boosts the ability of solutes to dissolve in the supercritical fluid, leading to increased extraction yields. Excessively high pressures might result in equipment constraints and safety issues (Akanda et al., 2012).

Temperature affects the ability of solutes to dissolve and diffuse in the supercritical fluid. Higher temperatures often improve extraction rates by enhancing the solvent solubility and fluid density. Temperature control within defined ranges is necessary to avoid thermal breakdown of thermosensitive substances and maintain the stability of the extraction technique (Akanda et al., 2012).

Flow rate is the rate at which the supercritical fluid transfers through the extraction vessel. Optimizing the flow rate is essential for attaining effective mass transfer and optimizing extraction efficiency. Increased flow rates may accelerate the extraction process but may negatively impact the extraction's selectivity and yield.

Co-Solvent: Adding co-solvents or modifiers to a supercritical fluid in some instances may improve extraction efficiency by modifying solute-solvent interactions and increasing solubility. Co-solvents are selected for their compatibility

with the supercritical fluid and their capacity to improve the extraction of certain molecules (Manjare & Dhingra, 2019).

Extraction time is the period during which the solid or liquid matrix interacts with the supercritical fluid. Increased extraction times often lead to increased extraction outputs by facilitating a more thorough transfer of solutes from the substance to the liquid. Extended extraction durations may result in higher energy use and processing expenses.

Particle size and composition of the matrix significantly influence the efficiency and selectivity of SFE. Finely powdered matrices provide a larger surface area for interaction with the supercritical fluid, which enhances the speed of extraction kinetics. The matrix's composition, porosity, density, and chemical composition impact both the extraction efficiency and the convenience of solute release (Ahangari et al., 2021).

Successful SFE depends on precise control and optimization of the mentioned parameters to produce desired extraction results in terms of yield, selectivity, and product quality. Researchers may customize the SFE process for individual purposes and efficiently extract desired molecules from various sources by methodically tweaking these parameters.

3.4 Pulsed Electric Field-Assisted Extraction (PAE)

The PAE technique utilizes short, high-voltage electrical impulses to cause disruption of cell membranes and enable the discharge of intracellular substances like bioactive compounds, enzymes, and nutrients from plant and microbial cells. PAE extraction provides numerous benefits in contrast with traditional extraction methods, such as increased extraction efficiency, shorter processing time, and enhanced product quality (Wang et al., 2018). Electric field strengths (EFS) used in the PAE technique range from moderate to high; they are in batch mode (100–300 V/cm), and in continuous mode (20–80 kV/cm) (Xi & Fan, 2021). Researchers noted the impact of electric fields on living tissues in the early twentieth century, resulting in the creation of PAE method (Ranjha et al., 2021). Through the utilization of specific electrical parameters, PAE can accurately focus on the cell membranes of the preferred components while keeping unwanted compounds unaffected. By being selective, the process reduces the reliance on harsh solvents or extreme temperatures, which in turn lowers the chances of damaging delicate compounds.

PAE extraction is fundamentally based on the disruptive effects of electrical pulses on cell membranes. There are a number of theories about the possible mechanism of PAE, however two popular theories centre on the biological cell membrane. One explanation emphasises the process of electroporation, while another contends that chemical interactions between various compounds are sped up, improving solvent solubility. Electroporation, also known as electro-permeabilization, is the utilisation of an external electrical force to enhance the permeability of cellular wall.

When an organic material, like plant tissues or microbial cells, is subjected to excessive levels of electric field intensity, temporary pores or openings develop in the cell membranes because of the reorientation of lipid molecules in reaction to the electric field. These openings facilitate the entry of solvent molecules and the exit of internal substances into the surrounding environment. During PAE extraction, electrical pulses are usually delivered in short bursts or pulses, with durations that vary from microseconds to milliseconds and voltages varying from several hundred to several thousand volts (Chemat et al., 2020). The PAE are precisely regulated to enhance extraction efficiency and reduce negative impacts like Joule heating and electrolysis (Pereira et al., 2024).

A pulsed electric field (PAE) unit comprises a major component are high-voltage pulse generator, a treatment chamber equipped with a fluid management assembly, and a monitoring and control system. (Alexandre et al., 2017). PAE equipment also includes a charger (to convert AC to DC) and a generator energy storage device. Electric pulses are produced by turning on and off a high-voltage circuit. When significant electric energy is released, the process becomes more complex due to the high voltage and short time pulses. Additionally, the capacitor is constantly monitored and increased if the voltage is interrupted (Ricci et al., 2018). The treatment chamber is comprised of two distinct electrodes, with one electrode connected to the high-voltage generator and the other to the ground, as well as a gap that is filled with the specific food being treated. An electric field is generated by the differential electric potentials on both sides of the membrane, which is dependent upon the type of electrodes and the distance between them, as well as the distance with the sample. Additional aspects include the characteristics of the electric pulses, the arrangement of the treatment chamber, and the conductivity of the product. The treatment parameters for polyphenol extraction, as determined through empirical experience, can be classified into three categories: strong electric fields ($E > 1 \text{ kV cm}^{-1}$), medium electric fields ($E \approx 0.1\text{--}1 \text{ kV cm}^{-1}$), and low electric fields ($E < 0.1 \text{ kV cm}^{-1}$). In general, the technique of extracting PAE can be classified into two main categories: batch extraction and continuous extraction, based on their operational methods (Xi et al., 2021).

Several factors influence the process of electroporation that are given below.

Electric Field Strength (EFS): The permeability of cell membranes and the release of certain compounds from the food matrix are influenced by the intensity of the electric field applied during PAE extraction. Effective extraction and less chemical degradation are required for optimal EFS levels (Sánchez-Vega et al., 2015).

Pulse frequency & duration: The frequency of electrical pulses in pulsed electric field (PAE) extraction has a significant impact on the degree of membrane permeabilization and the subsequent release of specific compounds. The total energy supply and its effects on the food matrix are influenced by the frequency of electrical pulses used during PAE extraction

Electrode Configuration: The distribution of electric fields within the food sample is influenced by the design and location of electrodes in the PAE system. Efficient extraction of selected substances is achieved by the utilisation of optimised electrode designs, which promote homogeneous treatment.

Sample Conductivity: The knowledge of the sample's conductivity plays an important role in the optimisation of PAE settings to get the highest possible extraction yield.

Extraction Time and Temperature: The release of targeted chemicals from the food matrix is influenced by the temperature and length of PAE treatment

Targeted Compound Properties: The release of targeted compounds during PAE extraction is influenced by their unique features, including molecular size, solubility, dielectric properties of the biological material and stability.

PAE extraction provides notable benefits in terms of process efficiency and sustainability. PAE stands out from mechanical or solvent-based extraction methods as it eliminates the need for excessive solvents or mechanical force, leading to lower energy consumption and environmental footprint. Moreover, the efficient and consistent spread of electric fields allows for quicker processing and higher productivity, establishing PAE method as an economical and expandable technology for industrial use. PAE method is applicable to a diverse array of food and agricultural products, such as fruits, vegetables, herbs, spices, grains, and algae (Naliyadhara et al., 2022). This method has been effectively utilized in extracting a diverse range of bioactive compounds including phenolic compounds, antioxidants, vitamins, pigments, enzymes, and essential oils. These compounds play a critical role in improving the flavor, color, and nutritional content of food items. Moreover, PAE has the ability to enhance the retrieval of intracellular enzymes and microorganisms, facilitating the creation of high-quality ingredients and functional foods. Lately, there has been a significant emphasis on enhancing PAE extraction parameters, expanding production systems, and researching potential applications in the food and biotechnology sectors. Progress in pulse generators, electrode design, and process monitoring has resulted in enhancements in extraction efficiency, product quality, and safety (Joannes et al., 2015). Moreover, combining PAE with additional processing techniques like ultrasound, high-pressure processing, and enzymatic treatment shows potential for further improving extraction efficiency and broadening the range of applications. This process is non-thermal nature in nature, has higher extraction efficiency, and has minimal environmental impact create an appealing option to traditional extraction methods in the food and biotechnology sectors (Kumari et al., 2018).

3.5 *Enzyme-Assisted Extraction (EAE)*

EAE represents an advanced technology utilizing enzymes' catalytic power to aid in extracting bioactive substances from numerous natural sources like plants, fruits, vegetables, and microorganisms (Patil et al., 2021). This advanced extraction technique has attracted considerable interest lately for its ability to improve extraction efficiency, selectivity, and sustainability; all while reducing the reliance on harsh chemicals and high temperatures.

EAE relies on the principle of enzymatic hydrolysis to break down complex macromolecules like proteins, carbohydrates, and lipids into smaller soluble parts. These fragments, instance phenolic compounds, flavonoids, antioxidants, and other bioactive compounds, get released from the cellular matrix and become more convenient to extract into the solvent phase. Enzymatic hydrolysis is a precise process where enzymes selectively target certain chemical bonds in substrate molecules (Yang et al., 2011). As an example, proteases break down proteins into peptides and amino acids, whereas carbohydrase hydrolyse carbohydrates into sugars and oligosaccharides. Lipases function as lipids by breaking ester bonds to free fatty acids and glycerol (Ray, 2012). The choice of enzymes is vital in influencing the outcome of enzyme-assisted extraction. Enzymes have specificity for various substrates, and their activity is affected by parameters including pH, temperature, and substrate concentration (Scopes, 2002). Cellulases, hemicelluloses, and pectinases are often used in enzymatic-assisted extraction (EAE) because they can degrade the intricate polysaccharides found in plant cell walls. Enzymes are used in a controlled way to extract specific components while reducing harm to delicate substances.

EAE functions through a set of well-characterized processes that include the interaction between enzymes and the plant matrix. Enzyme-assisted extraction typically entails numerous key stages:

Preparation of Raw Materials: The raw materials for extraction undergo different pretreatments such as grinding, drying, and size reduction to enhance the surface area and promote enzyme-substrate interactions.

Enzyme Treatment: After pretreatment, the materials undergo treatment with certain enzymes selected according to the substrate's composition and the desired chemicals for extraction. Enzymes are introduced to the substrate at appropriate quantities and under carefully regulated conditions of pH, temperature, and duration to enhance enzymatic performance.

Incubation and Hydrolysis: The enzyme-substrate mixture undergoes incubation for a set duration to enable the enzymes to catalyse the hydrolysis of macromolecules in the cellular matrix. This method releases the intended bioactive chemicals into the extraction medium, increasing their accessibility for future recovery.

Extraction and Separation: After enzymatic hydrolysis, the extraction medium composed of the evacuated compounds has to be separated from the remaining solids using methods such as filtering, centrifugation, or sedimentation. After extraction, the solution undergoes further processing to separate and purify the desired components (Nadar et al., 2018).

Enzyme-assisted extraction is beneficial because it increases extraction yields and enhances the bioavailability of essential compounds while simultaneously reducing the need for harsh chemicals and energy-intensive procedures. Enzymes facilitate the extraction of desired molecules from plant matrices by specifically targeting certain bonds and structures, resulting in increased efficiency, shorter processing times, and lower solvent use (Gligor et al., 2019). The EAE has been more popular in several sectors such as medicines, food, nutraceuticals and cosmetics, due to its ability to provide superior extracts with improved functionality and health advantages. Enzyme-assisted extraction has become an appealing option as both the scientific

community and industry look for sustainable and eco-friendly extraction solutions. This method is in line with the concepts of green chemistry, providing less environmental harm, reduced energy use, and gentler processing conditions contrasted with conventional extraction methods (Adetunji et al., 2017). This overview emphasizes EAE as a method that has the potential to transform extraction processes by using enzymes' catalytic abilities to improve yields, selectivity, and sustainability. Researchers will further investigate the mechanics, applications and difficulties associated with enzyme-assisted extraction in this comprehensive investigation.

4 Merits of Novel Extraction Techniques

There is an abundance of benefits that may be gained from the use of novel extraction technique in the food processing sector. These benefits include modernizing the industry regarding effectiveness, sustainability, and product quality. Some significant benefits include the following:

4.1 Improved Yield

When contrasted with conventional extraction methods, novel extraction techniques often produce larger proportions of extracted material. The extraction of target compound from raw materials may be accomplished using these procedures in an effective manner by optimizing factors such as temperature, pressure, and the elements of the solvent (Azmir et al., 2013).

4.2 Enhanced Selectivity

There are several innovative extraction methods that provide increased selectivity, which enables the extraction of certain compounds while simultaneously reducing the extraction of unwanted components. As a result of this selectivity, purer extracts with greater concentrations of the molecules that are required may be obtained, which ultimately leads to an improvement in product quality (Lefebvre et al., 2021).

4.3 Reduced Environmental Impact

Utilizing green extraction technologies like SFE and ultrasound-assisted extraction helps minimize the impact on the environment during food processing operations. Typically, these methods involve reduced energy consumption or the use of non-toxic solvents, resulting in decreased emissions and waste production.

4.4 Preservation of Nutritional Quality

Using gentle extraction techniques like MAE and EAE may preserve the nutritional quality of food ingredients (Nadar et al., 2018). By taking measures to reduce contact with extreme temperatures and strong chemicals, these methods help to preserve vitamins, antioxidants, and other beneficial compounds, ultimately boosting the nutritional quality of the end products.

4.5 Faster Processing Times

Novel extraction techniques provide quicker processing times than traditional methods (Jha & Sit, 2022). Systems for continuous extraction and high-throughput technologies allow for quick extraction and processing of large amounts of raw materials, resulting in improved production efficiency and shorter lead times.

4.6 Customization and Flexibility

Novel extraction methods provide more customization and flexibility in food processing processes. Manufacturers may customize their processes to meet market needs and customer preferences by adjusting parameters like extraction temperature, pressure, and solvent composition to suit various raw materials and target compounds (Chemat et al., 2017).

4.7 Enhanced Product Safety

Novel extraction methods allow for enhanced monitoring and control of food quality and safety criteria.

4.8 Innovation and Product Differentiation

Accepting new extraction methods encourages creativity in product development and sets products distinct in the competitive food industry. Food manufacturers have the opportunity to utilize distinct extraction methods to develop innovative food formulations, functional ingredients, and enhanced products that align with consumer preferences and current trends (Chemat et al., 2020).

4.9 *Cost-Effectiveness*

There is a possibility that the total cost of manufacturing may fall as extraction procedures grow more efficient. The decreased amount of time required for processing, the decreased amount of energy that is used, and the possibility of employing solvents that are less costly all contribute to an increase in the cost-effectiveness of food processing activities (Ameer et al., 2017).

4.10 *Versatility and Flexibility*

A broad variety of food matrices, such as fruits, vegetables, cereals, herbs, spices, and botanicals, are all suitable candidates for the use of novel extraction methods. Their adaptability makes it possible to extract a wide variety of substances, including essential oils, polyphenols, proteins, and pigments, which in turn makes it possible to generate novel food formulations and components.

4.11 *Enhanced Flavor and Aroma*

Instead of relying on more conventional approaches, novel extraction techniques have the potential to capture and retain the distinctive flavors and aroma of food items more efficiently. The use of these techniques helps to improve the overall taste and attractiveness of food items by preserving the integrity of volatile molecules that are responsible for their sensory qualities.

5 Limitations of Novel Extraction Techniques

Despite the fact that innovative extraction methods in food processing come with a number of benefits, it also come with a number of drawbacks and challenges that need to be tackled:

5.1 *High Initial Investment Costs*

In order to successfully implement revolutionary extraction techniques, it is often necessary to make substantial financial investments in specialized equipment, technology, and infrastructure. This first financial investment may be a challenge for food processing facilities that are smaller in size or for enterprises that have less resources available.

5.2 Complexity and Technical Expertise

Several advanced extraction methods entail intricate procedures and demand a significant level of technical expertise for operation and upkeep. Experienced professionals with a thorough grasp of the techniques are necessary, posing a challenge for some food processors to implement these methods without sufficient expertise. Training staff and ensuring adherence to safety regulations can be quite challenging, especially in sectors where conventional extraction techniques are common.

5.3 Scale-up Challenges

Moving from laboratory-scale to industrial-scale production can present certain challenges. Scaling up certain innovative extraction methods may pose challenges, requiring modifications to ensure optimal efficiency and productivity at larger production volumes (Tapia-Quirós et al., [2024](#)).

5.4 Lack of Standardization

There is often a lack of standardization in novel extraction techniques, that can make it hard to match up results across various studies or establish consistent quality control measures. This variability can impede widespread adoption within the industry and undermine trust among customers.

5.5 Market Acceptance and Consumer Perception

When innovative extraction techniques are introduced to consumers, they may be met with resistance or skepticism, especially if they view these methods as unnatural or unusual. For the purpose of establishing confidence and acceptability in the market, it is vital to educate customers about the advantages and safety of innovative extraction procedures.

5.6 Regulatory Compliance and Safety Considerations

Novel extraction techniques might bring in new compounds or processing aids into food products, leading to concerns about their safety and regulatory approval. It is crucial to adhere to food safety standards, labelling requirements, and regulatory guidelines to minimize risks to consumer health and safety.

5.7 *Unintended Consequences*

Implementing new extraction methods might lead to unexpected outcomes or unanticipated difficulties in food processing procedures. Modifications in product traits or shelf-life endurance may arise due to the extraction procedure, necessitating vigilant supervision and modification to maintain product quality and customer approval.

6 Future Scope

Advancements in food processing technology lead to the development of new extraction methods that provide enhanced efficiency, quality, and sustainability in the food sector. The strategies include several ways to extract beneficial compounds from raw materials while reducing waste and environmental harm. The future potential of innovative extraction methods in food processing seems promising and encompasses several significant domains.

6.1 *Novel Extraction Methods*

The future underscores development of extraction technologies that are beneficial to the environment and minimize the amount of energy and solvents that are used. Methods like SFE and UAE are becoming increasingly popular because of their low environmental impact.

6.2 *Enhanced Nutrient Retention*

Novel extraction methods have the potential to maintain the nutritious quality of food items by reducing heat and oxidation during the extraction process. Manufacturers can preserve vital minerals, vitamins, and bioactive components in the final product by adjusting factors which include temperature, pressure, and extraction time.

6.3 *Bioactive Compound Extraction*

There is an increasing curiosity in isolating bioactive molecules including antioxidants, polyphenols, and phytochemicals. These compounds provide several health advantages such as antioxidant capabilities, anti-inflammatory behavior, and

disease prevention. Novel extraction methods facilitate the effective retrieval of these bioactive components for incorporation into functional meals, nutritional supplements, and nutraceuticals (Lemes et al., 2022; Wen et al., 2020).

6.4 Tailored Extraction Processes

The future of extraction methods relies on customization and accuracy. Manufacturers are investigating customized extraction methods that correspond to particular food compositions and desired chemicals. This entails fine-tuning settings according to the source material's qualities, desired features of the finished product, and extraction efficiency.

6.5 Integration of Technologies

Combining several extraction methods like SFE with membrane filtration or integrating microwave-assisted extraction with enzymatic hydrolysis offers potential for improving extraction efficiency and product quality (Patil et al., 2021). These hybrid methods use the advantages of specific approaches to surpass limitations and get the best outcomes.

6.6 High-Throughput Screening

The development of future extraction methods may make it possible to conduct high-throughput screening of a broad variety of food ingredients. This is made possible by developments in automation and robots. It is possible that this will make it easier to conduct a fast screening of various sources for bioactive chemicals or other important elements.

6.7 Nanotechnology Applications

The use of nanotechnology has the potential to improve extraction procedures by raising mass transfer rates and expanding the surface area that is accessible for extraction. In the future, research studies may investigate the possibility of incorporating nanomaterials into extraction methods in order to improve both efficiency and yield (Noore et al., 2021).

6.8 *Process Intensification*

It is possible that future extraction methods may concentrate on intensifying the process in order to attain larger extraction yields in much shorter amounts of time. For this purpose, it may be necessary to use sophisticated reactor designs, process modelling, and optimization techniques to attain the greatest possible extraction efficiency.

6.9 *Blockchain Integration for Traceability*

There is the potential for the use of blockchain technology to improve the traceability of the extraction process. This has the potential to offer customers with comprehensive information on the origin, processing, and quality of the compounds that have been extracted, therefore increasing transparency and reliability throughout the food supply chain (Haji et al., [2022](#)).

6.10 *Biotechnological Approaches*

It is possible that the development of innovative extraction techniques will be significantly influenced by biotechnological approaches such as enzyme engineering, microbial fermentation, and other similar methods. It is possible for these approaches to provide a regulated and selective extraction of the molecules of interest, hence eliminating the use for harsh chemical solvents (Ghasemy-Piranloo et al., [2022](#)).

It is expected that the future of innovative extraction methods in food processing will be influenced by an amalgamation of sustainability, the integration of technology, and a deeper knowledge of the intricate interactions that exist between raw materials and the compounds. The persistent pursuit of innovation will be of critical importance in accommodating the constantly changing demands of the food sector as well as the needs of customers.

7 Conclusion

Concluding the thoughts on novel extraction techniques in food processing, it showcases a vibrant landscape of innovation and potential. Researchers and practitioners are exploring an extensive range of extraction methods to meet the demands of the food industry striving for sustainability, efficiency, and product quality. Novel extraction methods in food processing have great potential to revolutionize the industry in several aspects. The increasing need for sustainable, efficient, and

high-quality food products is driving the development and use of unique extraction technologies to meet these problems and discover new possibilities. The increasing need to extract bioactive components from plants motivates the ongoing quest for efficient extraction techniques. The traditional approaches rely on the solubility of solute from plant components in a solvent. Hence, it often requires a significant amount of solvent to extract the intended substances, occasionally aided by high temperature and mechanical agitation. The selection of appropriate standard procedures also impacts the assessment of extraction efficiency. In contrast, the growing economic importance of bioactive chemicals and products containing these compounds may drive the future advancement of more sophisticated extraction techniques. In this outline, the various breakthroughs that have been made in the field have been emphasized. These developments include the incorporation of nanotechnology and biotechnological techniques, as well as high-throughput methodologies and environmentally friendly extraction technologies. The extraction method utilized is crucial in organic product study as it is essential to isolate the desired compound derived from the untreated material altering or damaging them. Traditional extraction methods like percolation, reflux, maceration and Soxhlet extraction are known for being time-consuming, inefficient, and causing organic pollution that can be detrimental to both ecology and human well-being. To address these limitations, there have been various recent initiatives to enhance environmentally friendly and effective extraction methods like microwave and SFE, along with PAE and UAE. These methods provide numerous benefits, including boosting the extract yield, minimizing thermal destruction and selective heating of plant tissue, and cutting down on the use of organic solvents. Collaborations across different sectors such as industry, academia, and other fields enhance the innovation ecosystem by promoting interdisciplinary approaches and sharing knowledge. Novel extraction methods are expected to tackle the problem of by-product generation in food processing. Exploring approaches that utilize waste materials as a source of bioactive substances or incorporate circular economy principles to contribute to sustainable and zero-waste practices.

Acknowledgements The authors would like to extend their sincere appreciation to the National Institute of Food Technology Entrepreneurship and Management-Kundli, Sonapat, Haryana, India for providing library facilities.

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Chapter 18

Future Trends in Food and Dairy Process Engineering and Business: A Comprehensive Exploration



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1 Introduction

The food and dairy processing industries have had a great impact on human nutrition and well-being by offering a wide array of benefits. Over the years the sector has made significant contributions to providing safe, nutritious, affordable, convenient and variety. This facilitated the development of a wide range of food products with different flavors, textures, and forms (Knorr & Augustin, 2021). The sector is poised for remarkable growth in the future, driven by various factors including rapid population increase, evolving dietary preferences, heightened health awareness, rising incomes, and a shift in demand from food service to retail. As the global population continues to grow, especially in emerging economies, there is a rising demand for food and dairy products to fulfill expanding dietary requirements (Henchion et al., 2021). Concurrently, as consumers become more health-conscious and environmentally aware, there is a shift towards healthier, more sustainable food choices, including plant-based alternatives and products with clean labels (Tachie et al., 2023). Rising incomes further contribute to increased spending on quality food items, while the COVID-19 pandemic has accelerated the trend of cooking and eating at home, boosting demand for retail channels over food service establishments (Núñez-Fernández et al., 2021). Adaptation to these trends, coupled with innovation

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and technological advancements, positions the food and dairy industry to capitalize on these opportunities and drive significant growth in the years ahead.

The food and dairy processing industry in India had a market size of 239 billion USD in 2019 and is anticipated to grow to 530 billion USD by 2026 (Suryavanshi, 2023). Likewise, global milk production was 328 billion USD which is forecasted to grow by 23% by the year 2025 (Haas et al., 2019) owing to the increased population and huge demand for nutritious food showing significant potential for growth. To capitalize on this potential and meet consumer demands, the industry can explore various solutions such as utilizing waste to create new consumer goods and developing products with diverse nutritional compositions. These strategies could enable the sector to thrive exponentially while catering to evolving consumer preferences (Roy et al., 2023). Food wastage and losses remain significant global concerns, impacting both the environment and food security. Addressing this issue requires a substantial effort, and the concept of a sustainable agricultural practices and circular economy. By implementing strategies to minimize waste throughout the food production and distribution chain, such as reducing overproduction, improving storage and transportation practices, and redistributing surplus food to those in need, a more sustainable and efficient food system can be created. Embracing a circular economy mindset can help mitigate the adverse effects of food wastage while promoting environmental sustainability and enhancing food security worldwide (Maina et al., 2017). Food and dairy industries have been focused on the concept of resources-production-consumption-disposal which is called the one-way economy. It could be responsible for rising environmental concerns, increased wastage of energy, water, and resources, low consumer acceptance of processed foods, and reduced ethical considerations. Furthermore, high energy consumption with traditional processing technologies is disastrous in the current world where challenges are already existing to achieve sustainable development (Onyeaka et al., 2023). All these parameters could be the responsible factors for rising environmental concerns, increased wastage of energy, water, and resources, low consumer acceptance of processed foods, and reduced ethical considerations. Numerous initiatives such as the use of non-thermal technologies, the use of membrane processes for the economical use of water, 3D printing of food to achieve personalized nutrition, plant-based and cell-cultured foods to fulfill the global protein demand, and waste minimization by converting food waste to value-added products have been proposed to address the antecedent issues (Arshad et al., 2022; Eswaran et al., 2023; Roy et al., 2023; Tachie et al., 2023).

However, technologies being developed are still on a lab scale and huge efforts are required to make them available at a commercial scale for bulk processing. Nevertheless, the application of artificial intelligence, the internet of things, novel process technologies with advanced processing systems assisted with artificial intelligence for process prediction and optimization, appropriate waste utilization, and the adoption of a circular economy approach could be explored to achieve sustainable food systems (Onyeaka et al., 2023; Said et al., 2023). Appropriate market analysis to enhance consumer acceptance of newly developed food products could

also play an important role (Guiné et al., 2020). Apart from the sustainable processing system and production of novel food products with optimum and efficient use of energy and resources, a resilient food supply chain network is also an important concern of food and dairy industries to obtain food safety. Traditional methodologies adopted to reduce the risks of food contamination were insufficient and led to looking for new methodologies. Various researchers proposed different methodologies such as type-2 fuzzy modeling, and mixed-integer linear programming considering both operational and disruptive food safety risks to establish a resilient supply chain network (W. Mu et al., 2021; Wenjuan Mu et al., 2024). The potential future prospects could be the application of IoT for situational real-time awareness, blockchain for traceability, genome sequencing for outbreak monitoring, and artificial intelligence (machine learning and deep learning) for the prediction of food safety issues (Wenjuan Mu et al., 2024). Therefore, this chapter illustrates the advancements and future developments in food and dairy process engineering and management while achieving sustainability and global food security (Table 18.1).

2 Intelligent Processing Systems

Intelligent processing systems are advanced technologies and systems that leverage various forms of automation, artificial intelligence (AI), data analytics, and digital technologies to optimize and enhance food processing operations (Nayak et al., 2020). The global food industries are experiencing a significant transformation, and the demand for increased processing speed, reduced operating costs, and improved process efficiency is a crucial part of this evolution. An introduction of Artificial Neural Network (ANN) in food and agriculture has been exhibited as a promising tool for the prediction of various processing operations such as grading, sorting, mathematical modeling and process optimization, thermal and non-thermal processing of food processing operations, and non-destructive quality evaluation using image processing (Kyaw et al., 2022). Due to the robust and accurate analysis of neural networks, the deep learning concepts are gaining additional popularity in food quality evaluation (Nayak et al., 2020). Furthermore, the concept of utilizing a cyber-physical production system in food production is becoming increasingly essential to address the challenges and demands of the future (Smetana et al., 2021). This system is suitable for sustainability assessment, suitable for automated traceability, and personalized nutrition. In addition to that, food packaging systems are benefiting from the integration of AI algorithms. Moreover, risk analysis and reliability are establishing and maintaining a sustainable food production system. Fuzzy interface systems could be the way out for the risk analysis (Soltanali et al., 2022). Despite all the advantages of technology, ensuring food quality and safety during processing, handling, and transportation is primary importance in the food industries. Therefore, tracing and tracking of the entire food operations with

Table 18.1 Technological advancements shaping the food and dairy industry

S. No.	Technological advancements in food and dairy industry	Key observations	Reference
1.	Intelligent processing system Artificial Intelligence (AI) Internet of Things (IoT) Sensors Big data analytics (BDA) Cloud computing technology (CCT) Blockchain technology (BT)	Key observations AI: Application of AI in various areas written as follows: Product sorting and packaging Personal health sanitation Decision-making systems for the customers Equipment cleaning and maintenance Demand supply-chain management Launching new products IoT: IoT systems can provide decision-making in the food industry. It includes four layers namely the sensing layer, networking layer, service layer, and interface layer. IoT system to monitor gas, temperature, and humidity of packed food products, being able to provide more useful quality information than with traditional quality control systems that focus on weight, volume, color, and aspect inspection. Sensors: Different electrochemical sensors such as Hydrogel microsphere-based portable sensors for colorimetric detection of nitrite in food, colorimetric paper sensor for food spoilage, layer-by-layer deposited multimodal sensor to monitor temperature, relative humidity, and volatile organic compounds during storage of food, and nanomaterials based nanosensors for packaging application have been developed. BDA: BDA can be used to provide transparency, traceability, and predictive insights of various activities. It helps in making real-time decisions as well as developing the monitoring and sampling strategies for safety evaluation. CCT: It could be applied in different ways as mentioned below to enhance process efficiency and efficient resource utilization: Data management and analytics Supply chain management Quality control and compliance Process automation Traceability and recall management Product development and innovation Sustainability and resource optimization BT: Used for monitoring and traceability in food supply chain Food loss traceability is difficult using blockchain Major food suppliers such as Walmart, Nestle, and Unilever built a consortium in collaboration with IBM to apply blockchain technology. Consumers could track the food journey right from raw material procurement to the end product just by scanning a QR code available on the food packet.	Kumar et al. (2021) Hassoun et al. (2023) Sarmah and Aruna (2020) Al-Hamry et al. (2023) Calabretta et al. (2023) Liu et al. (2023a, b) Jin et al. (2020) Ramanathan et al. (2023) Kayikci et al. (2022) Varavallo et al. (2022)

2. Novel nonthermal processing Ultrasound technology (US) High pressure processing (HPP) Pulsed electric field processing (PEF) Cold plasma processing (CP) Pulsed light technology (PL) Ozone processing	US: Can be used to improve the process of emulsification and foaming, freezing and thawing, concentration, drying, tenderization Could control and modify the microstructure and textural properties of starch, protein, and fat-rich food HPP: Replaced the use of emulsifiers/stabilizers while developing novel food ingredients including dairy products. Improved colloidal stability in various plant-based beverages. The nutritional value of dairy-based products has been retained after HPP treatment. HPP is less environmentally impactful but highly expensive. PEF: Ineffective for gram-positive bacteria, yeasts, and spores. Structural modification and reordering of food compositions, enzymes, and bacterial cells. Useful in the treatment of wastewater being a non-chemical method and reduces pesticides in food. Reduces the energy consumption. Surface treatment improves the seed yield. CP: Microbial load of up to 4 log cycle reduction have been achieved for food materials using cold plasma technology. Cold plasma combined with other technologies such as nanotechnology, pulsed light, and pulsed electric field for packaging, structural modification, quality improvement, and food safety have been reported for better outcomes. High initial investment and operational risks for cold plasma technology need to be addressed. PL: Highly recognized for surface sterilization. Polyphenols and flavonoids were reported higher in fruits and vegetables after pulsed light treatment. Could enhance the shelf life of seafood up to 10 days. Further study is needed for the commercial feasibility of the process. Ozone: Utilized to reduce the biofilm formation in dairy manufacturing plants. Has been applied to disinfect dairy equipment Used for microbial inactivation and preservation consequently reducing the β-carotene content of milk and milk products. Has been reported for mycotoxins reduction in various food materials.	Bhargava et al. (2021) Ravash et al. (2022) Levy et al. (2021) Cacace et al. (2020) Arshad et al. (2021) Ki et al. (2015) Ferreira et al. (2019) Ahmad et al. (2020) Chang et al. (2020) Cui et al. (2020) Faria et al. (2020) Lee et al. (2020) Shiekh et al. (2021) Ucar et al. (2021) Liang et al. (2023) Yao et al. (2023) Zhang et al. (2022) Panebianco et al. (2022) Khanashyam et al. (2022) Afsah-Hejri et al. (2020) Nickhil et al. (2021)

(continued)

Table 18.1 (continued)

S. No.	Technological advancements in food and dairy industry	Key observations	Reference
3.	Nanotechnology in Food Safety and Packaging Nanotechnology in food safety Nanotechnology in food packaging	Sources of nanomaterials (organic/inorganic) have been greatly emphasized for food packaging and risks associated with the safety of food. The barrier properties (for gases and moisture) of the packaging materials have been greatly improved with nanotechnology. Future research in the area of nanotechnology could be the impact of nanoparticle release on the environment during production, use, and disposal.	K. Ahmad et al. (2024)
4.	Plant-Based and Cell-Cultured Foods	Consumer reluctance from plant-based foods is mainly due to the presence of beany flavor and anti-nutritional compounds such as phytates, saponins, tannins, protease, and amylase inhibitors. Poor bio-availability of minerals in plant-based foods have been constantly reported. Cultivated/cell-cultured meat is still on the emerging stage. Monitoring and optimization of various bioprocess parameters such as CO ₂ , dissolved oxygen, pH, cell density, humidity, glucose, and lactate are very crucial. An optical technique could be explored in the future for cultured meat production.	Banach et al. (2022) Tachie et al. (2023) Pawar et al. (2023)
5.	3D Printing of Food, personalized nutrition, and dietary monitoring	Additive food printing technology allows food materials and processes to be combined in customized ways and think beyond conventional cooking. The food production rate is extremely low. 3D printing assisted with digital technologies (IoT, blockchain) could enable the end user for customization. Future research could be the utilization of insects, fungi, and algae with food inks while 3D printing for protein-rich food.	Eswaran et al. (2023)
6.	Sustainable Processing Techniques	Lower energy consumption, higher microbial inactivation, and longer shelf life of food have been reported by using novel non-thermal processing techniques such as HPP, PEF, and US. Membrane technologies could be adapted to save energy and water usage. Food waste could be utilized for bioactive compound extraction and energy generation using a hydrothermal carbonization process instead of pyrolysis and gasification.	Niknaram & Rosentrater (2019)
7.	Waste Valorization and Circular Economy	Valorized food waste by developing high-value products (For example: bioethanol from food waste) AI could accelerate the waste valorization process by better prediction and optimization.	Sahoo et al. (2023) Said et al. (2023) Echave et al. (2023) Dhar et al. (2023)

real-time monitoring and risk identification system is a current demand in the industry to produce high-quality and safe food products for consumers (Kong et al., 2021). Application of real monitors using radio frequency identification, controller area network, internet of things, and embedded system technologies could ensure real-time product monitoring and safety (Yi et al., 2010). Food safety could also be improved by implementing transparent supply chain monitoring systems. Enhancement of transparency in the supply chain and food production system using an artificial intelligence approach would be further useful to produce a resilient supply chain network in the future.

3 Novel Non-thermal Processing

Green and energy-efficient technologies have gained popularity across various industries, including the food sector, due to their capacity to address a wide range of critical issues such as increased energy consumption and processing time, retention of maximum original quality, extension of shelf life, eco-friendliness, sustainability, and overall cost-effectiveness. Novel non-thermal technologies such as ultrasonication, high pressure processing, pulsed electric field, and membrane processing are synonymously known as green technologies, have been used mostly as a suitable alternative to thermal technologies. The non thermal technologies facilitate various operations such as extraction, diffusion, freezing, drying, and dehydration for the processing of food with higher nutrient retention (dos Santos Rocha et al., 2022). The demand for non-thermally processed food has increased due to the enhanced health consciousness, huge demand for quality products, and increased per capita income of consumers. The novel technologies are beneficial to serve the purpose as they use electromagnetic, light, electrical, and mechanical forces as driving forces for processing operations instead of high temperatures (Neokleous et al., 2022). Apart from these technologies cold-active enzymes have also gained attention of the researchers as a useful non-thermal technology (Hamid et al., 2022). An application of cold plasma treatment on surface of foods reduces the pathogens without affecting the food quality. However, the literature on process optimization for cold plasma and other non-thermal technologies is limited (Hernández-Torres et al., 2022). Hence process optimization is very important for technology commercialization. The shelf life extension and storage stability of the products processed using non-thermal technologies would be the key factors in the future for determining their huge potential. However, non-thermal technologies would be of prime importance in the future of the food processing sector as they help in implementing the circular economy and achieving sustainable development goals (Arshad et al., 2022).

4 Nanotechnology in Food Safety and Packaging

Nanotechnology has gained considerable popularity in recent years and has found a wide range of applications in various sectors, including the food industry. Nanotechnology involves the manipulation of matter at the nanoscale i.e., level of individual molecules and atoms. In the food sector, it has a wide range of applications that offer benefits in terms of food safety, quality, packaging, and sustainability (Eleftheriadou et al., 2017). The application of nano-technology i.e., nanoparticles, nanocomposites, and nano-coatings, are popular area to ensure food safety and used to enhance food packaging. Nano-technology in packaging addresses the issues related to chemical additives and petroleum polymers present in the packaging material and offers suitable alternatives. Biodegradable and biocompatible packaging materials are the appropriate substitutes. However, despite putting a lot of effort into developing biodegradable packaging materials, achieving a balance between sustainability, water-oxygen barrier, and mechanical strength of conventional plastics is a complex task. Nanotechnology is an upcoming trend at the front line as it offers better physical, functional, and mechanical properties of the packaging polymers (Barage et al., 2022; Bangar et al., 2023). However, the major challenges faced by the industries are the migration of packaging materials to food, presumed toxicity, and risk assessment. Therefore, the type, benefits, risk assessment, and permissible limit of nanoparticles in food packaging must be defined as some of the nanoparticles are harmful to human health. Furthermore, the focus of the packaging must be in the direction of reducing the large surface area to volume ratio of nanoparticles as this could be the key reason behind the nanoparticle toxicity. It plays a significant role in developing novel packaging systems. The thrust areas to improve food packaging are the addition of functional nano ingredients based on organic, inorganic, and combined materials such as antimicrobial, UV protective, and antioxidative materials to the packaging materials (Ansari, 2023). In addition to this, the incorporation of smart nanosensing materials for product identification, and detection of gases and organic molecules are also important to produce the smart packaging system for spoilage detection. Antigen-specific biomarkers, smart packaging, and the use of nanosensors to detect pathogens are the future needs in food packaging (Singh et al., 2023). Moreover, artificial intelligence-driven sensors could be placed to transfer the data between the biosensors and other intelligent systems such as smartphones for the information of users (Singh et al., 2023).

5 Plant-Based and Cell-Cultured Foods

The shift toward vegan food represents a broader movement toward more conscious and sustainable eating habits. There has been a significant shift in dietary preferences, with more consumers adopting vegan and plant-based food options. This

shift is driven by various factors, including health, environmental concerns, animal welfare, and a growing awareness of the benefits of plant-based diets (Langyan et al., 2022). This increased the demand for plant-based and cell-cultured food (Langyan et al., 2022). The most responsible factors for increased demand have been the dietary lifestyle, urbanization, enhanced individual economic conditions, health awareness, environmental awareness, and the global population (Green et al., 2022). Milk, fish, cheese, egg, yogurt, and meat analogs have been gaining the attention of researchers and scientists to address the above issues. The technologies involved in producing these food products have been fractionation, extrusion, tissue engineering, and fortification (McClements & Grossmann, 2021). However, the structural, nutritional, and sensorial properties haven't yet been comparable with animal-based products. In this regard, the meat analog has exhibited remarkable progress in ensuring a meat-like texture. The innovative technologies that have been used to prepare meat of animal-like structures are mycelium cultivation, shear cell technology, recombinant protein additives, and 3D printing (Rubio et al., 2020). Cell-based meat, also known as lab-grown meat, cultured meat, or in-vitro meat, is a novel approach to meat production that involves cultivating animal cells in a controlled environment instead of raising and slaughtering animals (Pawar et al., 2023). It has also gained attention to fulfill the global protein requirement. However, the organoleptic properties of plant-based and cell-cultured meat such as color, structure, and marbling are pivotal parameters for consumer acceptance. The next-generation sources that enhance the color, structure, and marbling properties of plant-based meat are heme proteins/fruits and vegetable extract, fungi-based products, and plant-based fats respectively (Rubio et al., 2020). Moreover, food safety, health concerns, and nutritional hurdles are yet a pivotal part of food consumption. Hence future research must involve in-vitro studies, protein digestion, protein absorption, in-vivo studies, and allergenicity on human health (McClements & Grossmann, 2021)

6 3D Printing of Food, Personalized Nutrition, and Dietary Monitoring

3D food printing, also referred to as additive manufacturing, entails the layering of edible filaments to produce a diverse range of consumables suitable for various age groups. This technology has capacity to fabricate intricate geometric designs, facilitating widerange of customization. Beyond its inherent nutritional benefits, this technology has opened doors to the idea of tailored or personalized nutrition. Personalized nutrition and dietary monitoring have become increasingly popular among consumers who desire for proactive health management. This may be due to the increased risk of various cardiovascular, celiac, and gut-related diseases. 3D printing of food is the most advanced technology to enable personalized nutrition, creative culinary, and monitoring of the human diet (Dankar et al., 2018). This

additive manufacturing technology has the potential to create customized foods with complex shapes, geometries, textures. Food-grade syringes hold the printing material, and this material is subsequently deposited through a food-grade nozzle in a layer-by-layer fashion. Food inks are the heart of 3D food printing technology that plays a significant role in food printability. Inks based on various formulations such as food hydrogels, protein emulsions (Isolated from algae, insects, micro-organisms, and food residues), emulsion gels, and starch gels have been reported so far (Baiano, 2022). Different colorants and flavoring substances have also been reported as inks for 4D food printing (Dankar et al., 2018). For example, milk powder was fortified with rye flour and used as printable ink to produce baked food. As per the results of the study, higher concentration of milk powder resulted in collapse of multilayer baked food structure while the fortified ink produced the acceptable product (Lille et al., 2020). Furthermore, rennet-induced gelated milk proteins were also reported to be a good printable ink for formulation of 3D food structures (Uribe-Alvarez et al., 2021). However, despite significant advancements in the 3D printing the printability of various food inks are challenging due to texture, consistency, ingredient compatibility, temperature sensitivity, etc. Complexity of the rheological properties of the individual food components limits the speed of printing and eventually creates obstructions in large-scale productions (Ma & Zhang, 2022). Optimization of process parameters and innovation in production can't be ignored either. The existing printers are either custom-built or modified plastic printers which are slow in food production based on 3D printing technology. The way forward could be the design of appropriate 3D food printers for diverse rheological emulsions to control the structure and texture of developed food products. Furthermore, the development of integrated 3D food printers associated with machine vision could be useful for both qualitative and quantitative evaluation of food printability. It could also be beneficial for defect identification in 3D-printed food objects. The existing applications of 3D food printing for personalized nutrition are sugar, salt, and fat reductions (Ma & Zhang, 2022). However, future research could be on customized nutrient delivery for distinct age groups. Some of the data on 3D printed food production based on the design direction of improving proteins (by increasing the intake of protein sources such as soya protein and gluten), carbohydrate limitations, salt & sugar reduction initiative, balancing the consumption of saturated and unsaturated fatty acids (adding oleogels and using emulsions as fat substitutes), and increasing fiber intake (by addition of inulin and soy dietary fiber) have been reported (Xie et al., 2023). The validation of customized nutrient intake is very crucial to exhibiting the desired health benefits of individual nutrients. Therefore, the development of wearable devices to monitor and validate nutritional intake and to provide real-time feedback is the current need. Wearable biosensors and electrochemical sensors have contributed significantly to personalized nutrition and dietary monitoring (Sempionatto et al., 2021). However, the data generated from the sensors could be coupled with the AI-based algorithms for further prediction and customization of nutritional intake.

7 Sustainable Processing Techniques

The food processing sector is known to be resource-intensive, particularly in terms of water and energy consumption compared to various industries. Higher energy consumption may be due to the utilization of conventional thermal processing technologies (Wang, 2014). Moreover, a total of $192.5 \times 10^6 \text{ m}^3$ of wastewater is generated from dairy industries only across the European countries (Stasinakis et al., 2022). However, higher water consumption is due to the application and wastage of large amounts of water during the washing and cleaning of various food commodities. The adoption of green and energy-efficient technologies such as non-thermal processing methods, novel heating methods, novel thermodynamic cycles, and membrane processes could offer a potential solution to improve sustainability, reduce production costs, reduce carbon dioxide emission, and efficient energy utilization (Wang, 2014). High water usage and extensive waste generation are the next primary concern to achieve sustainable processing. Water reconditioning using physical (membrane processes such as ultrafiltration, microfiltration, nanofiltration, and reverse osmosis), chemical (application of chlorine, hydrogen peroxide, ozone, and chloramines), or a combination of both processes enables the recycling and reuse of water by reducing the microbial load and other contaminants in the wastewater (Nikmaram & Rosentrater, 2019). Apart from the recycling and reuse of wastewater, water consumption itself could be reduced in food and dairy industry by reducing leaks, water pressures, and uncontrolled water by using spray nozzles (Shrivastava et al., 2022). Reconditioning could offer a potential solution to increase the water use efficiency. However, the monitoring of pathogens in water, optimization of process parameters, treatment reliability, and assessment of treatments are the way forward for sustainable processing during the application of physical and chemical processes. Furthermore, waste generation and its reduction from the food industries have gained huge attention due to the availability of high-value components in food waste such as amino acids, polysaccharides, vitamins, and bioactive compounds (Asgharnejad et al., 2021). For example, essential polyphenols from cranberry pomace, citrus peel, spent tea leaves, and grape skin, vitamin E, carbohydrates, dietary fiber, single cell protein from barley by-products, wheat, and milk by-products respectively (Jayanthi Antonisamy et al., 2023; Liu et al., 2023b). These food components can be used for both the development of value-added products and energy. Various technologies have already been reported for the sustainable processing of food waste. However, commercial-scale processing is yet to be discovered to achieve a circular economy, establish a green environment, reduce carbon emissions, and complete valorization to accomplish zero waste (Sharma et al., 2021).

8 Waste Valorization and Circular Economy

Food and dairy industry generates a significant amount of food waste. Food processing involves various stages, from harvesting raw materials to the final production of consumer goods, and each stage can contribute to waste generation. Food waste in the processing industry can have environmental, economic, and social implications (Santagata et al., 2021). According to the recent data published by the Food and Agriculture Organization of the United Nations, 570 million tonnes of food are wasted every year globally at household levels (Sonnet Malakaran George & Galvez Nogales, 2023). Food wastage occurs at every stage of postharvest, processing, distribution, and consumption. Reducing food waste is essential for promoting sustainability, efficient resource utilization, and addressing global food security challenges. It eventually gained the attention of researchers due to its association with high economic and environmental impact. Conversion of industrial by-products based on food and dairy into valuable ingredients has been reported as the probable solution to minimize food waste and promote a circular economy (Onyeaka et al., 2023; Choudhury et al., 2023). A circular economy is an economic model that prioritizes the sustainability of resources by minimizing waste and reusing or recycling materials to create a closed-loop system. Food waste has been valorized to produce bioenergy as they are good source of protein, carbohydrates, lipids, and essential bioactive compounds and help in exhibiting the fermentation process (Meenakshi et al., 2024). Waste rich in fibers has been explored to produce polymeric mixtures, biocomposites, sustainable pots, films, containers, and nonwoven tissues (Roy et al., 2023). Usually, mixed food waste is explored for biofertilizers, biomaterials, and energy recovery to date. Moreover, the specific flour waste streams from flour processing industries have been reported to produce amylolytic and proteolytic enzymes and microbial oils using flour hydrolysate (Maina et al., 2017). However, the future trend could be the extraction, and isolation of high-value bioactive and food ingredients from individual food waste streams (peels, seeds, fibers, shells, bran, and polysaccharides) and dairy by-products (whey, skim milk, buttermilk, etc.). The standardization and optimization of process parameters while utilizing energy-efficient processing technologies are equally crucial to scaling up the bulk production processes. Furthermore, the concept of integrated biorefineries with the processing of individual food waste streams could be a possible and sustainable approach to achieve a circular economy and waste valorization. The application of artificial intelligence (AI) could accelerate the waste valorization process by determining and predicting the composition and suitability of food waste for the systematic production of individual value-added products (Said et al., 2023).

9 Ethical and Social Considerations

The developments in food and dairy processing sector has given rise to various ethical and social concerns. These concerns often arise from the scientific processes involved in food processing, raising questions about the impact on health, the environment, animal welfare, and other ethical considerations. Many emerging food processing technologies rely on electricity and radiation. Examples include ultrasound, high-pressure processing, pulsed electric field, pulsed light technology, ohmic heating, irradiation, ozone, atmospheric cold plasma, and ozone processing (Arshad et al., 2022). The changes in process parameters, such as radiation dosage, pressure, and applied electrical energy, plays a crucial role in achieving the desired modifications in the final food product. These technologies often aim to extend the shelf life during which a food product remains safe for consumption while maintaining its quality and freshness. Shelf life enhancement is vital for reducing food waste, improving distribution efficiency, and ensuring that consumers receive products with optimal attributes over an extended period. The extended shelf life has also been reported for various food products treated with noval and non-thermal emerging technologies. For example, the raw milk treated with radio frequency heating, milk treated with PEF, and skim milk treated with ultrasound technology exhibited the extended shelf life of 45 days, 21 days, and 50 days respectively at 4 °C (D’Incecco et al., 2021). However, various ethical, social, and economic barriers are involved in their commercialization such as high initial investment, technologies being under development, lack of scientific data on various processed foods, lack of quality equipment, lack of funding, high end-product cost, lack of training, and lack of regulatory government approvals (Khouryieh, 2021). Furthermore, technological risks taking while food processing using emerging technologies have been considered unethical due to apparent health issues (Frewer, 1999). Therefore, public perception and consumer acceptance towards food processed using emerging food technologies could be worthy of future research. Moreover, corporate social responsibility regarding emerging technologies has yet to be discovered. The most relevant factors could be the integration of consumer health with environmental and economic impact, appropriate labeling of genetically modified food, uniform regulations on the processing and packaging of food products globally, establishment of tough regulation and auditing on processed food to avoid contamination at individual stage, and capacity building of staff for corporation act, competitive practice, and dishonest advertisement (Omer et al., 2010). A sustainable marketing strategy could play a crucial role in staying ahead of environmental regulation.

10 Conclusion

Over the years food and dairy industry played a crucial role in providing essential nutrition for humans on a daily basis. However, as the global population continues to expand rapidly and dietary preferences evolve, combined with increasing health awareness, rising incomes, and a notable shift in demand from food service to retail, the demand for these foods is expected to surge even further in the future. Therefore, this chapter explores various aspects essential for the industry's future readiness, including the integration of intelligent processing systems, the emergence of novel non-thermal processing methods, and the implementation of enhanced food safety and quality measures. Additionally the chapter also highlighted the requirement of advanced packaging solutions, plant based and cell cultures foods, personalized nutrition, sustainable processing. Embracing circular economy practices shows the industry's commitment to reducing its impact on the environment by using resources wisely and minimizing waste. It becomes evident that collaboration, innovation, and a forward-thinking mindset are paramount importance to navigate the complexities of the food and dairy industry's evolution and disruption. Understanding the future trends and harnessing the power of technology and sustainability will help in a new era of food production and consumption that is not only efficient and safe but also ethical and environmentally responsible. Future research could totally rely on big data, informatics, and the digital universe that brings abundant opportunities for growth, resilience, and positive impact on both food systems and the well-being of consumers.

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