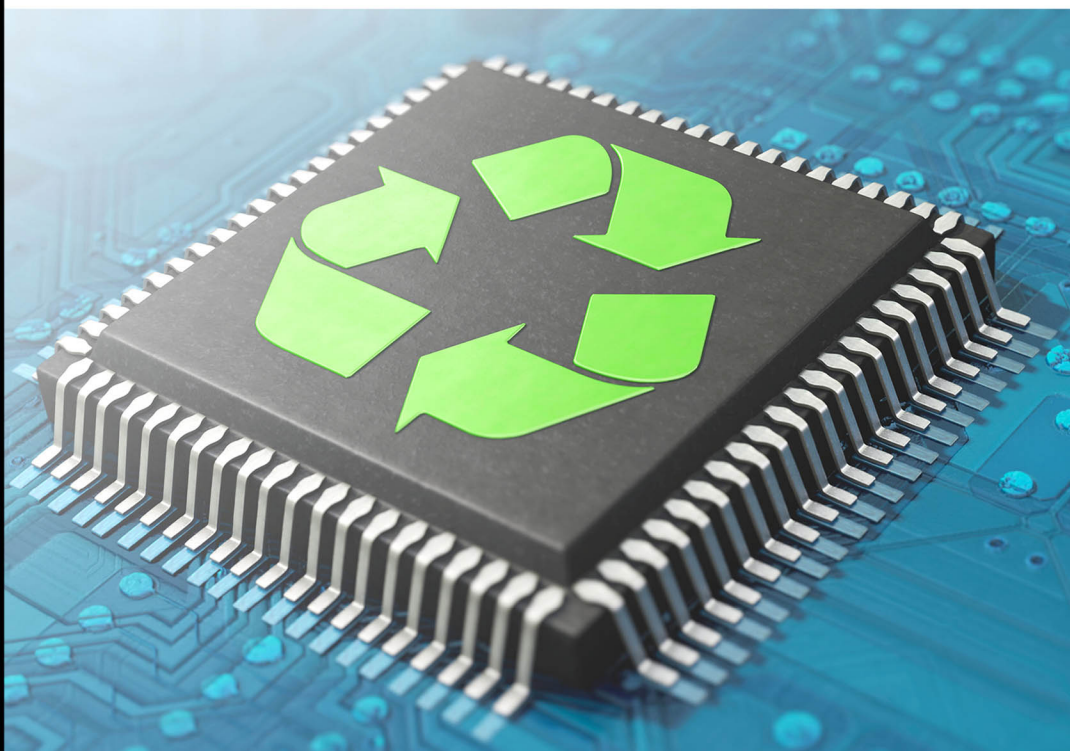


Sustainable Electronics

The Future Ahead



EDITED BY
Farkhanda Ana, Sandeep Arya,
and Haider Mehraj



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Sustainable Electronics

This book discusses the development and use of sustainable materials in electronics, such as biodegradable and renewable materials. Focusing on the principles of designing sustainable electronics, including considerations for reducing the environmental impact of electronics during the design phase, *Sustainable Electronics* covers topics such as product life cycle assessment, eco-design, and green materials selection.

Features:

- Discusses the importance and adoption of sustainable designs in electronic applications.
- Covers the application areas ranging from devices to circuits, computer-based applications, deep learning, and brain interfacing within the framework of sustainability.
- Describes materials such as edible dielectrics, organic semiconductors, and perovskites in a comprehensive manner.
- Illustrates electromechanical stability, electrochemical stability, and environmental stability.
- Highlights the importance of recycling and reusing materials in electronics and the role of circular economy in sustainable electronics.

It is primarily written for senior undergraduates, graduate students, and academic researchers in the fields of electrical engineering, electronics and communications engineering, energy, environmental engineering, and electronic materials and devices.



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Preface

Sustainability in electronics arises when the devices are designed keeping in view the impact on the people and planet. Sustainable design has become critical because of the irreversible effects of electronic waste on the environment. The processing of semiconductor materials, release of toxic gases, and non-biodegradability of hazardous materials particularly metallic oxides have an adverse effect on the planet. To fulfill the dream of a green planet, we need to devise eco-friendly policies and design methods and materials meeting not only the performance requirements but also resulting in a low-carbon society. During the past two decades, the demand for sustainable design practices has increased to help the society survive longer. To accomplish the goal of sustainability in the electronics market, the materials domain plays a key role. Materials that are biodegradable and biocompatible can be integrated with the electronic device design to result in a sustainable world of electronics. Sustainable manufacturing and fabrication processes reducing the release and production of toxic emissions is the second important factor toward a sustainable electronic world. Adopting sustainable practices and devising policies becomes the third and equally important factor toward sustainability in electronics.

The aim of this book is to bring in valuable scientific reports and research on sustainability in the field of electronics. Through careful selection of the topics and rigorous reviews, this book covers the entire spectrum of sustainability in electronics. This book caters to diverse topics from the fundamentals, sustainable materials, wearable electronics, solar cell applications, nanoparticles, internet of things, electronic waste management policies, circular economy and the future, and innovative trends to sustainability. Though the selection and use of electronic materials for high-speed design applications is a critical issue, its impact on the environment with the use of metallic and non-biodegradable components is immense. As a result, the number of obsolete devices per user increases per year resulting in an increase in electronic waste. It has been reported by the United Nations in 2021 that each person on the planet would produce on average 7.6 kg of e-waste generating approximately 57.4 million tons of e-waste worldwide. Only 17.4% of this electronic waste containing a mixture of harmful

substances and precious materials is being properly collected, treated, and recycled. According to the Global E-waste Monitor 2020, the world generated 53.6 Mt of e-waste in 2019, only 9.3 Mt (17%) of which was recorded as being collected and recycled. To reduce electronic waste and its detrimental impact on the planet, the quest for biodegradable and biocompatible electronic materials has caught the attention of many researchers. Materials science engineering has resulted in the synthesis and identification of conductive/insulating materials from natural substances or their derivatives. These materials when integrated with electronics result in biodegradable and sustainable electronic applications reducing the hazardous effect on the environment. The sustainable policies and circular economy has been discussed in detail in this book. This book will serve as a reference and informative literature for researchers in the field of materials science, electronic and electrical engineering as well as physicists and design engineers.

This book comprises the following chapters:

Chapter 1: This chapter discusses the key principles of sustainability, environmental concerns, and government regulations adopted to achieve a sustainable future. Furthermore, research and development of eco-friendly, biodegradable, or reusable materials such as bioplastics, graphene, nanomaterials, and organic materials is also discussed.

Chapter 2: Numerous investigations on the usage of spinel ferrite nanocomposites (SFNCs) and spinel ferrite nanoparticles (SFNPs) throughout the treatment process of water and tainted water have revealed their perilous part in ensuring fresh water obtainability for human consumption and the well-being of aquatic life on a global scale. This chapter elucidates the latest developments and possible uses of SFNs for absorbing organic and heavy metal ions as well as bacterial and fungal microbes and other aquatic impurities. Excellent magnetic properties, great explicit active surface area, tunable shape, and sizes with giant stability are the foremost physiochemical characteristics of SFNs.

Chapter 3: This chapter discusses the material properties and applications of nanocellulose as an electronic material. Nanocellulose is considered biodegradable, reducing electronic waste. This chapter discusses in detail the challenges, applications, manufacturing methods, and potential advantages of nanocellulose.

Chapter 4: Sustainable dielectric systems have become the greatest attention among the research community in the age of modern technology and scientific research evolution, not only due to their exciting utilization in several solid-state devices, such as optoelectronics devices, IR transmission, fiber optics, memory sensors, holography, and laser technology, but also due to academic engrossment in thermo-electrical and structural transport properties. Fe-doped -CdO-ZnO glassy dielectric systems have been developed and their electrical and dielectric properties have been explored extensively in terms of hopping of small polarons. The microstructure of

the as-developed system has been revealed in terms of identifying various nanophases such as ZnO, CdO, $\text{Cd}_{9.5}\text{Zn}_{0.5}$, ZnV, $\text{Zn}_3\text{V}_2\text{O}_8$.

Chapter 5: This chapter covers a wide spectrum of solar cells, including photovoltaic (PV) cells, organic PV cells, thin-film PV cells, and the most recent advances in solar cell technology. The chapter also examines the materials, manufacturing procedures, and life cycle evaluations necessary for the ecologically sustainable progress of solar cell technology. In this chapter, the challenges in implementing sustainable solar cells, laying the groundwork for a discussion of current studies, financial factors, and policy ramifications have also been discussed.

Chapter 6: This chapter proposes and investigates regular Perovskite Solar Cell (PSC) design. Initially, regular homojunction PSC with layered structure has been designed and investigated. The proposed architectural framework identifies different physical parameters of the perovskite material as key contenders influencing the design of PSC. In this chapter, the crucial parameters of the proposed PSC are systematically evaluated, analyzed, discussed, and subsequently calibrated to achieve optimized outcomes, yielding a PCE of 26.8%, V_{oc} of 1.2 V, FF of 87.9%, and J_{sc} of 26.6 mA/cm².

Chapter 7: Numerous advancements have been made in this area of wearable textiles for improving the life quality of people, especially those with dementia or moderate cognitive impairment. This chapter also discusses the concept and challenges associated with electronic textiles development for meeting specific functions like behavior assessment for people with Alzheimer's disease and moisture assessment on the skin. Further to this, architecture is discussed in detail in order to design the product with flexibility for a better living environment.

Chapter 8: MXenes, a group of 2D transition metal carbides and nitrides, exhibit remarkable mechanical flexibility, electrical conductivity, and ease of production, making them highly attractive for use in flexible electronics. This chapter provides a more in-depth analysis of the production procedures, mechanical and electrical properties, and many uses of MXenes in the field of flexible electronics. Due to their remarkable characteristics, MXenes have garnered significant interest for incorporation into flexible electronics, hence creating novel prospects in several sectors.

Chapter 9: In this chapter, the semiconducting properties of graphene and its applications have been discussed in detail. The wide variety of applications of graphene as biosensors, energy storage devices, batteries, super capacitors, and solar cells have been reviewed to catch the reader's interest in this chapter.

Chapter 10: This chapter discusses the sustainability principles in Internet of Things (IoT). The key aspects of Green IoT, smart cities, smart grids, and waste management have been broadly discussed in this chapter.

Chapter 11: In this chapter, the integration of Artificial Intelligence/ Machine Learning with wearable Electronic devices/body sensors/wearable

sensors has been discussed. This chapter focuses on the practical application and investigates the role of Machine Learning in the wearable Electronics field. The integration of Artificial Intelligence/Machine Learning in wearable devices can make these devices learn and adapt to the user's habits, which will make this technology seamlessly integrate into our daily lives.

Chapter 12: This chapter deals with the fabrication processes of electronic components with a particular emphasis on environmentally friendly methodologies. It investigates novel materials and manufacturing techniques that minimize ecological impact while maintaining performance standards. The book chapter not only focuses on the green aspects of fabrication but also extends its scope to the application of these eco-friendly electronic components. It examines the integration of green technologies in various electronic devices, highlighting real-world scenarios where sustainable practices can be implemented without compromising functionality.

Chapter 13: In this chapter, the problem of electronic waste has been addressed. This chapter discusses some venues of sustainability for electronics for making electronic products durable, ideal, and for technological solutions. It also examines ways that can foster a circular economy for electronics from businesses' operations, policies, and users' behaviors. This chapter explores sustainable manufacturing processes for electronics, including energy-efficient production techniques, waste reduction strategies, and green supply chain management.

Chapter 14: Materials science advances are leading to environment-focused components, as newer design techniques increase product life and recyclability. The future of sustainable electronics is massive due to energy breakthroughs for greater efficiency and flexible electronic integrations. This chapter explores these developments and looks at how they might turn the electronics industry into a greener and more responsible one. A number of innovative trends like biomimicry, energy harvesting, and wireless charging have been elaborated in this chapter.

Editors

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Fundamentals of sustainable electronics

*Farkhanda Ana, Haider Mehraj,
and Hazi Azamathulla*

I.1 INTRODUCTION

The rapid growth of the electronics industry has undoubtedly created an electronics revolution. As a matter of fact, the technological advancements coupled with Artificial Intelligence (AI) and Machine learning have opened an era of humanoid and other robotic services in various fields of applications. The fields of space exploration, medical surgeries, military and defence are among a few dominated by the electronics industry besides the day-to-day life of any human individual. This technological evolution has resulted in an increase in the average number of gadgets per person. The computational time for highly complex tasks has been reduced and the results are more accurate because no human error is involved. All the electronic devices involve procuring and processing of raw materials, fabrication and use. The concern arises when the products reach their end-of-life cycle. When electronic equipment/devices are no longer useful, they are either discarded or some parts are reused. If these electronic devices are discarded in the form of garbage, they pose serious risks to the environment because of some toxic elements which may be present. The question arises, “What are we leaving for the future?” “What will our future generations see?”

The United Nations has provided a definition of e-waste as any abandoned items that have a battery or plug, and contain toxic and dangerous elements like mercury, which may present significant threats to human and environmental well-being [1]. The United Nations data reveals that in 2021, the typical individual on Earth created 7.6 kg of electronic trash, resulting in a tremendous global production of 57.4 million tonnes [1]. Just 17.4% of this electronic garbage, which includes a combination of hazardous chemicals and valuable materials, has been documented as being handled, processed and recycled correctly [2]. Based on this, the creation and adoption of sustainable strategies in electronics is the need of the hour to save the planet Earth for our future generations.

Sustainable electronics refers to the design, production and disposal of electronic devices in an environmentally responsible manner. The approach aims to minimize the negative impacts on the environment associated with

the entire life cycle of electronic products, from raw material extraction and manufacturing to use and eventual disposal or recycling.

The key aspects of sustainable electronics include the following [3]:

1. **Design for recyclability:** Creating products that can be easily disassembled and recycled.
2. **Energy efficiency:** Developing devices that consume less power and have longer battery life.
3. **Use of eco-friendly materials:** Selecting materials that can be recycled and biodegradable.
4. **Responsible sourcing:** Ensuring that raw materials are obtained from environmentally and socially responsible suppliers.
5. **Waste reduction:** Minimizing e-waste through recycling, reuse and proper disposal.
6. **Circular economy:** Encouraging the reuse and recycling of electronic products to reduce the need for new raw materials.

1.2 PRINCIPLES OF SUSTAINABLE ELECTRONICS

To reduce the menace of electronic waste (e-waste) and develop a sustainable electronics industry requires the design and implementation of sustainable strategies through all stages of the product life cycle [4]. The formulation of sustainable policies should commence during the design phase, encompassing measures to assess the environmental consequences, opt for biodegradable or abundant materials as substitutes for scarce metals or dangerous chemicals, or employ sophisticated manufacturing techniques to produce smaller and shape-adjustable components that are suitable for reuse and recycling [5]. The sustainable principles should further be adopted in the manufacture, use and disposal of electronic devices. The ideas of circular electronics, consisting of nine core concepts (Rethink, Redesign, Reduce, Reuse, Recycle, Repair, Remanufacture, Refurbish and Recover), have been proposed to address the pressing need for sustainable solutions that minimize waste and maximize resource efficiency [6]. These principles serve as a guiding framework for the transformation of electronics design, production and consumption, therefore fostering sustainability across all phases of their lifespan.

In the pursuit of design sustainability, the lifespan and fate of small electronic devices are taken into consideration. To address environmental concerns, three key strategies have been adopted [7]:

- **Design for disposal:** Materials that facilitate bio-sourcing, clean incineration or biodegradability have been given priority when creating short-lived items. Careful selection of environmentally friendly products may guarantee appropriate disposal procedures.

- **Design for disassembly:** If non-sustainable materials are unavoidable for particular electronic application, smart miniaturization approach is followed. These materials are designed in separate sub-sections/sections simplifying reuse and recycling.
- **Design for longevity:** The notion of “design for longevity” endeavours to create goods that have longer operating lifespans, hence offsetting their environmental impact. In order to do this, it will be necessary to address issues with materials, processes, wireless power transmission, battery recycling and design sciences while also taking into account the societal effects of electronics on laws, regulations and public opinion.

1.3 ENVIRONMENT AND SUSTAINABILITY: REGULATIONS AND STANDARDS

Designers of environmentally friendly, or sustainable, electronics take into account every stage of the product’s lifespan, from mass manufacturing and functional aspects to innovation recycling. Experts use components and procedures that have the least negative effects on the environment while doing this, such as [8]:

- i. Creating equipment that are recyclable, simple to repair, and energy efficient.
- ii. Making use of less hazardous, lighter materials.
- iii. Cutting down on their carbon impact.
- iv. Using a circular economy to reduce waste.

These implications may be calculated due to life cycle evaluations. Sustainable electronics are also made with social responsibility in mind. This guarantees that the individuals engaged in their production get fair treatment and that their methods of production do not negatively impact the environment or local communities.

The governments have imposed laws that provide a minimum standard for sustainable electronics. The industry’s initial eco-design rules limited the use of several hazardous compounds in electronics [8]. One such law is the Restriction of Hazardous Substances (RoHS), which forbids the use of several hazardous materials in electronic equipment, including lead, mercury, phthalates and cadmium [9]. Significantly, the RoHS restrictions affect the whole world, since several nations have adopted laws akin to them. California Proposition 65, which includes a safe-harbour warning label for compounds that are carcinogens and reprotoxic, is another example of an environmental policy pertaining to the management of substances [10].

The US Toxic Substances Control Act (TSCA-PBT) governs the use of persistent bio-accumulative and toxic chemicals in the United States [11].

The European Union (EU) has implemented the Eco-design Directive (ErP Directive 2009/125/EC) and the Regulations of Persistent Organic Pollutants (POP) and the EU REACH Regulation on Substances of Very High Concern (SVHC) [12–14]. Further, regulation 2019/2021 of the eco-design directive establishes requirements for the energy efficiency of various devices, including electronic displays seen in computers and TVs such as [15]:

- i. Regulatory framework for motors (2019/1781)
- ii. Exogenous electricity sources (Regulation 2019/1782)
- iii. Hardware devices for storing data (Regulation 2019/424)
- iv. Illumination sources (2019/2020 Regulation)

Thus, guidelines and specifications for eco-designing sustainable electronics include the following examples [15]:

- i. **Energy efficiency specifications:** The minimal energy efficiency requirements for in-scope electronics might differ according to the product type and energy mode (active, standby, etc.).
- ii. **Easy repair and disassembly:** To promote recycling and cut down on waste, devices should be designed with these two goals in mind. This might include having maintenance manuals, disassembly instructions and replacement components available.
- iii. **End-of-life management:** In accordance with the Extended Producer Responsibility (EPR) concept, this can include funding collection plans and putting take-back initiatives into action.

Manufacturers have the option to voluntarily follow these criteria in addition to government restrictions. The Electronic Product Environmental Assessment Tool (EPEAT) is, in fact, one of the most well-known standards [16]. The EPEAT grading system assesses the environmental effect of electronics by looking at a number of factors, including:

- i. Design and Construction
- ii. Output
- iii. Utilization of Energy
- iv. Discarding

The EPEAT grading scale has established itself as a well-acknowledged standard for environmentally friendly devices. Regulatory bodies and commercial enterprises mandate that their goods adhere to EPEAT criteria. Another emerging benchmark is Environmental, Social and Governance (ESG) Due Diligence, which specifically examines the environmental and social effects of a company, along with its corporate governance [17]. Indeed, organizations that comply with ESG principles are dedicated to diminishing their ecological footprint and advocating for sustainable methodologies.

Additional well-recognized instances of voluntary standards include [18,19]:

- i. Energy Star establishes energy efficiency standards for electronics, including power management measures and standby power consumption limitations.
- ii. Blue Angel is a voluntary certification initiative in Germany that aims to advance sustainable electronics technologies and foster customer confidence.

Simply said, opting to follow voluntary standards enables producers to distinguish themselves in the market and demonstrate to customers their dedication to manufacturing environmentally responsible goods.

1.4 RESEARCH AND DEVELOPMENT OF SUSTAINABLE MATERIALS

To develop sustainable electronics, one of the potential areas is the research and development of sustainable materials which are eco-friendly, biodegradable or reusable. Some of the sustainable electronic materials are [20–23]:

- i. Bioplastics are synthetic polymers derived from sustainable sources, such as maize starch or sugarcane, as opposed to petroleum. By serving as a substitute for conventional polymers in electronics components, such as casings, they have the potential to mitigate the reliance on fossil fuels.
- ii. Graphene, a robust and lightweight semiconductor, has exceptional electrical characteristics, making it a very promising material for the development of environmentally friendly electronics. Graphene enables the production of flexible and transparent gadgets, as well as battery and solar cell technologies that are more energy efficient. Furthermore, scientists are investigating other applications for graphene, including conductive inks and sensors.
- iii. Nanomaterials have the capacity to enhance the energy efficiency of electronics via the reduction of power consumption and the extension of battery life. Furthermore, they may contribute to the mitigation of e-waste generation by extending the lifespan of equipment. Consider, for instance, carbon nanotubes and nanowires.
- iv. Organic materials offer a wide range of advantages from flexibility, light weight, low-cost and low-temperature processing compared to silicon-based electronics. They have made possible the realization of wearable textiles, smart sensors, artificial skin, ingestible electronics, etc. Organic batteries provide a viable alternative to

the existing lithium-ion batteries that rely on transition metals. An innovative organic battery technology may circumvent the need for mining and manufacturing of transition metals, as well as the disposal of obsolete batteries, which have detrimental effects on the environment.

1.5 EMBARKING ON THE PATH TO SUSTAINABILITY

Key factors to consider before starting a sustainability journey include:

- i. Perform a risk assessment to identify areas of susceptibility and possible consequences on operations.
- ii. Evaluate the markets and nations in which the firm conducts its operations, the nature of the product marketed, the demands of customers and the intended brand image.
- iii. Establish sustainability objectives and design programmes to reduce recognized risks and provide value for all parties involved.
- iv. Establish communication with customers, suppliers, workers and other stakeholders to guarantee that sustainability initiatives are in line with their expected outcomes and requirements.

1.6 ECO-DESIGN AND ECO-LABELS

Product eco-design is a comprehensive process that involves the careful selection of raw materials, the production of an article, its sale, usage, recycling, treatment and various other factors that significantly influence the environment [24]. All these need to be taken into account at every design and production stage of the product to minimize its environmental impact and reduce the use of raw materials and energy. Eco-design aims to lower the impact of a product on the environment by reducing the amount of raw materials and energy it utilizes over its life cycle, using either totally organic non-toxic raw materials or, when organic is not possible, the materials that have the lowest possible environmental impact, minimizing possible waste of raw materials and associated substrates, and emitting the lowest possible amount of pollutants over its life cycle [25]. One relatively new approach to environmental management is the eco-design concept that arose in the Netherlands in collaboration with the United Nations Environment Programme (UNEP) [26,27]. It is widely regarded as one of the most effective strategies for advancing the circular economy development model. Eco-design is an engineering practice that draws on a range of related disciplines, including ecology, management sciences, economics and environmental science. It is sometimes called environmental design or “green design”. There are two key components to eco-design activities: reducing the consumption of materials

and implementing a plan for sustainable development. A sustainable strategy should contain the following materials: (1) factors related to the environment; (2) the cost factor; (3) the matter of liability issued on the company; and (4) the commercial competitiveness level. For a business, if these factors are not considered, it will not have a real eco-design strategy, and the energy consumption rate will remain high.

Eco-design emphasizes the necessity of integrating traditional design methods with considerations for potential environmental issues that products may cause. Although the fundamental steps of product creation are not changed, this approach requires designers to evaluate the environmental impact of the products they create throughout the standard design phase and hence develop new designs to minimize the product's negative environmental impacts. Therefore, when designing new products, designers are required to take the environmental impact information of the product they intend to make into account. They have to filter the relevant information that is already available and incorporate the information they have about it into their designs. This is a complex process, especially when choosing the most appropriate material for product creation in the eco-design process. It might be that the most suitable material of a product is not the most eco-friendly option for the product. In common design, during the design process, designers do not have to pay attention to these kinds of environmental considerations. This is a main difference between common design and eco-design for products.

Conventional design, so-called “cradle-to-grave” design, is based largely on fulfilling the essential characteristics the consumer needs from the product [28]. This approach fails to evaluate the environmental consequences of the product throughout its life cycle. Consumer costs include costs related to consumption, such as use and maintenance, but they are generally negligible or completely ignored in the design process. Still, there is no consideration in the design of post-consumer disposal costs, treating them like free goods. In contrast to conventional design, the aim of eco-design is to take into account the environmental cost produced at all the stages of the product's life cycle. Eco-design encompasses the redesign, recovery, regeneration and recycling of abandoned objectives. Eco-design of discarded products reduces the environmental impact of discarding products and increases the amount of used material that is recovered. For this reason, another term that has been used to define eco-design is “cradle-to-cradle” design [28]. This term expresses the essence of eco-design: products are designed to consider their entire life cycle and, at the end of their life cycle, to be regenerated in new designs rather than being discarded in a landfill.

The eco-design philosophy requires the transition from the traditional raw materials-product-residue-product manufacturing model to what we called the “Ecologicalized” model, focusing on creating products that are not only useful, viable and attractive for consumers, but also socially responsible using environmentally friendly materials and end-of-life scenarios, favouring reusability and recycling. By adopting eco-design, companies

can develop innovation and creativity processes, leading to a development of new products attractive not only from the environmental point of view, but also benefiting the competitiveness of products, evolving in new “greener” products, facing the consumer’s sensibility and the growing environmental consciousness. Considering the potential negative environmental impact resulting from goods production, consumers are more than ever concerned about the social responsibility of products which can consequently become one of the decisive factors in the goods purchase. Product eco-design is one of the strategic issues in modern product development initiatives, able to reduce the environmental impact, increasing the resources efficiency, by applying in any phase of the process environmental and ecological criteria. Companies with a better capability to integrate in their production processes the principles of sustainable development in which the environmental considerations are a core component will be able to go further in the creation of better products, for the consumer and for the environment. The transition from traditional design approach to eco-design is probably crucial, not only from the environmental point of view, but also from the eco-conscious business competitiveness.

Following eco-designs are the eco-labels used by the companies to show that they are manufacturing sustainable products. Eco-labels are marks that indicate that products or services comply with established objective environmental and sustainability criteria according to internationally recognized standards. Hence, they are put on the packaging of the product, the product itself, the accompanying documentation, or other means such as web based [29]. The US Environmental Protection Agency (EPA) explains that, because of their nature as marks used in trade, industry and commerce, eco-labels reduce the consumer’s information search by conveying important environmental information via a symbol or statement rather than through a discursive form of communication [29]. In turn, this can empower citizens to influence consumer demand in a way that can lead businesses to proactively change their manufacturing practices and production in a way that benefits the environment. According to the EPA, eco-labels can help consumers and institutional purchasers find those products that meet certain environmental performance criteria and are thereby deemed as “environmentally preferable”. Eco-labels can be owned or managed by government agencies, necessary environmental advocacy organizations or private sector bodies. At the same time, there is a wide range of certifications available to manufacturers of many products and services, some of which are presented to the customers as green choices. According to the Ecolabel Index, there are more than 450 eco-labels available worldwide across all types of industries (carpets, cosmetics, coffee beans, etc.) and geographies [30]. The International Organization for Standardization (ISO) has a series of international standards for environmental management which apply to eco-labels and categorizes them. ISO 14020 identifies three main types (which will be explained below) [31]:

- i. **Type I (ISO 14024):** Certification processes for products or services that track compliance with a third-party-selected criteria.
- ii. **Type II (ISO 14021):** Mounts self-declared eco-labels, based upon third-party standards (that is, determined independently from the eco-label holders), as a designation for voluntary, environmental claims.
- iii. **Type III (ISO 14025):** The third category applies to self-declared conformity with previously defined categories of parameters according to ISO 14040, but without any conclusions on whether that conformity refers to sustainability properties.

Type I eco-labels are by definition broader and more ambitious, most often applied to products that go beyond mandatory requirements, such as in relation to energy efficiency, resource use or GHG emissions, and identify reduced environmental footprint products. Eco-labels should be distinguished from an “energy” label, which signals the energy efficiency of a consumer product [32]. For instance, the energy label is mandatory in the EU and is provided for several product categories such as “refrigerators, washing machines or televisions”, that follow the scale from G (least efficient) to A+++ (most efficient), the energy label indicating the energy efficiency of the product [32]. A few relevant eco-labels are specifically aiming at the energy of electronic B2B equipment, such as 80 PLUS or ENERGY STAR, while other labels, such as EPEAT or TCO Certified, also include environmental and social aspects [33].

- i. **80 PLUS:** a voluntary Type I certification programme launched in 2004 that focuses on improving the efficiency of power supply units (PSUs) by setting minimum benchmarks for energy used at 10%, 20%, 50% and 100% of rated load and at a power factor. The certified product can reach Bronze, Silver, Gold, Platinum and Titanium certification levels.
- ii. **ECMA 370:** A Type II procedure for use by companies that will declare whether and which specified environmental attributes (e.g. recycling, recycled material content, reduction of hazardous substances and energy consumption in stand-by mode) are met and which methods of measurement are applied in use and function of ICT and consumer electronics, per defined standards, guidelines and current best practice.
- iii. **ENERGY STAR:** Voluntary programme designed and verified by the EPA and the Department of Energy to address energy consumption of products using standard, quantifiable methods. The programme helps customers save money through lower energy bills and help reduce greenhouse gas emissions. ENERGY STAR programmes operate for enterprise servers and large networking equipment (LNE), along with small networking equipment (SNE) and VoIP Phones.
- iv. **EPEAT:** A Type I eco-label, managed by the Global Electronics Council (formerly known as the Green Electronics Council), based on criteria that changes over time as sustainability changes – assessing

the social and environmental impacts of products from extractive supply chain to end of life. Many governments and large businesses use EPEAT certification in formulating procurement policies.

- v. **TCO Certified:** TCO Certified is the leading global sustainability certification for IT products, covering both social and environmental aspects. It helps purchasing organizations and the IT industry strike a balance between technological development, financial growth and the most pressing sustainability challenges related to electronics: climate, circularity, hazardous substances and supply chain responsibility. All criteria are mandatory and verified by independent, accredited experts regarding compliance with all the criteria.
- vi. **EU eco-label:** The eco-label of the EU is run by the European Commission and the EU Member States. It is a voluntary EU-wide Type I eco-label. The only evaluated product group for electronics is electronic displays, consisting of televisions, computer monitors and signage displays.
- vii. **Environmental Product Declaration (EPD):** An EPD (ISO 14025, Type III) is a standardized document that is developed by or on behalf of an organization and is used to communicate the environmental performance of a product. It provides quantified information about the environmental impact of a product or material for its entire life cycle.

1.7 EMERGING TECHNOLOGIES FOR SUSTAINABLE ELECTRONICS

The last decade has seen promising new technologies that promote sustainability in the realm of electronics, an area that is globally becoming increasingly significant. In this section, three technologies that have the potential to transform the way the electronics industry thinks about sustainability are discussed.

1.7.1 Artificial intelligence for energy optimization

AI can help to make electronic systems more energy efficient. Increasingly, AI is being used to analyse large quantities of energy production, consumption and behaviour data and then make real-time decisions about computation and power use. This can alter energy consumption to match requirements, improving the flexibility of energy use across electronic, IT-based systems, such as provisioning, server-side processing, through to compute-hungry user applications, cooling and networking equipment. Predictive analytics and machine learning algorithms are being applied to help maintain acceptable levels of energy distribution within networks and balance overall energy demand and supply.

Predictive maintenance using AI is another key application in the area of energy optimization. Unlike the previous method of maintenance scheduling based on calendar dates, AI-based predictive maintenance using the data

analytics of heavy equipment continually foresees the failure of equipment before it malfunctions, minimizing energy waste and prolonging the life cycle of IT equipment [34]. Recently, AI-powered workload management has played an increasingly important role in energy optimization of data centres. Using dynamic workload optimization to manage the mismatch between workloads and computing resources through advanced analytics and optimization algorithms, AI can automatically classify resource allocation and task scheduling, ensuring servers to be utilized at their optimal levels, while minimizing idle capacity [34].

1.7.2 Blockchain for supply chain transparency

Blockchain technology has shown the most potential for application in optimizing supply chain management, for example, by creating greater supply chain management process transparency and increasing traceability of items within their life cycle [35]. With blockchain, as a digital record-keeping technology, the shared ledger can be recorded, validated or viewed across highly complex, interconnected supply chains involving multiple parties and is by definition authenticated and tamper evident.

Blockchain can transform global supply chains for sustainable electronics by increasing supply-chain visibility and transparency for key components, improving the quality and accuracy of data, and boosting trust among value partners. This technology enables seamless transaction of value, whereby a single source of truth can be input. Moreover, blockchain can integrate with other new technologies such as Internet of Things (IoT) and AI to provide a more robust, secure supply chain [35].

1.7.3 Internet of things for efficient resource management

IoT technology, still among the latest technological trends in the field of sustainable electronics, is a network of physical objects (sensors, appliances, vehicles, etc.) that are connected to the internet and that collect, analyse, share, organize and manage information and data [36]. IoT is becoming important in sustainable electronics, especially in improving resource management. In this context, IoT can be viewed as an extension of the internet so that physical objects (goes beyond your phone and computer) become part of the information system network, thus making them potentially more functional and useful. The need for IoT solutions in sustainable electronics has particular relevance to specific sectors, such as manufacturing, healthcare and public utilities management. At the healthcare level, IoT-enabled devices that monitor vital signs and track patient data in real time can help with more accurate diagnoses of diseases and give patients improved treatment plans [37]. For the public utilities management, IoT installations that track energy consumption in sections of the city in real time are improving

the management of utilities; they enable utility providers to see problems in real time, anticipate customer problems and save money by seeking solutions for client's complaints. Thus AI, blockchain and IoT technologies could potentially help solve many environmental challenges in addition to improving some of the key issues that have been traditionally raised by environmental stakeholders about the electronics industry.

1.8 CHALLENGES IN ACHIEVING ELECTRONICS SUSTAINABILITY

Sustainable electronics is held back by many barriers that require new thinking and global industry collaboration: the complexities of global supply chains; the difficulty of coming up with new technology continuously to stay abreast of changing needs; the need to balance performance and eco-friendliness.

1.8.1 Complex global supply chains

The global reach of electronics supply chains opens them to systemic risks and so-called black swan events and offers new opportunities for complexity management and increasing sustainability at the same time. Despite enabling the transitions towards renewable energy systems and circular production systems, the electrical and electronic equipment (EEE) sector incurs a severe and growing environmental footprint [38]. Two main problems affect the manufacture and use of EEE: their dependency on rare minerals and rare metals, and e-waste generated that often contains hazardous substances.

1.8.2 Rapid technological obsolescence

The rapid technological obsolescence in the electronics industry is the reason for increase in e-waste due to the constant need to replace and upgrade the old models. Every year, e-waste generated is growing at a rate of 3%–5%, and this makes e-waste the fastest-growing waste stream in the world [1]. In 2019, the world produced more than 50 million tonnes of e-waste, and this figure is projected to increase to 74 million tonnes by 2030 [1]. The reason for this rapid obsolescence is because of the technological progress, consumer preference or company policy to frequently upgrade our gadgets. This results in more excess resources, manufacturing of devices and increased waste.

1.8.3 Balancing performance with eco-friendliness

There is a delicate balance to be struck between the performance required from devices (for example, to maintain quality calls from a smartphone) and the sustainability of the production of such devices. Historically, materials used in electronics have relied upon metals or metal oxides, which are notoriously difficult

to recycle and are produced using extremely energy-hungry fabrication techniques. Industries need to identify how to best measure environmental impact, to identify biodegradable or Earth abundant materials to use, and combine these with advanced manufacture techniques to create smaller, shape-shifting chips and components that are more suitable for reuse and recycling. We also want to identify alternative business models that can replace revenues that businesses might lose as a result of reduced purchases of new devices, even as we try to incentivize longer use and appropriate disposal pathways.

1.9 CONCLUSION

Sustainable electronics has made important advances in addressing major environmental challenges relating to the production, use and disposal of electronic devices. Improved techniques in sustainability reporting, informed by new technologies such as AI and blockchain, are becoming ever more sophisticated in promoting energy use optimization, documenting supply-chain information, and analysing and improving material flow. Further different forms of collaborative consumption such as buyback schemes and the rise of innovative and disruptive business models suggest some forms of optimism for the future direction of the electronics industry. However, national and international reporting standards illustrate that there are tremendous challenges that still require addressing. Global supply chains remain complicated, obsolescence rates continue to accelerate and the trade-offs between performance and eco-friendliness are immense. While many advances in circuits and connected devices are already being developed, standardizing sustainability reporting formats, applying deeper life cycle assessments to major supply chains or developing more refined carbon-credit calculation methodologies are essential if the electronics industry wants to further innovate while minimizing its environmental impact.

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Spinel nanoferrites in wastewater treatment for sustainable electronics

A review

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2.1 INTRODUCTION

The need for sustainable electronics for drinking water and waste water treatment ensuring universal access to clean water and sanitation is a critical first step in ending poverty, enhancing public health, and promoting sustainable development in both rural and urban communities. Though the traditional water supply and sanitation system will always be valuable, new approaches to providing for people's requirements must be included. Solutions that can safely and affordably treat water in a hygienic manner are required. Numerous novel solutions for sanitation and water supply have been put forth; nevertheless, more than just scientific advancement is needed for effective and dependable implementation. According to Wildere [1] affordably appraised services must be offered, and expert assistance must be assumed. Better engineering skills are necessary for sustainable water treatment, but other aspects like financial, administrative, and cultural considerations are also prerequisites to be taken into consideration. The possibility of significantly reducing costs through mass manufacture of decentralized system components is something that should be prudently considered.

Industrialization and scientific encroachment present both prospects and challenges for the environment and human populations. As per the Central Water Commission of the Government of India [2] predominant concerns include drinking water contamination, with groundwater pollution extending up to 3.5 km from the abandoned facility and with a depth of 40 m below the surface. Closely 40K people have been drinking this contaminated water for the past 14–20 years, and the community has had a higher frequency of malignancies, birth defects, skin, lung, brain, kidney, and liver disorders than any other place in the nation [3]. It has also been mentioned that water-borne illnesses that arise from contaminated drinking water and inadequate sanitation are widespread in developing nations [4–6]. According to the World Health Organization and Hanna et al., water is used in many different ways. Without water human survival would not be feasible. People cannot survive

deprived of water. Water that is devoid of pollutants and pristine is essential for good health. Human beings and other living species are forced to consume contaminated water when it exists in that place, as they are left with no other opportunity and cannot survive without it. Water contamination and the lack of clean, freshwater have grown to be major issues in the nation and the world in recent years [7,8]. Following the United Nations (UN) endorsement of the Sustainable Development Goals (SDGs) in September 2015, nations worldwide established intentions and yardsticks to ominously enhance the state of humankind by 2030. Goal 6 (Ensuring access to and sustainable administration of water and sanitation for everyone) and Goal 14 (Seas, oceans, and marine resources should be preserved and responsibly used for sustainable development) are two of the 17 SDGs that specifically address (fresh)water [9]. The sixth SDG of the UN calls for widespread admittance to clean water and sanitation, which advocates that ecosystems dependent on water must be preserved and water quality must be elevated. The UN SDGs will be accomplished in 15 years, which accentuates the inevitability for quick synthesis and efficient rendition of current scientific and technological advancements for research on water purification keen on workable, affordable elucidations through improved policy choices and implementation [10]. Water quality exacerbated as a consequence of an outdated water distribution system and the need for high-energy consumption, which posed a serious risk to society. This calls for a reformation of technology and a paradigm shift in the water management system. Recycling freshwater from contaminated water may be a way to alleviate the global shortage of potable water, but the existence of various deadly chemicals in filtered water that come from various industrial, urban, and agricultural wastewater sources is a serious risk to community health and the environs [11–15].

2.1.1 Global challenges in water purification

One of the top global challenges, referring to the UN Millennium Development Goals [16] was confirming that everyone had consistent access to affordable, clean water sources (to “halve, by 2015, the proportion of the population without sustainable access to safe drinking water and basic sanitation”). The budding world population guarantees the quick spread of the challenge. Reduction in obtaining fresh water for drinking and food production is the effect of industrial and municipal wastes, greater amounts of water required to generate more energy from conventional sources, drawing large amounts of diminishing groundwater supply for agricultural process. Due to seawater intrusion, variations in the global climate are expected to significantly impact already scarce freshwater resources. Furthermore, excessive use of pesticides, fertilizers, and other chemicals for agricultural reasons contaminates groundwater resources, reducing the availability of clean, usable water. In the near future, changes to current technology and policies will be necessary to mitigate freshwater shortages and reduce the increasing costs of

water pollution. Poignantly, even faster translation of scientific information into goods and amenities will be necessary for emerging nations, particularly people in Africa, parts of Asia, and South America, who have fallen behind in technological advancements because of inadequate funding and insufficient scientific research. According to Wilderer [1], the main impediments to the implementation of sustainable water management structures in developing nations are: (1) insufficient funds, which can affect populations that are small and dispersed; (2) inadequate technical expertise to maneuver current technologies, and (3) lack of supply of electrical power to run some of the more affordable existing processes (e.g., electro-coagulation, reverse osmosis).

Famiglietti [17] and Biewald [18] claim that to sustain human populations, industries, and living things, uncontaminated water is required; in fact, a global decline in groundwater supplies has been documented. Water is no longer seen as a free resource for all the reasons mentioned above. Depletion of ground water, contamination of freshwater, and excessive demand for freshwater are the three main significant water problems, according to reports from UNESCO [19] and AG Fane et al. [20]. Emerging countries must promote a sustainable and secure water supply, especially for urban and metropolitan areas facing mega-urbanization, which includes a shortage of infrastructure for wastewater treatment and purification.

2.1.2 Importance of spinel nanoferrite particle in water treatment

Applications of nanotechnology are used for the treatment and reuse of wastewater. They also present a chance to reduce energy consumption, mitigate the risk of water quality degradation within network distribution, lessen reliance on key system infrastructure, and use unconventional water sources for agricultural and potable use. In underdeveloped nations where freshwater quality is drastically deteriorating and posing a threat to public health and food safety, nanotechnology can provide an intricate class of trailblazing water treatment technology. A gestalt of the use of nanoparticles for water cleansing was provided by T. Pradeep et al. [21]. A few instances of engineered nanomaterials (ENMs) that can support this vision and move us closer to the ultimate objective of a zero-discharge archetypal were compiled by J. Brame et al. [22]. Toxic trace metals [13,14,22,23] as well as dyes [12,24] and phenols [14,15] have all been removed from wastewater by using spinel ferrite nanoparticles (SFNPs) in industry. Another benefit of SFNPs is that they may be effortlessly recovered from reaction mixture with the help of a peripheral magnetic field, making it reusable [25–27]. This review aims to discuss the important roles that superfine nanoparticles and its composites play in the applications of treatment of water and wastewater. These applications comprise pathogen disinfection, adsorption, photo catalysis, modifications of membrane, analyte extraction, sensing, and metal ion recognition.

2.1.3 Future prospective

For the full elimination of harmful contaminants in water, the application of SFNPs requires appropriate quality control. This quality control offers two main benefits: first, it can collect and reuse SFNPs after they are used, which lowers their relatively high cost; second, it can reduce any latent deleterious health effects on the treated water's final user. Furthermore, proficiency in managing all the procedures is necessary; thus, it is imperative that human resource development keep up with the rapid advances in technology. If these prerequisites aren't met, using SFNPs extensively for wastewater and water treatment could have unintended effects. Therefore, widespread SFNP use may not be able to address longstanding difficulties in water sustainability, particularly in emerging nation-states with several challenges in the treatment of water and wastewater. The other momentous gaps in the literature include the paucity or lack of direct SFNP uses in actual water and wastewater. Majority of the time, simulated wastewater is examined instead of actual wastewater, with coexisting variety of cations and anions. Every anion and cation has a unique capacity for binding. Antagonism for the SFNPs' active sites grows as the quantity and kinds of pollutants in wastewater rise. As a result, cations and anions are eliminated according to their preferred outflow. This demonstrates that simulating wastewater and conducting trials to find the elimination of a small number of cations or anions has never been precisely replicated in the real world. Therefore, for utilizing simulated wastewater, a systematic process including all of the components found in the real environmental samples of interest should be used. This will help with technique design by giving a clear image of each species showing how they affect or are affected by SFNPs.

2.2 OVERVIEW OF SPINEL NANOFERRITE

Nanocrystalline magnetic materials have attracted interest from a diversity of sectors, including general science, biology, materials science, and engineering, because of their unique and distinctive properties. Regarding comparison to their bulk equivalents, nanomaterials show reformed or enriched thermo-mechanical, reactive, optical, magnetic, and electrical assets owing to their larger surface-to-volume ratio and particle dimensions nearly equal to 100 nm [25,28,29]. Although the bulk materials' primary determinant is their chemical composition, the properties of the nanomaterials are determined by their shape and particle dimension in addition to their chemical makeup. Furthermore, these characteristics can be tuned based on the chemical composition and particle dimensions [28,30,31]. From a theoretical and practical perspective, ferrites are imperative and intriguing materials. Due to their exclusive structural, dielectric, and other previously mentioned properties, as well as their thermo-chemical stability, magnetic nanoparticles, or MNPs,

have garnered a lot of interest. These nanoparticles have an extensive array of technological applications, like photoluminescence, biological and humidity sensors, catalysis, refrigeration related to magnetic properties, permanent magnets, magnetic drug transportation, and magnetic hyperthermia [32,33].

2.2.1 Structural study

New studies on spinel nanoferrite (SNF) materials are very imperative since they are indispensable to our understanding of magnetic resources in general and specifically in ferrites [34,35]. Ferrites are types of material with a broad assortment of physical properties, excellent chemical constancy, and cheap production costs. Contingent on their original crystal lattice, ferrites have diverse structural properties from garnet, hexagonal, and spinel. Spinel ferrites (SFs, PFe_2O_4) are composed of Fe in the +3 oxidation state and a divalent ion of a transition or post-transition metal (P) [36]. The complex oxide crystal ferrite face centered cubic (fcc) core single cell contains 32 closely spaced atoms of oxygen that have 64 divalent tetrahedral sites and 32 trivalent octahedral sites. To preserve the anions within the crystal structure in an electrically equilibrium state, P^{2+} and Fe^{3+} typically occupy 8 tetrahedral and 24 octahedral positions, respectively [37–39], as shown in Figure 2.1.

With 8 cations present in 64 tetrahedral interstices (P sites) and the remaining 24 cations occupying quasi-32 octahedral interstices, each unit cell with 8 formula units ($P_8Fe_{16}O_{32}$) and 32 oxygen anions forms a compactly packed FCC cubic structure, providing lattice electrical neutrality. A significant amount of vacant interstitial space is created by each spinel cell's 96 interstices that are engaged by a total of 24 cations. This allows cations to migrate between sites. Spinel ferrites are categorized as normal, inverse, or mixed based on their cation distribution across the lattice structure. The interstices' valence size, energy, electrostatic energy, and the specific ion's radii are the main dynamics sampling the dependence of cation occupancy [40,41]. Instead of the smaller divalent ions (P^{2+}) occupying the tetrahedral sides,

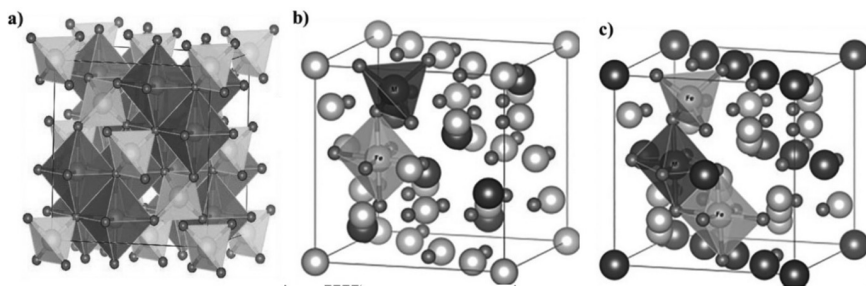


Figure 2.1 Spinel ferrite structure: (a) bold (octahedral sites), italics (tetrahedral sites), and bold italics (oxygen atoms); (b) normal spinel ferrite; and (c) inverse spinel ferrite [26].

the major trivalent cations (Fe^{3+}) occupying the octahedral sites produce the usual structure of a spinel PFe_2O_4 (ZnFe_2O_4 and CdFe_2O_4). The structure $\text{Fe}[\text{PFe}]\text{O}_4$ ($\text{P} = \text{Mg}, \text{Ni}, \text{Co}, \text{Cu}$) is formed when half a part of trivalent metal ions in the inverse spinel structure occupy the tetrahedral sites and the rest portion, composed of the divalent cation, occupy the tetrahedral sites. The degree of inversion is denoted by x , tetrahedral sites are marked in parenthesis, and octahedral sites are indicated by square brackets. This depiction of the mixed spinel structure can be written as $(\text{P}_{1-x}\text{Fe}_x)[\text{P}_x/2\text{Fe}_{1-x}/2]_2\text{O}_4$ [42].

2.2.2 Magnetic properties

The mounting need for smaller technological gadgets has drawn a lot of attraction to nano-sized materials with magnetic properties for improving the performance of magnetic materials (permanent) requiring a deep understanding of magnetic characteristics at the nanoscale. It is apt to know that the magnetic characteristics of nanoparticles are critically inclined by their size, shape, surface effects, magnetic anisotropy, and additional factors [43].

Oxygen ions regulate the magnetic interfaces among the spins of divalent metallic cations in the octahedral and tetrahedral interstitial sites in SFNPs. Spin interfaces contribute to SNF magnetic features by influencing the alignment of adjacent atoms. The super exchange process governs the three distinct variations of JAA (A-O-A), JBB (B-O-B), and JAB (A-O-B). The nature of these interfaces depends on the distance of metal ions after the oxygen atoms. Super exchange A-O-B interface is more predominant than the A-O-A and B-O-B interactions. Among the A and B sub-lattices, the dominating negative intra-lattice JAB interface causes uncompensated anti-ferromagnetic order, or ferrimagnetism. Since the impact of the Fe^{3+} ions at site B cancels that of the cations of Fe at site A, the total magnetic moment in a spinel with inverse structure is solely determined by the divalent cations' magnetic moments at site B. In a typical spinel, the Fe ions' magnetic moments are arranged in an antiferromagnetic manner at site B.

The assortment of dopants and production conditions influence the SPs' magnetic structure, additionally the ferrites' composition determines their magnetic properties. Consequently, the property of intrinsic magnetism of compositional materials mediate the physical characteristics of magnetic spinels, such as saturation magnetization, magnetic anisotropy, and magnetostriction. Based on different previously mentioned materials (P), the researchers have demonstrated SFs along with increasing magnetic saturation.

2.2.3 Impact on environment

Because spinel nanoferrites are used in various applications, variations in material composition have an influence on the environment. The presence of metallic cations in nanoferrites in smaller amounts than iron oxides has the greatest environmental impact, primarily due to Ni and Zn. Every 3 years

starting from 2011, the European Union carried out an economic analysis of the criticality of the raw material. They elucidated that of the 78 strategic materials, many are thought to have a severely adverse impact on the environment. MnZn ferrite, ZnO (6.5%) with MnO (17%), has a lesser environmental impact, according to an analysis of the results obtained by the ReCiPe and carbon footprint (CF) procedures. However, it is quite concerning when the percentage changes to 7.5 and 24.5 for the same composition, respectively. According to this analysis, the Mn impact value is 3.59 kg CO₂ equivalent per kilogram using the CF approach and 8769 milli points (mPt) per kg in the ReCiPe. Using ReCiPe and carbon footprint technologies, NiZn ferrites demonstrate an impact range for 1 kg of 272–1682 mPt/kg and 0.94–3.46 kg CO₂ equivalent per kilogram, respectively, according to the same technique [44].

2.2.4 Synthesis methods

The invention process for MNPs, which are recurrently used in composite materials, consists of two stages: surface functionality modification and MNP synthesis. Nanoparticles of different sizes are manufactured simultaneously by using different techniques. It is identified that nanoparticles' chemical and physical behavior is influenced by their production method. Since the recognition of MNPs, major areas of research expanded to new grounding approaches and application scenarios. These days, the most popular procedures for manufacturing are chemical and physical ones [45,46].

Several studies of the literature have led to the supposition that variations in the synthesis process creates an impact on the sizes and other physico-chemical features of nanoparticles. Recent developments are concentrated on the formation of innovative synthesis methods of SNFs, which are concerned with their varied sizes, shapes, orientations, aspect ratios, surface areas, purity and stability, compositions, and morphologies, parallel to the commonly used physicochemical synthesis processes [47]. For the synthetic preparation of SNFs, a few top-down (chemicals are grounded to form particles) and bottom-up (ions combine chemically for NPs) approaches are involved. The top-down approaches include milling and pulsed laser ablation, while the bottom-up approaches include the methods like hydrothermal, sol-gel, coprecipitation, microwave, electrochemical deposition processes, and micro-emulsion techniques [26,48,49]. A few of the several synthesis techniques are outlined in the following sections.

2.2.4.1 *Techniques using chemicals to create magnetic nanoparticles*

The maximum prevalent technique to produce NPs is chemical synthesis. Meanwhile it can produce a hefty number of nanoparticles quickly and affordably. To date, a number of MNP preparation techniques have been proposed and successfully applied to yield a series of MNPs. Regarding cost,

measurement of size, and form controllability, all the synthetic procedures can be alienated into two groups based on the kind of solvent used: aqueous solvents and non-aqueous solvents.

A. Sol-gel

This method (Figure 2.2) is another bottom-up SNF synthesis process. The gel formation in this approach is failsafe by the hydrolysis and condensation polymerization processes of metal alkoxide solutions at normal temperature [50]. Any volatile by-product must be released using an auxiliary heat treatment in order to achieve the final crystalline state. The main benefits of that process are its ability to regulate the reaction at low temperatures (25°C – 200°C), its ease of adjustment for stirring rate, composition, sol concentration, and its low annealing temperature, ensuring sufficient amount of narrowly shaped, controlled SNF preparation. Impurities in the processed SNFs from the reaction by-products entail additional processing in order to produce pure NPs.

B. Hydrothermal and Solvothermal

The most effective and effectual process for producing high-purity crystalline nanoparticles with tunable shape are hydrothermal and solvothermal processes. In this wet chemical process, the metallic precursor is dissolved using an aqueous solvent at large pressure and moderate temperature ($>100^{\circ}\text{C}$) for the hydrothermal approach; in the solvothermal method, the metallic precursor is thawed using a non-aqueous organic solvent, for instance, methanol, ethanol, or ethylene glycol (Figure 2.3). Temperature and time are adjusted according to the SNFs to get a pure crystalline structure. Solvents are exploited at high temperatures and pressures in that procedure to preclude the production of disarticulations in single-crystal nanoparticles, which causes the crystalline phase to become unstable around its melting point. Using this technique, hollow or shaped ferrite can be created.

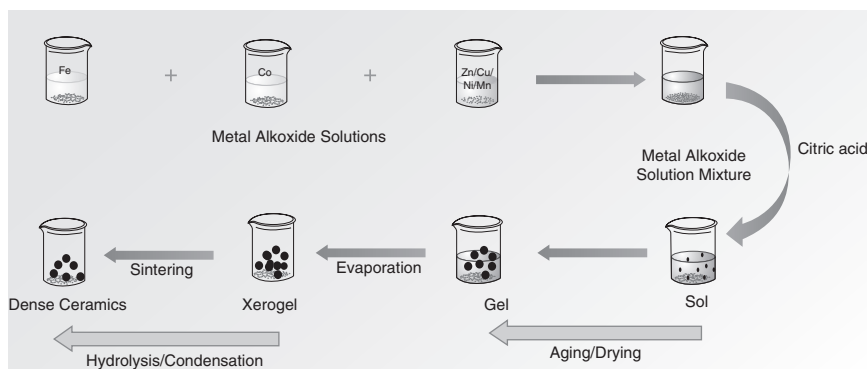


Figure 2.2 Synthesis of spinel ferrite and spinel ferrite nanoparticles utilizing the sol-gel technique in place of transition metals.

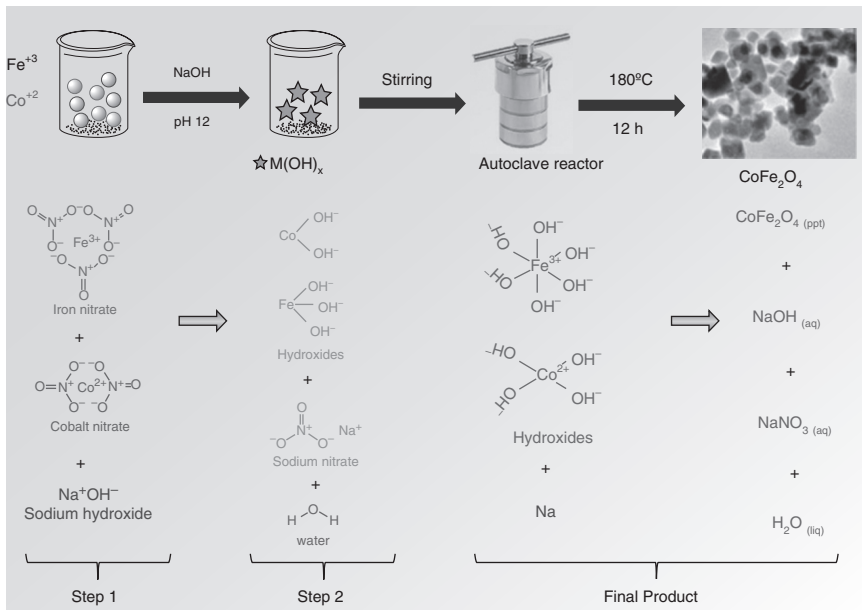


Figure 2.3 Schematic representation of the hydrothermal reaction procedure.

C. Co-precipitation

The synthesis of XFe_2O_4 NPs can be done easily and economically using co-precipitation. This process produces SFNPs with a homogeneous structure, excellent purity, and controlled size. This method combines a solution with stoichiometric quantities of metallic salts (chlorides, nitrates, or sulfates) with a base, which acts as a precipitating agent at high enough temperatures. The size, form, and features of SF NPs are predisposed by various types of variables, together with pH, temperature, reaction duration, and the ratio of precursors. This method yields SFs that are uniformly sized, highly pristine, and have a regulated structure. In this sense, the conformist method of generating XFe_2O_4 MNPs using chemical methods is co-precipitation. An aqueous solution comprising a 2:1 molar ratio of divalent and trivalent transition metals is combined, and the reaction is conducted using a basic medium. For trivalent metal ions, soluble salts of Fe(III) are typically applied. After the pH of the solution is found, a number of variables comprising temperature, duration of reaction, and precursor ratio are crucial in defining the size, shape (spherical), and durability of the SNFs. For the alteration of pH to the solution, solutions of NaOH or NH_4OH are used. After correcting the pH toward an inert condition, vigorous stirring of the solution is essential with or without heat to precipitate the precursors, depicted in Figure 2.4. The produced SFs are untainted, homogeneous, and have regulated sizes and shapes, usually between 15 and 25 nm [51].

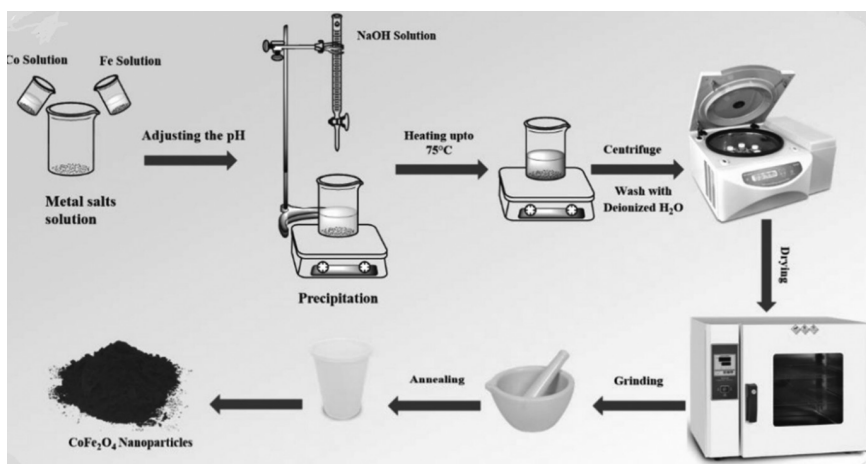


Figure 2.4 SNF nanoparticle synthesis using the co-precipitation method.

Great amounts of MNPs can be effortlessly dispersed in aqueous medium using this technique. With this process, the base is added in an inert atmosphere, and the precursor components co-precipitate within a solution at room temperature or at high temperature. This co-precipitation technique has several advantages, chief among which is its capacity to produce massive quantities of XFe_2O_4 MNPs through scaling up. For this reason, the most common chemical process in use in industry to create thousands of kilograms of XFe_2O_4 nanoparticles is co-precipitation [52].

Inorganic salts like nitrate and chloride are dissolved in polar solvents to produce a homogeneous solution in this process, which serves as the preparatory material. It should be mentioned that the dimension and form of nanoparticles can be meticulous through variables such as pH, temperature, and salt content that are harmful for crystal development and aggregation of the particles. When precipitation occurs, the solid bulk is gathered and cleaned. Crystalline oxides are then created by calcining the hydroxides.

D. Microwave assistance

All materials consist of mobile charges, such as conducting ions in solid or liquid or polar molecules in a solvent, and are generally heated by microwaves. In polar liquids like water, heat is released through the molecules' friction, revolution, and impact that oscillate in response to a fast-changing electric field alternating in nature. When molecules collide with one another in a solvent, energy is lost. Microwave heating is a powerful technique for producing MNPs with better eminence and possessions because it speeds up, cleans up, and lowers the cost of chemical reactions compared to traditional methods, illustrated in Figure 2.5. It also increases the percentage of chemical reactions between various metallic salts [52,53]. Microwave-assisted

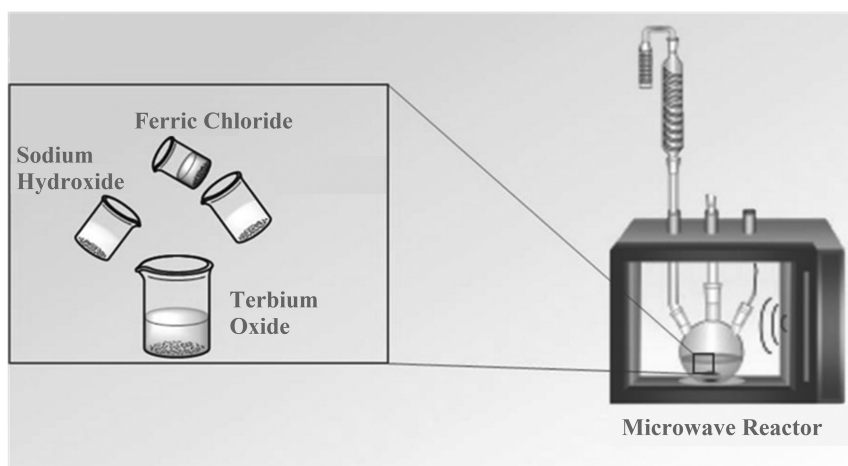


Figure 2.5 Magnetic nanomaterial synthesis using a microwave technique.

synthesis of NFPs with tunable shape and size has been considered an environmentally benign method. One of the major benefits of this synthesis process is its capacity to yield metal NFs with varying phases and coatings, desired for a variety of applications, including biological ones. Moreover, the use of microwaves in conjunction with other methods may yield highly colloidal stable MNPs that are readily dispersed in water, negating the necessity for costly and slow ligand exchange and purification procedures. These features have made microwave-assisted synthesis comparable with thermal breakdown for the mass production of MNPs [52].

E. Micro-emulsion

Micro-emulsions are stable, transparent, and isotropic mixes of water, oil, and surfactant. For cohabitation of two immiscible liquids in one phase, surfactants are essential. Water and oil are two types of micro-emulsion solvents that are used to prepare solutions by dispersing immiscible liquids. For production of MNPs, the two most common micro-emulsion techniques are the reverse process where water disperses in oil (water/oil), and the opposite is called direct process.

An oil-soluble hydrophobic head of a monolayer molecule along with a water-soluble hydrophilic tail or the reverse may be used as surfactant. $\text{CH}_3(\text{CH}_2)_{11}\text{OSO}_3\text{Na}$ acts as surfactant, which is used to sustain the constancy of the solution. In the aqueous phase, the precursor of MNPs is usually distributed as 1–100 nm droplets. Water droplets are encircled by surfactant molecules, creating “micelles” that function as nanoreactors. In consequence MNPs are created within the micelles, containing the particles and averting their nucleation, growth, and agglomeration. To precipitate the nanoparticles, another emulsion is supplemented to the solution at the

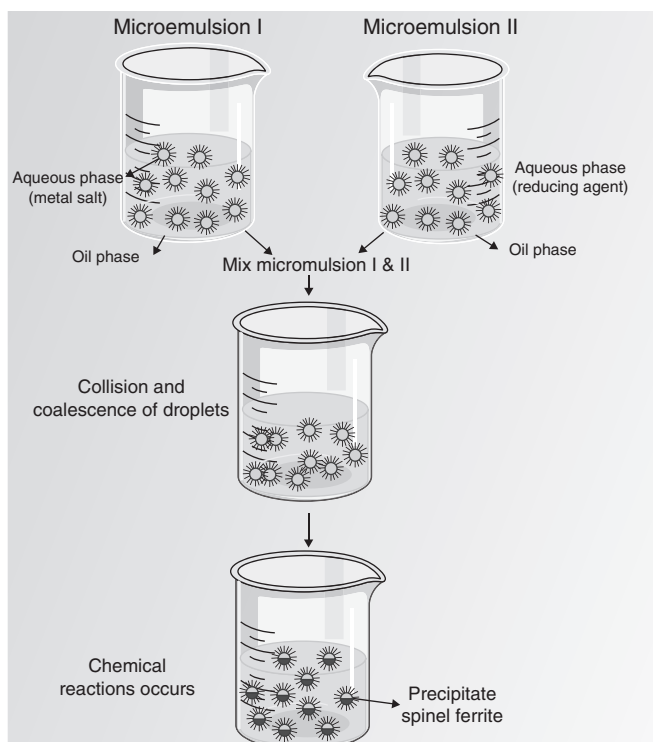


Figure 2.6 Synthesis of spinel ferrite NPs using microemulsion technique.

end (Figure 2.6). To synthesize ferrites of Ni and Zn NPs as a photocatalyst for water splitting, for instance, SFNPs with diameters less than 20 nm were prepared using the oil in water micro-emulsion [46].

F. Biosynthesis

As an ecologically acceptable substitute to chemical and physical slants, biosynthesis of SNPs employing microbial enzymes or phytochemicals of plant with alleviating and/or dropping characteristics is an incipient field of study. Magnetic MNPs have typically been synthesized using magnetotactic and iron-reducing bacteria. Through cobalt doping, this technique has demonstrated promise in augmenting the magnetic appearances of MNPs. Types of bacteria and the circumstances of preparation (aerobic or anaerobic) decree the magnetic particles phase that is formed. For instance, in an aerobic environment, *Acinetobacter* bacteria can be engaged to create superparamagnetic maghemite nanoparticles (Figure 2.7). Difficulties arise to identify the parameters that regulate the figure and dimension while preserving the appropriate saturation magnetization; meanwhile the process of MNP biogenesis is typically lesser known (Table 2.1) [52,54].

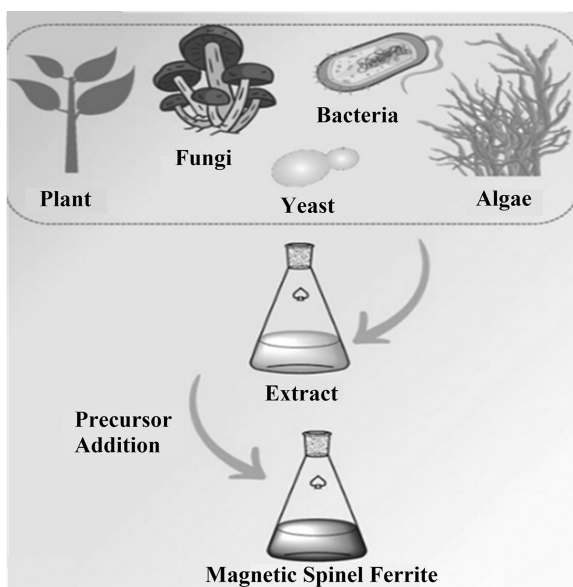


Figure 2.7 Illustration for biosynthesis of spinel ferrite nanoparticles.

2.3 APPLICATION IN WATER TREATMENT

2.3.1 Adsorbent for contaminant removal

Using an adsorbent to treat water and wastewater is one of the supreme affordable alternative ways since it is easy to operate, economical, and doesn't produce any secondary pollutants when treating toxins. Use of absorption technique is reported in the majority of literature to clean up water and wastewater. Due to their large surface area and increased number of active sites for interacting with the contaminants in the solution, SFNPs have become the preferred choice for treating wastewater due to their high adsorption capacity. Additionally, because of their nanoparticle size, which makes it easy to eradicate them from a solution by a peripheral magnetic field, SFNPs exhibit super paramagnetic (SPM) behavior. For the persistence of treating water and wastewater, by covering these SFNPs with the proper functional groups, they can be used as the core material or directly. The adsorption isotherm equations play a crucial role in supplying the adsorbent's affinity for the adsorbate, helping to calculate the adsorption capability and supporting the design of the adsorption system. The kinetic equations help find potential ways to maximize the adsorption's residence duration as well as the adsorption rate [59].

Table 2.1 Comparative studies among different synthesis methods

Process	Temperature	Solvent	Iron precursor	Spinel ferrite	Reference
Thermal decomposition	300°C	Benzyl ether	Fe(acac) ₃	CoFe ₂ O ₄	[55]
Sono chemical	Room temperature	H ₂ O	Fe(NO ₃) ₃ ·9H ₂ O	MnFe ₂ O ₄	[56]
Microwave assisted	Room temperature/800 W	H ₂ O	FeCl ₂	TiFe ₂ O ₄	[53]
Micro-emulsion	40°C	Isooctane/H ₂ O	C ₂₄ H ₄₅ FeO ₆	NiFe ₂ O ₄	[46]
Polyol technique	280°C	Ethylene glycol	Iron (III) acetylacetonate Fe(C ₅ H ₇ O ₂) ₃	PFe ₂ O ₄ (P = Zn, Mn, Co, Ni, Cu)	[57]
Electrochemical	Room temperature	H ₂ O/ tetrabutylammonium bromide (electrolyte)	Fe(As electrode)	PFe ₂ O ₄ (P = Zn, Mn, Co, Ni, Cu)	[58]

2.3.2 Mechanism of SFNP adsorption

The types of contacts that occur between the adsorbent and the adsorbate are what largely regulate adsorption; in particular, hydroxyl groups and surface charge are important adsorption regulators. The elimination of numerous contaminants from wastewater through adsorption can be attributed to a variety of physicochemical interactions, including ion exchange, the creation of inner- or outer-sphere complexes, the interplay of weak forces such as hydrogen bonds, van der Waals forces, dipole–dipole, and Pi–Pi interactions. While physisorption happens when the previously designated weaker forces of attraction amid the contaminants and hard exteriors are present, strong chemical bonds are possible when two electrons are shared between the surfaces of the adsorbate and adsorbent, leading to chemisorption. Broadly speaking, the kind of contaminants present in wastewater and the SFNPs/SFNCs employed to treat it can affect the adsorption mechanism. In contrast, it was found that inner-sphere surface complexes are the primary adsorption mechanism at pH values higher than 7, with ion exchange and the formation of outer-sphere complexes driving the adsorption mechanism at pH values lower than 7. The adsorption experiments of cationic dyes on a variety of SFNPs revealed ion exchange and electrostatic interaction are the main adsorption mechanisms because of the surfactant groups on the SFNPs. Overall, the adsorption mechanism's result is greatly influenced by the features of the impurity and adsorbent, including their functional groups, porous construction, state of oxidation, and charge present on the surface [60].

2.3.3 Factors affecting SFNPs' ability to adsorb

SFNPs' adsorption capability and the associate composites are influenced by a number of variables, including synthesis techniques, adsorbent types and particle sizes, quantities, wastewater pH, initial contaminant concentrations, system temperature, adsorbate charge and size, etc. Despite the advanced superficial area to volume ratio, the adsorption ability is often higher for smaller particle sizes. Similarly, as pH controls the SFNP/SFNC surface charge and the extent to which the adsorbate molecules ionize, it affects the efficacy of adsorption. The surface of SFNPs is positively and negatively charged in aqueous solution at lower and higher pH values, respectively. In this case, cations adsorb at higher pH values while anions do so at lower pH values. This suggests that two crucial elements in the removal of pollutants are the type of contaminants present in the solution and the surface charge of the SFNPs. The adsorption capabilities of SFNPs are also primarily impacted by the temperature at which the experiment is conducted, because the type of preferred chemical reaction determines how positively or negatively the temperature influences the accessible permitted adsorption site. Adsorption capacity rises with temperature in case

of endothermic reactions, whereas for exothermic reactions, it falls. One of the key variables influencing the adsorption capability of SFNPs is their calcination temperature. This is because the temperature and duration of calcination affect NP growth, which directly affects NP surface area and porosity [61].

2.3.4 Dye removal

Because of their intricate aromatic molecular structures, dyes are more stable and challenging to break down. The textile industry's waste discharges are contaminated with dyes, which can quickly contaminate water systems, pose health risks, and harm the environment. Through oxidation, hydrolysis, and other chemical processes, dyes can produce perilous compounds even at low concentrations. It is well-recognized that dyes are responsible for causing cancer and mutations in both people and aquatic life. Applications of bare and modified XFe_2O_4 have recently been shown to be among the finest solutions for eradicating dyes because of their strong adsorption capacity and simplicity of recovery and reuse. NiFe_2O_4 NPs have excellent photocatalytic capabilities and a high adsorption capability; they are recurrently used in wastewater treatment for dye removal. For instance, lately, activated carbon- NiFe_2O_4 (AC- NiFe_2O_4) composite was utilized to treat colored wastewater that was brought on by the presence of methyl orange. At 303 K, methyl orange, a contaminant, exhibited a high adsorption capability of 182.8 mg out of 1 g said pollutant against AC- NiFe_2O_4 . The remarkable adsorption capability of the pollutant onto AC- NiFe_2O_4 was proposed to be caused by a strong hydrogen bond between the methyl orange and AC- NiFe_2O_4 . A comparable methodology was employed to generate NiFe_2O_4 nanoparticles, with an approximate average particle dimension of 17 nm, which were then added to wastewater to remove reactive blue 5 (RB5) dye. At pH = 1, the NPs demonstrated a high adsorption capacity toward the RB5 dye, through RB5 elimination exceeding 90% maintaining the temperature and pH at 25°C and 1 respectively [62].

2.3.5 Pesticides

The use of pesticides is becoming more and more vital in agriculture worldwide to protect crops and boost yields by preventing and managing hazardous pests including weeds, fungi, and insects. The danger of pesticides resulting from their leakage into water systems from agricultural areas, however, causes great worry. Among pesticides, organochlorine is measured as the most durable and ancient synthetic pesticides used in industry and agriculture to suppress a variety of illnesses like typhus and malaria. Despite being banned in many nations since 1970,

organochlorine pesticides are nevertheless frequently found in ground and surface waters because of their great environmental stability. Currently, farmers use a lot of organophosphorus insecticides and triazine herbicides to control pests and broadleaf wildflowers in the majority of agricultural harvests. Their exceptional resistance to deterioration and toxicity has also drawn a lot of attention to them in recent years. Atrazine is also thought to be a human carcinogen and an endocrine disruptor. Even at low concentrations, these pesticides create harmful effects on human health and require pre-concentration, extremely delicate detection, and quantification technology. These pesticides are easily released into the environment and can contaminate water systems. These days, there is an increased focus on the use of SFNPs to extract pesticides with low concentrations. Fe_3O_4 NCs in particular are frequently used to remove pesticide pollutants from wastewater [63].

2.3.6 Inorganic contaminant

Since SFNPs with their composites have so many advantages over other materials—like high capacity of adsorption, low production costs, and ease of separation and regeneration—they are crucial for water and wastewater management for the elimination of inorganic contaminants, both technologically and economically. Pollutants may easily attach to SFNPs during wastewater treatment, and then be extracted from a matrix utilizing the properties of an external magnetic field. Fe_3O_4 NPs are considered as the most extensively utilized SFNPs for treating water and wastewater, either in their raw form, covered with metal oxides, doped with transition oxides of metal, or superficially functionalized through appropriate organic moieties. It should be mentioned that depending on their surface characteristics and the kind of divalent cation they conjugate, SFNPs with comparable surface areas may inhibit varied adsorption capacities. The increased removal of As(III) by CoFe_2O_4 and MnFe_2O_4 compared to Fe_3O_4 was associated with the presence of more hydroxyl ions on their surfaces. Under these circumstances, inner-sphere complexes between the adsorbent and arsenic were found to be the adsorption processes. Furthermore, the selective removal of metals is greatly influenced by the pH of the solution, and the adsorption process may diverge reliant on the kind and charge of the metals. For example, it was found that the adsorption of Cr(VI) and Cu(II) on $\gamma\text{-Fe}_2\text{O}_3$ from the wastewater was due to both ion exchange and electrostatic attraction, but that the adsorption of Ni(II) was only caused by electrostatic attraction. Consequently, varying removal capacities of pollutants by various SFNPs were expected to be seen, contingent upon their kind, particle size, surface modification, and experimental conditions. Likewise, the kind, size, and charge of the pollutants have a big impact on their removal from wastewater [64].

2.3.7 Membrane modification

The foremost component of cutting-edge water filtration technologies is the membrane process. Membrane fouling is the main issue that prevents the membrane from functioning properly, apart from that other issues are also present. One of the most important requirements for lowering fouling is changing the membrane surface due to significant interactions between the foulants and the membranes. The surface of the membrane experiences membrane fouling initially. The membrane material's composition affects the surface-modified membrane system's performance. Specifically, one of the most crucial prerequisites to enhancing the membrane's quality is the makeup of the membrane's surface modifiers. Changing the surface's hydrophilicity, surface roughness, and/or surface charges is an example of surface modification. Adding SFNPs to a membrane is one of the finest ways to change its chemical and physical properties and enhance its functionality. Improved permeability of membrane, fouling resistivity, and thermo-mechanical solidarity, in addition to functions for pollutant degradation and self-sanitization, are all made possible by the incorporation of SFNPs. The increased surface hydrophilicity following SFNP inclusion causes a decrease in the membrane fouling capacity. NC membranes made up of Fe_3O_4 -polyethersulfonate (PES) were recently synthesized by means of (Ng et al. [65]) Fe_3O_4 which is capping at end side firstly onto the PES membrane superficially using a polyelectrolyte modification technique. During the filtering investigations, a peripheral magnetic field that alternately switched and oscillated was applied to these sorts of membranes. This caused torque effects on the NPs and twisted the Fe_3O_4 nano colloids that had been deposited. This reformed membrane demonstrated a normalized flow of 0.96 ($J = 32.8 \text{ L/m}^2/\text{h}$) through 99.4% humic acid rejection capability during a 48-hour filtration period. The winding action of the Fe_3O_4 NPs decreased concentration polarization close to the membrane's top surface, in turn decreasing the possibility of membrane fouling and contributing to enhanced rejection capacity of Fe_3O_4 -PES. Considering all of this, this study recognized the significance of SFNPs in raising the caliber of membranes that may be used to treat water and wastewater.

2.3.8 Photocatalysts

Another main use for SFNPs and their matching NCs is the photodegradation route for the exclusion of contaminants from water and wastewater. Ideally, organic pollutants can be broken down via photocatalysis into gaseous CO_2 , H_2O in liquefied condition, and additional gaseous complexes without generating additional waste. SFNPs/SFNCs can be employed as a photocatalyst in a photocatalytic study in a diversity of settings, comprising the absence of semiconductors, the presence of oxidants like H_2O_2 , or both. In actuality, when SFNPs are employed in conjunction with added

photo-sensitive semiconductors and oxidants, their photocatalytic function is more operative and efficient compared to single utilization. For the photo-degradation of organic pollutants spinels comprising lower bandgap energy and absorbing visible light shows better result compared to widely utilized semiconductor materials of larger bandgap energy (Table 2.2) where the latter solely uses UV light. For photocatalytic applications in the breakdown of pollutants in water and wastewater treatments, they are therefore highly attractive. Combining SFNPs with polymers and inorganic oxides boosts their chemical stability in basic and acidic conditions, in addition to improving photocatalytic efficacy. Meanwhile, the inclusion of SFNPs in the composite improves recovery and reuse while also simplifying the process of removing photocatalysts from the reaction system [66,67].

2.3.9 Pathogen disinfection

One of the primary causes of death for children is polluted water caused by several bacteria: diarrheal sickness accounts for deaths of around 1.3 million children globally each year. The primary cause of this is pathogen-contaminated water. *Escherichia coli* is a general pathogen that originates in water and is frequently utilized as a fecal indicator of bacteria for assessing water excellence. SFNPs and their NCs, which are believed to possess antimicrobial properties, are utilized to clean wastewater and contaminated water. For instance, clear observation indicated that SFNPs, in particular iron oxides (Fe_3O_4 , $\gamma\text{Fe}_2\text{O}_3$), exhibit operational antibacterial possessions against *E. coli*. It is anticipated that the cytotoxic effects of these SFNPs will be linked to the existence of distinct iron oxidation states. Furthermore, when SFNPs are combined with other NPs, such as graphene/graphene oxide (GO), they exhibit potent antibacterial qualities in comparison to graphene alone. This is mostly explained by how graphene/GO and SFNPs worked in concert to increase the antibacterial activity, recognizing and finding metal ions. Numerous investigations have noted the exceptional and noteworthy antibacterial commotion of SFNP-GO nanocomposites, exclusively due to

Table 2.2 Comparison between semiconductor and spinel ferrites

Material type	Material	Band gap energy (eV)	Absorbent
Semiconductor	ZnO	3.2	UV light
	TiO ₂	3.2	UV light
Spinel ferrites	Fe ₃ O ₄	1.92	Visible light
	$\gamma\text{-Fe}_2\text{O}_3$	2.03	Visible light
	CoFe ₂ O ₄	2.31	Visible light
	NiFe ₂ O ₃	2.2	Visible light
	CuFe ₂ O ₄	1.89	Visible light
	ZnFe ₂ O ₄	1.91	Visible light

the elimination of *E. coli* from drinking water and wastewater. These investigations unequivocally showed how iron oxides and GOs work in concert to have antibacterial effects. It has been demonstrated that SFNPs-GO NCs are one of the possible antibacterial agents for cleaning up tainted drinking water. For illustration, solvothermal preparation of the Fe_3O_4 /graphene composite has been used to treat water, eliminating several germs including *Shigella*, *Staphylococcus aureus*, *E. coli*, *Salmonella*, *Enterococcus faecium*, and *Enterococcus faecalis*. Graphene incorporation not only improves pathogen removal but also inhibits Fe_3O_4 aggregation and increases pathogen removal capacity. It was previously thought that the antibacterial properties of graphene and the SFNPs-graphene bacterial elimination method caused damage to the cell wall and membrane, ultimately resulting in the mass cell death of the bacteria. Aside from that, these studies have shown the value of SFNPs and their composites as useful and effective antimicrobial agents. It was previously believed that the bacterial mass death produced by the antibacterial capabilities of graphene and the SFNPs-graphene bacterial eradication approach damaged the cell wall and cell membrane [68].

2.3.10 Heavy metal removal

The presence of countless heavy metals (Cu, Se, As, Hg, Pb) resulting from industrial and agricultural processes has disastrous effects on human, agricultural, and marine life. With their graphene nanocomposites, metal ferrites have excellent performance in eradicating heavy metals from wastewater. Disappearance of heavy metals by means of a combination of reduced GO and magnetic SFs has demonstrated outstanding results. Fe_3O_4 -reduced GO composites were found to have the greatest capacity of 99.9% removal effectiveness of arsenic [As(III) and As(V) respectively] [56]. Negative surface charge is increased in GO owing to rising pH value, a combination of spinel nanoferrites and GO has demonstrated a 98% absorption capacity for the abstraction of ions of Co(II) and Cd(II) from water with varied pH standards [69].

2.4 FUTURE POLICIES

One of the most momentous gaps in the research is the dearth or scarcity of direct uses of SFNPs in actual water and wastewater. Most of the time, tests are conducted on simulated wastewater, which differs from actual wastewater in which different cations and anions coexist. Every anion and cation has a unique capacity for binding. There is more competition for the active sites of SFNPs when the quantity and kinds of contaminants in the wastewater rise, the cations and anions are eliminated according to their preferred outflow. This demonstrates that simulating wastewater and conducting trials to find the abstraction of a little amount of cations or anions never accurately reflected the factual world. As a result, a methodical procedure for including

every element found toward the actual environmental trials of interest must be followed when using simulated wastewater. This will help with technique design by giving a vibrant depiction of exactly how each species affects or is affected by SFNPs. Despite SFNPs' great ability to remove a vast range of toxic chemicals from wastewater, there are limited and incomplete studies on their effects on human health, their behavior in the environment, ecological risk, and what happens when SFNPs end up as environmental pollutants. Consequently, a thorough toxicity analysis is necessary.

2.5 CONCLUSION

Water and life have always been related to one another on Earth. Water has always played a momentous part in the development of economic structures. The evolution of civilization has always depended heavily on the flow of water. Water is one of the purest symbols of prosperity, health, peace, beauty, and creativity. As water is synonymous with human civilization, so too are noble metals. Noble metals are applied in medicine by numerous societies. Throughout the long history of noble metals like gold and silver, no known hazards have been connected to them when used in large quantities.

Moving on to modern civilizations, it is only realistic to expect increasing ecological contamination as we progress through the rapid stages of industrialization and economic advancement, despite our best efforts to maintain harmony with the natural world. The biggest problem in the world is the inaccessibility of clean drinking water for everyone. There are several dangerous microorganisms in large amounts of drinking water. Examples include pesticides, heavy metals, microbes, etc., especially in the vicinity of industrial regions. The gravity of the crisis is demonstrated by the fact that 1.8 million people die annually from diarrheal infections, with children aged below 5 years being the most seriously impacted. Similarly, accessibility to potable water is lacked by 1 billion people. It follows that rather than interfering with science's process of discovering new materials and bringing them to market, we should focus on developing preventive remedies to decrease their harmful environmental effects.

The growing shortage of water besides the inevitability for water treatment designate the importance of effective adsorbents. Currently, nanoparticles having magnetic properties along their complexes—which may be in terms of dimensions, configuration, magnetic features, and construction—are used to treat contaminated water. Although Fe_3O_4 is used in water treatment applications, there is a growing trend toward the use of ferrites with spinel structure, such as PFe_2O_4 (where $\text{P} = \text{Mn, Co, Cu, Zn, Mg, Ca, Ni, etc.}$). Here, we investigated the potential of SFs and their derivatives to remove impurities such as metal ions. Ultimately, SF will save money by using industrial waste for preparation, which is also sustainable and kind to the environment.

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Nanocellulose

Pathway to green electronics

Mehvish Shah and Najeeb ud din Hakim

3.1 INTRODUCTION

As a result of devices malfunctioning or becoming outdated, countless electrical and electronic devices are discarded every year. We call these discarded electronic devices “e-waste,” and if they are not dealt with, eliminated appropriately or reused, they could pose to be a menace to human health and the environmental safety. E-waste encompasses discarded large home appliances, laptops, computers and cellphones, and even medical appliances. E-waste is exported, stored in households and warehouses, recycled under hazardous conditions, either being shipped overseas or upcycled under substandard conditions, totalling tens of millions of tonnes annually. Inadequate handling procedures may result in the discharge of up to 1000 distinctive chemical substances into the surroundings from electronic trash, including hazardous neurotoxins such as lead [1]. Children and pregnant women are more sensitive because of their developmental stages and specialized exposure routes. Waste processing is one among the industrial sector’s subsectors, with an estimated 16.5 million children employed there in 2020, according to the International Labour Organization (ILO) [2].

Because of the use of a variety of hazardous materials and chemicals in the manufacturing process, these toxins might leach into the environment upon unsound procedures followed in their disposal. At e-waste facilities, a number of questionable activities have been noted, including scavenging; dumping; burning; heating; acid baths or acid leaching; land-filling in addition to routine waste disposal; stripping and shredding plastic coatings; and manual equipment disassembly. The heating or burning of components poses the greatest risk of exposure to these toxins due to their presence in the vapours and fumes. The effect of the release of these toxic chemicals is not limited to the e-waste sites but can rather disperse to locations far from these sites, thereby posing a threat to human health even at far-off places [3].

Exposure to e-waste during pregnancy may have the following health impacts in fetuses and young children:

- High levels of contaminated air have been linked to detrimental health in newborns, even proving fatal in the form of increased numbers of premature and stillbirth.
- Affected neurological development, which is particularly related to release of lead through unsafe procedures.
- Affected respiratory functioning and increase in the occurrence of asthma, which is a consequence of breathing contaminated air.

Due to their particular vulnerabilities, pregnant women and children become more susceptible to these contaminants. Mercury is another neurotoxin released during unsafe recycling of the e-waste that is able to permeate the placenta and taint breastfeeding, thereby compromising the neonatal nervous, respiratory and immunological systems. Children may suffer lifelong consequences and irreversible harm from e-waste's alteration of their developing systems.

Hazardous waste management and transboundary transportation are presided over by the Basel Convention. It is an all-encompassing environmental accord that attempts to manage the issues related to toxic wastes, including the management of e-waste. The Ban Amendment enforced by the Basel Convention in 2019 forbids the shipping of toxic wastes, which include e-waste as well. It also gives states standards for separating garbage from non-waste and for moving e-waste across borders. There are also regional conventions, such the Waigani Convention and the Bamako Convention, seeking to limit the flow of toxic wastes throughout the countries of the South Pacific and Africa. The global e-waste production in 2019 was approximated to be 53.6 million tonnes; however, only 17.4% of the total solid e-waste produced was cumulated in order to recycle [4].

One important step towards solving this problem is to look for alternative semiconductor materials in place of silicon and germanium, which are environmentally friendly and can biodegrade easily and quickly, without leaving any toxins behind. This measure would change the face of the semiconductor industry at present and pave the way for reducing the harmful effects on environment and human health.

The major goals of present and upcoming innovations in renewable input materials and biodegradable polymers are product characteristic enhancement and production scale-up. Some biopolymers are conducting and their conductivity is at par with semiconductors like silicon and in some cases even with conductors. Hence they can be used in place of inorganic semiconductors such as silicon and germanium. Some conducting biopolymers include polypyrrole (PPy), polyaniline (PAn), polyacetylene (PA), etc. However these are all conjugated polymers, that is, they have double or triple bonds in their chain structure and hence with little energy, they start conducting like pure conductors, which in turn makes them lose the quality to be used as semiconductor.

One such compound that may have the possibility to be used as a semiconductor is cellulose. Cellulose is a long chain organic polymer derived from plant cell walls and various algae. It is biodegradable and compatible with the environment. Cellulose is also compatible with the human body as we ingest cellulose in the form of “fibre” from plants every day.

One of the promising benefits of using cellulose as a semiconductor is its potential low cost compared to traditional inorganic electronics. Another potential advantage may be to synthesize flexible electronics, that is, mounting of electronics onto flexible material like cellulose. These materials will be thinner than conventional circuits and be easier to fabricate, allowing for wider application domain.

3.2 INTRODUCTION TO CELLULOSE

The biosphere's most ubiquitous natural polymer is cellulose, which is produced and broken down globally at a pace of around 1.5×10^{12} tonnes each year, which is equivalent to the planet's stocks of the primary mineral and fossil fuel sources. Utilizing cellulose as a sustainable and biodegradable material for several uses is one intended solution to the current industrial predicament of efficiently meeting environmental and recycling requirements, apart from the material's long-standing scientific interest. Because cellulose can be structured in a variety of ways using both physical as well as chemical methods, it can be employed in extensive applications, including as filler substances, coatings, papers, fabrics, optical films, absorption media and even advanced materials with functional properties. The French scientist Anselme Payen's work from 1837 signified the start of the methodical endeavours eventually leading to the discovery of cellulose. In addition to heat and mechanical treatments, cellulose may now be isolated using a variety of techniques, including as the alkaline, sulphite, and sulphate procedures. The pulp's fibre strengths change depending on the various methods used [5]. Cellulose is categorized as a polysaccharide, or complex carbohydrate, which is made of 3000 or more glucose monomers; having chemical formula $(C_6H_{10}O_5)_n$, it is an organic polysaccharide made up of a linear chain of $\beta(1 \rightarrow 4)$ connected D-glucose monomers. Cellulose is a substantial constituent of the cell walls of oomycetes, many algae and plants. Ninety percent of cotton, 40%–50% of wood and around 50% of dry hemp are composed of cellulose [6].

3.2.1 Hydrogen bonding in cellulose

The many hydrogen bonding systems found in cellulose greatly impact its characteristics. For example, the hydroxyl group's reactivity, the cellulose samples' low solubility in most solvents and their crystallinity are all caused by strong hydrogen bonding systems. These hydrogen bonds have a strength of around 25 kJ/mol, which is approximately a hundred times more compared

to van der Waal's forces (about 0.15 kJ/mol), but it is still only a tenth of the energy of the O-H covalent bond (460 kJ/mol) [7]. Hydrophobic regions of cellulose, such as those around the C atoms, also affect the material's general characteristics, including its solubility. Each anhydroglucose unit bears three hydroxyl (-OH) groups, which form intermolecular and intramolecular hydrogen bonds with nearby oxygen atoms. There are several three-dimensional configurations arising from these hydrogen bonds. This interaction results from the powerful intermolecular hydrogen bonding among the cellulose chains. Hydrogen bonds are established between hydroxyl group (-OH) at C6 and the oxygen atom (O⁻) at C3 in the native cellulose structure, formed between the adjoining cellulose molecules in the (002) plane [7]. The construction of cellulose in layers is caused by fragile C-H-O bonds, hydrophobic interactions and hydrogen bonding together [5].

3.2.2 Sources of cellulose

Cellulose serves a skeletal or structural purpose. Similar to how human bodies are supported by our hard, bony skeletons, which serve as attachment sites for our muscles, any plant's rigidity or stiffness is ascribed to the strength of its cell walls. When cellulose fibres are examined under a strong microscope, they exhibit a crisscross or mesh pattern that gives the impression that the material is woven. The process of creating the cell wall has been compared to that of making reinforced concrete, with the cellulose fibres serving as the extra strength-producing steel rods or rebars in concrete.

An extensive variety of plants have been researched with regard to cellulose and nanocellulose extraction, as cellulose is an integral component of the plant cell wall [8]. In addition, many families of algae are employed to extract cellulose including *Cladophora*, *Boergesenia*, *Micrasterias denticulata*, *Valonia*, and *Micrasterias rotata*, where cellulose is mainly recovered from the cell wall of these algae and it exists in mainly the allomorphs I_α and I_β [9]. Apart from plants and algae, bacteria are also a source of pristine bacterial cellulose (BC) and species of *Gluconacetobacter xylinus* is the most repeatedly used bacterial species that produces cellulose [10]. In addition, marine invertebrates known as tunicates have been the subject of much study in the field of cellulose extraction, where variety of species, including *Halocynthia papillosa*, *Metandrocarpa uedai* and *Halocynthia roretzi* have been identified as source of cellulose [11].

Further, the methods of extraction of cellulose can vary depending on the sources [12].

3.2.3 Material characteristics of cellulose

As a semi-crystalline polymer, cellulose consists of crystalline sections divided by disordered portions. For a broad range of temperatures, it is comparatively thermally stable. At about 200°C, it begins to degrade thermally. The glassy phase, devoid of extensive molecular mobility, and

mechanical characteristics of the amorphous portions of cellulose are preserved up to this temperature. Cellulose is a fibrous material, white in colour and has a density of 1.52–1.54 g/cm³ at 20°C. Cellulose is dissolved in organic solvents that have added electrolyte complexes. Moreover, cellulose dissolves in intense phosphoric and sulphuric acid solutions, dimethylformamide solutions containing nitrogen dioxide, and cellulose breaks down as it dissolves in these acids. Due to its hygroscopic nature, cellulose may absorb 8%–14% of water at 20°C and 60% relative humidity. Water plasticizes amorphous cellulose, as cellulose sponges demonstrate, becoming stiff when dry and pliable when wet. Glass transition temperature of the resulting cellulose-water system is decreased below ambient temperature because sponge suppleness occurs in the system due to the presence of moisture. Since cellulose is a biodegradable material, bacteria may break it down without finding any traces of poisons. Melting temperature of cellulose was determined at 467°C [13]. It may be chemically reduced to its glucose units by heating it to a high temperature and treating it with concentrated mineral acids (hydrolysed). Apart from these attributes, cellulose is substantially more crystalline compared to starch. Upon heating at over 60°C–70°C in water while cooking, starch changes from crystalline phase to amorphous phase, whereas cellulose needs to be heated to 320°C or treated under 25 MPa of pressure in order for it to undergo the same changes. Because of the preferred position of the molecular chains along the fibre axis, cellulose shows significant birefringence [14]. Crystalline cellulose has various structural modifications, known as allomorphs that include cellulose I also called native cellulose and cellulose II known as hydrated cellulose. These allomorphs can further be classified as cellulose I_α and I_β . Besides these, regenerated cellulose is another allomorph of cellulose [15].

3.3 INTRODUCTION TO NANOCELLULOSE

Recent industrial revolution is strongly driven by nanotechnology, ranging from bio-composites, nanotechnology-based medical devices to biosensing. Nanoscale represents a material of size approximately 100 nm in at least one dimension where the properties of these nanomaterials are quite different than the bulk material. Nanocellulose broadly means nanostructured cellulose, cellulose structures of size spanning from a few nanometres to a few hundred nanometres. The term microfibrillar cellulose or nanocellulose was first coined in the late 1970s by Turbak, Snyder and Sandberg while working at the ITT Rayonier Labs at New Jersey. Since then numerous research studies on nanocellulose were conducted, resulting in patents and publications granted to ITT Rayonier [16].

Nanocellulose owes its popularity to abundance of sources, excellent characteristics including high aspect ratio, increased strength and improved

mechanical properties besides being nontoxic, non-hazardous, biocompatible and sustainable. Nanocellulose exhibits lightweight nature, increased crystallinity and elevated specific surface area, with promising rheological and chemical reactivity properties, due to which nanocellulose is slowly but steadily emerging as a substitute to petroleum-based and other non-renewable materials. Given such excellent properties, nanocellulose can be utilized in varied applications encompassing biomedical, sensors, electronics and energy. The vast surface area allows for extensive absorption of various molecules and atoms, a property that is utilized for controlled drug delivery systems and various innovative biomedical applications. Inertness and tuneable physical, chemical, barrier and thermal characteristics of nanocellulose make it an exceptional candidate for implementation in a variety of industrial applications that include filtration, purification, food packaging, manufacture of thermal insulators, sensors and actuators and energy extraction [17,18].

According to recent surveys, during the years 2022–2030, the international markets for nanocellulose have been predicted to grow annually at 21.9%, from its predicted worth of USD 0.4 billion in 2022 and reach the valuations of USD 2.0 billion in 2030. Growing concerns about the environment and a shift in consumer demand towards biodegradable products are the catalysts for this surge. The growing trend of innovation in bio-based products is the driving force behind the boom in the nanocellulose markets, significantly influencing the corporate investments globally. One of the challenges faced by the market is the lack of product standardization. Nanocellulose production on a global scale needs its quality to be maintained throughout all batches and countries. Based on applications, pulp and paper segment accounts for the majority of its market share, followed by composites, pharmaceuticals, coatings and electronics sensor industry [19].

3.3.1 Classification of nanocellulose

Several terminologies have been and are being used to define nanocellulosic materials. In order to remove ambiguities, a standardized nomenclature was introduced for the nanocellulose family based on its structure, size and methods of extraction. Recently, a Nanotechnology Division was established by the Technical Association of the Pulp and Paper Industry (TAPPI), dedicated to standardizing the nomenclature of cellulosic nanomaterials and in this direction, resulting in establishing a draft standard WI 302: Standard Terms and Their Definition for Cellulosic Nanomaterials, based on the size of cellulose nanomaterials [20]. Broad categorization of the cellulose nanomaterials can be understood from the chart in Figure 3.1.

Cellulose nanomaterial is broadly classified into two categories: first category is called Nanostructured Cellulose, which includes Microcrystalline Cellulose (MCC) or Cellulose Microcrystal (CMC) and Cellulose Microfibrils (CMF) and the second category is comprised of

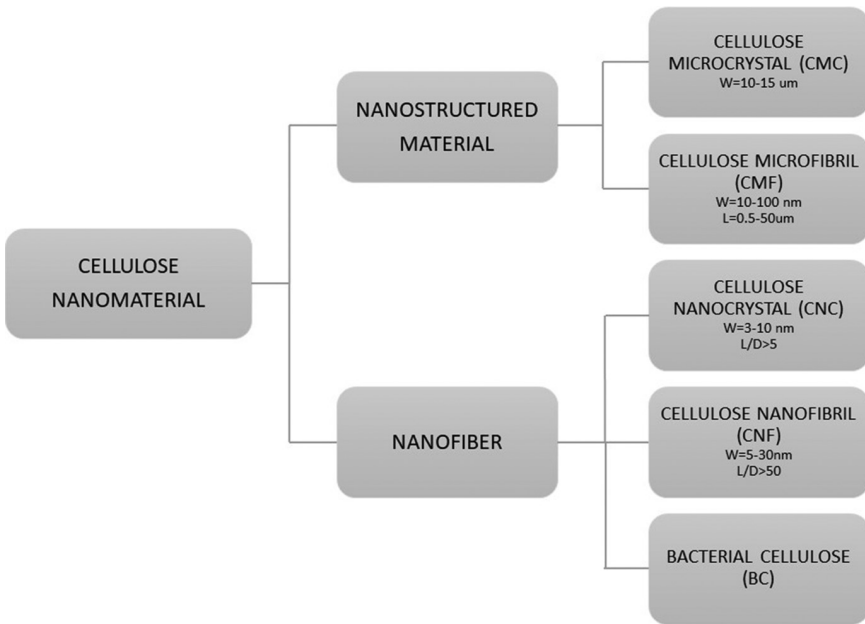


Figure 3.1 Broad classification of nanocellulose.

Cellulose NanoFibrils (CNF), Cellulose NanoCrystal (CNC) and Bacterial NanoCellulose. A brief overview of these nanomaterials follows:

- **Cellulose microcrystal (CMC)/microcrystalline cellulose (MCC)**
MCC is the form of cellulose which is available in an industrial capacity, manufactured by the process of hydrolysing purified cellulose using dilute mineral acids, resulting in partial depolymerization of cellulose. As cellulose is semi-crystalline in nature, dissolution of amorphous domains of cellulose in the acid solution produces shortened and more crystalline fragments, known as MCC. The particles usually exist in spherical or rod-shaped structures of dimensions from 10 to 200 μm [21].
- **Cellulose microfibrils (CMF)**
CMF can be considered as aggregates or bundles of elementary nanofibrils of cellulose, having dimensions ranging between 20 and 100 nm, with length varying from 500 to 2000 nm. CMF are generated by rigorous mechanical procedures that include high-pressure homogenization, microfluidization, cryocrushing and grinding [22].
- **Cellulose nanocrystals (CNC)**
CNC are small nano-sized crystallites of cellulose, elongated rod-like in shape, having limited flexibility and higher crystallinity [18]. They vary in width from 5 to 50 nm and are typically 100–500 nm in length.

The index of crystallinity and their length is particularly reliant on the source and method of extraction. For example, CNC obtained from tunicates and BC have larger size and higher degree of crystallinity compared to wood and cotton sources. The principle behind the generation of CNC from cellulose is to split the amorphous domains in cellulose and hydrolyse the localized crystallite contacts across cellulosic fibrils using strong acids of 6–8 M strength [23]. The acid hydrolysis is followed by ultra-sonication treatments to homogenize the CNC suspension. Common alternate names for CNC include nanowhiskers, nanorods, etc.

- **Cellulose nanofibrils (CNFs)**

CNFs are bundles of basic nanofibrils of cellulose made of a combination of crystalline as well as amorphous domains. Their dimensions fall in the range of 20–50 nm with length varying between 500 and 2000 nm. CNFs can be visualized as an entangled network of nanofibres that are flexible and long. CNF has reduced crystallinity when compared to CNC and is broadly derived from cellulosic pulp using mechanical treatments [18,24].

- **Bacterial cellulose**

Certain bacteria, under favourable conditions, are able to secrete CNFs as extracellular metabolite. These nanocellulose-producing bacteria primarily include bacteria which are a member of the genera *Gluconacetobacter*, *Agrobacterium*, *Alcaligenes*, *Pseudomonas*, *Aerobacter*, *Azotobacter*, *Achromobacter*, *Sarcina* and *Salmonella* [25]. The nanocellulose produced by these bacteria is distinguished by an elevated degree of polymerization, higher crystallinity and more stable fibres. These ribbon-shaped nanocellulose generally exhibit rectangular cross-section, with dimensions of around 30–100 nm in width, 1–9 μ m in length with a thickness of around 3–10 nm. Besides having the above-mentioned advantages over plant-based nanocellulose, bacterial nanocellulose is free of hemicelluloses and lignin, thereby eliminating the need for chemical treatments to remove these compounds and subsequently eliminating higher biological and chemical oxygen demands in order to process the wastes. Thus, bacterial nanocellulose possesses high chemical purity. However, its production is especially expensive, given the steep costs of artificial media and the risks of contaminating the bacterial strains during incubation [26].

3.3.2 Isolation and properties of nanocellulose

Extraction and isolation of pure cellulose is a complicated process, involving various processes of chemical, physical and enzymatic processes and their combinations. Extraction of nanocellulose is preceded by the segregation and purification of cellulose from various sources, a process that involves treatment using acid or alkali, followed by delignification or bleaching for which sodium chlorite and hydroxide peroxide are used.

Chemically purified cellulose produced using the above two-step process is followed by various processes to produce nanocellulose, including acid hydrolysis, mechanical processes such as grinding, steam explosion, cryocrushing, etc. to produce different nanocellulosic materials [27,28].

Given its unique and inherent properties including high surface area, higher thermal stability, better mechanical properties, easy surface modification, nanocellulose has garnered a rising interest in multiple fields of application. For an enhanced comprehension of these properties, a multitude of characterization techniques are employed.

These characteristics are imparted to nanocellulose by the hydroxyl (-OH) groups positioned on its surface. The hydroxyl groups have strong ability to interact with one another and contribute to formation of hydrogen bonds, contributing to self-association. This property reinforces the mechanical properties of nanocellulose and makes it a useful agent for reinforcement in amalgamated polymers [29]. Zeta potential measurements are used to calculate the electrical charge on the surface of nanocellulose [30], where negative values point to the surface hydroxyl groups with negative charge. Stable suspensions of nanocellulose in aqueous media are the outcome of the negative values of the zeta potential.

The strong network of hydrogen bonding in cellulose results in generation of the ordered arrangement of molecular chains, particularly in case of nanocellulose, where the amorphous domains of cellulose are removed, and thereby higher crystallinity is achieved. Crystallinity index is strongly determined by the source and methods of extraction of nanocellulose, based on which the crystallinity of nanocellulose can range from 60% to more than 80% [31]. Crystallinity index is indicative of the microstructure and the mechanical properties of nanocellulose, and is determined using X-ray diffractometry. Broadly, Segal's equation gives an empirical estimation of the crystallinity index; however, recently, more refined methods are being used, which take into account the contribution of smaller crystallite sizes in cellulose, which might be mistaken for the amorphous contribution and thereby result in erroneous calculation. Methods such as amorphous subtraction and peak deconvolution are being used increasingly as the Segal method provides an empirical measure of crystallinity [32,33].

Microscopic techniques such as the Field Emission Scanning Electron Microscopy (FESEM), Atomic Force Microscopy (AFM) and the Transmission Electron Microscopy (TEM) are used to quantify the shape and dimensions of these particles. These morphological attributes of length and width of nanocellulose particles are particularly determined by the source of the pretreated cellulosic material and the factors influencing the hydrolysis treatment employed [34]. Nonetheless, it is possible to obtain the desired dimensions of the nanocellulose particles by controlling the external variable factors such as filtration, ultrasonication and centrifugation [35]. Usov et al. captured microscopic images using AFM, TEM and

cryo-SEM to show that the nanocellulosic fibrils and crystals possessed right-handed chirality, both at fibrillar as well as at bundle levels [36]. AFM has also been employed to examine the morphology and mechanical characteristics of nanocellulose, this characterization was used to calculate the elastic modulus of CNCs derived from wood and that of CNFs and their values were found to be 18–50 GPa and 6.9 ± 0.4 GPa respectively [37]. The extraordinary mechanical properties of nanocellulose entail a high modulus of elasticity, in the range of 110–220 GPa, and high tensile strength in the range of 7.5–7.7 GPa [38] being equivalent to glass and aramid fibres that are traditionally used in fibre-reinforced composites. Recent research is focused to amplify the mechanical characteristics of polymer matrices by reinforcing them with nanocellulose and remarkable enhancement in mechanical properties has been observed. Likewise, the mechanical attributes of the poly lactic acid such as loss and storage modulus were augmented by addition of CNC in contrast to the purified polymer. Particularly at low concentrations, the stiffening effect of nanocellulose is profound, resulting in an extensive specific surface area which allows for exceptional interconnections to take place between nanocellulose and polymeric structure. Nanocellulose is thermally stable up to the temperature of 200°C and thermal decomposition of nanocellulose takes place in the temperature range 200°C–300°C; however, it is possible to augment the thermal strength of nanocellulose upon physical and/or chemical alterations to the nanocellulose structure. These include desulphation of the CNCs isolated using sulphuric acid hydrolysis [39]. Thermal stability of nanocellulose is determined by techniques including Thermogravimetric Analysis (TGA), Differential Thermogravimetry (DTG) and Differential Scanning Calorimetry (DSC). More recently, approaches other than sulphuric acid hydrolysis have been researched, including a mixed acid hydrolysis and hydrolysis using organic and non-corrosive acids to obtain better thermal stability.

Nanocellulose is able to form stable and free-standing films and coatings having versatile barrier applications. The films have excellent resistance to gas transport and this property has great importance in the domain of packaging operations. The resistance to oxygen transport exhibited by these films is comparable to the films generated from synthetic materials. Again this property is an implication of the extensive hydrogen bonding network. Combining nanocellulose with PLA gave rise to an impermeable surface for oxygen, nitrogen and carbon dioxide [40].

3.3.3 Nanocellulose substrates

The objective of this chapter is to elucidate the usefulness of nanocellulose in the field of electronics. Having already briefly painted a grim picture of the harms of extensive amounts of electronics waste clobbering our planet, it becomes even more essential to combat its effects and make our

electronics more sustainable in line with the global sustainability objectives. The advances in the field of nanocellulose electronics research have yielded the following results of importance:

3.3.3.1 Flexible and printed electronics

- a. **Nanocellulose as a flexible substrate:** Transparent flexible substrates, including polymer films, lead the development and advancement of flexible printed electronic devices such as solar cells, flexible screens, sensors, etc. Substrates used for printed electronics are required to be non-porous and smooth so that discontinuities in printed films are avoided. Cracks and adsorption of ink lead to breaking of the path of conduction, reducing the electrical conductivity. In addition, the substrates should be able to withstand high temperatures when occasional sintering of samples is required. Nanocellulose films, besides fulfilling these requirements, are recyclable as well, thus making them a superior choice for green electronic uses. These nanocellulose films are based on CNF rather than CNC because of the brittle nature of the CNC films. CNF films, also known as nanopaper, have low porosity and smoother finish when compared to traditional paper. This was emphasized [41], whereby conductive lines using two techniques for deposition, inkjet printing and sputtering, were used, with two distinct functional inks including silver ink and metal-organic deposition ink. Electrical resistance on the traditional paper was $6430\ \Omega$ and on CNF nanopaper was $34\ \Omega$, which is 180 times lower. Owing to low porosity of the CNF nanopaper, the ink infiltration was inhibited. Similar results were obtained for both deposition techniques. In addition, CNF nanopapers were able to withstand higher sintering temperatures up to 200°C , confirmed with thermal analysis. Enhanced thermal stability of the CNF nanopapers is a favourable attribute in order to replace plastic-based substrates. Nge et al. [42] obtained similar results by printing silver nanowires (AgNWs) on traditional paper and plastics and compared them to CNF nanopaper. Higher resistance was obtained on traditional paper compared to plastic and nanopaper; however, the resulting conductivities on plastic and CNF nanopaper were comparable and in some cases CNF nanopaper conductivity was higher than the plastic substrate. It is more important for CNF fillers to provide lower porosity rather than higher smoothness. Further research has been conducted in this field where CNF films were chemically altered using carboxymethylation and hexamethyldisilazane (HMDS), polydopamine (PDA), making composites of kaolin filler with CNF suspensions and by combination of CNF with conductive materials like graphene and carbon nanotubes (CNTs), resulting in formidable substrates for use in flexible electronics [43–45].

The attributes of increased surface smoothness and flexibility are favoured in the actualization of flexible thin film transistors (TFTs). The use of CNF substrates was reported for fabrication of an organic thin film transistor (OTFT) by Fujisaki et al. [46], where they reported improvement in the layer properties because of the roughness in the texture of nanopaper. It was reported that the OTFT performed at par with those TFTs obtained on plastic substrates. Further, the carrier mobility of $1\text{ cm}^2/\text{V/s}$ was reported with an on/off current ratio of 106–108 and lower leakage currents of below 10^{-8} A/cm^2 were reported as a result of low surface roughness ($\sim 1.9\text{ nm}$) of the spin-coated dielectric layer. All the more, the device was held under different conditions of bending for an hour and no decrease in the carrier mobility was reported. Similar fabrication was performed by Huang et al. by utilizing CNF substrates for an organic transistor device [47], where they made a transparent conductive gate with single-walled nanotubes (SWNTs) on the substrate. Carrier mobility of $4.3 \times 10^3\text{ cm}^2/\text{V/s}$ and on/off current ratio of 200 were reported. However, in this case, it was reported that the carrier mobility decreased by up to 10% when flexibility tests were conducted. Nanopapers based on cellulose have also been developed as electroactive paper (EAPap) in order to be used in sensor and actuator-based applications [48]. In order to overcome the low actuating frequency and decreased output force in the EAPap, it is strengthened using cellulose nanoparticles, which provide stable electron pathways and improve the mechanical strength of the EAPap as well. This reinforcement results in increment in the resonance frequency of the EAPap. Flexible humidity sensors have been developed using CNF modified with CNTs, utilizing the swelling characteristics of nanocellulose [49]. Flexible aerogels based on CNF are a favourable system for flexible electronics given their compatibility and, more importantly, their porous structure [50].

- b. **Nanocellulose as a transparent substrate:** Transparency is a significant property of cellulose nanopapers, consisting of densely packed bundles of microfibrils of cellulose having diameters of 15–20 nm. The dense packing results in the intervening space between fibres being small enough so as to avoid the light scattering, resulting in the transparency and high performance of CNFs, and resulting attributes are low thermal expansion (Coefficient of Thermal Expansion $< 9\text{ ppm/K}$) and flexibility [51]. Plastic substrates are currently being utilized as substrates for transparent conductive films, because of being flexible and transparent. A major limiting factor of these plastic substrates is their poor thermal stability. Transparent and translucent nanocellulose films provide a substitute to the plastic substrates, given their flexibility, biodegradability and improved thermal stability. Additional to thermal stability, haze is a critical characteristic in the production of transparent substrates. Haze is the percentage of incident light that is scattered by more than 2.5° through the film specimen.

Hu et al. compared light scattering of CNF films, traditional papers and plastic films, to compare their angular reflection and transmission [51]. Due to the nanoscale dimensions of CNF, the films made from CNF exhibit transmitted and reflected light scattering and CNF substrates scatter the light, unlike the plastic substrate but are transparent, unlike the traditional paper. The haze of the CNF films is tuneable, given the dimensional dependence of the nanocellulose particles and the proportion of CNF and CMF in the film [52]. Upon deposition and drying of aqueous conductive inks onto the CNF films, discontinuities in the conductive path might disturb the stability of the CNF substrates. The use of cellulose nanopapers in flexible devices is further propagated by the depositions of conductive materials onto the nanopapers. These materials include CNTs, AgNWs and tin-doped indium oxide [51]. Silver being one of the best conductors makes AgNWs a promising candidate, in order to produce an electrical network and maintain heightened optical clarity. A plethora of investigation has been conducted in the field of AgNW/nanopaper in order for it to be employed as a transparent and flexible substrate. Initially, Koga et al. produced the AgNW-based transparent and conductive nanocellulose-based nanopaper, by simple filtration process of an aqueous dispersion of CNFs, leading to formation of a wet nanopaper, followed by deposition of aqueous dispersion of AgNW onto it. This nanopaper was then hot pressed and peeled from the filter membrane, resulting in the fabrication of a transparent flexible substrate. The hot pressing process also resulted in strong adherence between the AgNW and nanopaper surface. This nanopaper demonstrated a sheet resistance of 12 U/sq and a transmittance of 88% at wavelength of 550 nm. The sheet resistance, when compared to that of PET substrate (900 U/sq and transmittance of 87% at 550 nm) was 75 times lower [53]. Further, hybrid nanopapers have been fabricated using a variety of chemical modifications done to nanocellulose and utilizing different fabricating techniques [54]. While the positive attribute of pure cellulose membranes is the biodegradation of the device, numerous examinations have assessed the eco-friendliness of such electronic devices and components. Recycling of CNC substrate has been carried out where the transparent and even CNC substrate that was employed in solar cell devices was simply immersed in water, which led to water absorption and ultimately dispersion of the substrate [55]. The components of solar cell were then segregated by simply washing and filtering, thus giving rise to a very easy and green recycling process. This research has proved renewability of nanocellulose substrates for both CNF- and CNC-based components, thereby giving an encouraging alternative to plastic and glass substrates. The major challenge in this route, however, is the performance evaluation of these electronic components and improving their robustness in order for them to compete with standard electronic devices.

3.3.4 Nanocellulose-based applications in electronics

3.3.4.1 *Electronic skin*

Electronic skin is a stretchable, flexible and a self-healing device which is able to bond to human skin and produce responses based on the movement, pressure and temperature of the skin, thereby having promising applications in the field of biomedicine, artificial intelligence and diagnosis. Flexibility of Cellulose Nanopaper (CNP) and its compatibility with the human skin has made it a material of choice for sustainable skin electronics applications [56]. Nanomaterials based on cellulose have exhibited piezoelectric effect, which has been implemented for use in skin and sensor-based applications, including robotics and microelectromechanical systems [57]. The piezoelectric effect of CNC films, comparable to that of ZnO film, was demonstrated by Csoka et al. as having a shear piezoelectric constant of $2.1 \text{ A}^\circ/\text{V}$ [58]. Similarly, research conducted in the BC films also showed that these films could be bent by electrical signal input that can further be enhanced by chemically modifying the BC [59]. Modifications in the nanocellulose with TEMPO-mediated oxidation and chemicals such as PPy and AgNWs have resulted in the fabrication of electronic skin with excellent sensing capacity [60,61].

MXene is a category of two-dimensional inorganic compounds, consisting of carbides, nitrides and carbonitrides of transition metals. MXenes have exhibited higher electrical conductivity compared to graphene and have great potential for flexible electronics. However, MXene powders ($\text{Ti}_3\text{C}_2\text{T}_x$) are metastable and this is the main hurdle against using MXene on a larger scale. Additionally, at temperatures above 200°C , MXene powders are thermally unstable and surface modification needs to be further explored to develop efficient techniques in order to put MXene to use in skin and flexible electronics. These drawbacks of MXene have been overcome to some extent by the addition of pure and modified nanocellulose and these composites have been used to develop sensors for electronic skin [62,63]. Nanocellulose-based electroactive devices have enormous potential and for use in sustainable electronics, this potential needs to be tapped into, in order to shrink the gap in fundamental understanding and fabrication of electronic components and devices.

3.3.4.2 *Organic light-emitting diode*

Organic light-emitting diodes (OLEDs) are a type of LED where the electroluminescent component is an organic compound (carbon-based) film that emits visible light when stimulated by electric current. Unlike LEDs where the light source is small point, OLEDs have diffused area light source made in sheets of organic compound. OLEDs are lightweight, flexible and power efficient, flexibility being the attribute of importance in

electronic displays. Thin film is fabricated from the OLED material, followed by sandwiching the film between two conductors. Upon applying electric current, the electroluminescent film starts emitting visible light. The OLED displays emit their own light, therefore they do not need a backlight, resulting in deep black levels in the display, in addition to the displays being thinner and lighter. Cellulose-based nanomaterial has found its use in the field of OLEDs as well, being used for device fabrication as a substrate. In order to assemble an OLED, multiple layers of materials such as aluminium and lithium fluoride deposited onto the cellulose nanopaper can act as cathode in an OLED construction [64]. Cellulose nanopaper when compared to regenerated cellulose films and conventionally used flexible plastics has amplified haze, thereby making it a feasible choice for solar cells and displays with a low glare [65]. These OLED devices have a robust performance in flat as well as bent states [66]. CNP is poised to become a significant component of multitude of new electronic devices. However, certain factors limit the applicability of nanocellulose when compared with plastic and glass substrates: (1) increased surface coarseness, (2) elevated hydrophilicity, (3) relatively lower breakdown temperatures and (4) costly material and processing.

3.3.4.3 Foldable antennas

Nanopaper antennas with printed AgNW were first reported by Nogi et al. Owing to their smooth surface and high flexibility, these antennas are highly sensitive. AgNW lines deposited in v-shaped patterns were able to transmit and receive high-frequency signals, thus acting as antenna lines. This transmission and reception was modulated by folding and unfolding the nanopaper, where the antenna was able to transmit and receive signals when the device was unfolded and while in the folded state, the nanopaper antenna did not transmit or receive any signal [67]. The reported return losses of this foldable antenna were valued at $0.5e^{4.0}$ GHz.

3.3.4.4 Radiofrequency identification

Flexible antennas fabricated on transparent nanopaper for potential radiofrequency identification (RFID) applications were reported by Zhu et al., where the antennas were made by printing nanoparticled silver ink on transparent nanopaper and gravure printing was utilized [68]. In order to impart dimensional stability in water, the nanopaper was cross-linked with glutaraldehyde and hydrochloric acid as catalyst. The research reported the insertion loss of the antennas to be 37.9 and 38.85 dB for 100 and 120 lpi respectively at a maximum gain of 683.75 MHz. This research demonstrated that using printing technology for fabricating the flexible RFID antennas for numerous electronic devices is feasible and sustainable.

3.3.4.5 Micropatterning

Highly flexible and transparent microelectrodes have been developed by Kim et al. using conductive AgNW upon TEMPO-oxidized CNFs [69]. Microcircuit based on AgNW was fabricated using polyethylene glycol (PEG) photolithography upon glass substrate, this was followed by transferring the micropattern to the transparent TEMPO-oxidized CNF nanopaper using vacuum-assisted microcontact printing. This microcircuit was utilized for fabricating a transparent electrical circuit and LED bulbs were successfully operated using this circuit. The research group also fabricated a solid state electrochromic (EC) device, utilizing the nematic chiral properties of nanocellulose. The EC devices are able to reversibly change colours upon the application of an electric field. These EC devices were AgNW sandwiched between nanopaper and indium tin oxide (ITO) film on one end. The device colour was switched by applying electric field from a transparent state at 0 V to a dark purple colour at 2 V. This EC device may be used as sustainable material in smart windows which could be used to block certain wavelengths of ultraviolet, visible and infrared spectra.

3.3.4.6 Energy storage devices

a. Supercapacitors

Supercapacitors are the power devices of the future, suitable to be implemented in the area of power devices and hybridized electric automobiles. Being a category of energy storage devices, supercapacitors have four basic components of anode, cathode, electrolyte and a separator. Anode and cathode are electrically isolated from each other by the separator, which is generally a semipermeable membrane. In order to facilitate the circulation of electric current across the electrodes, the electrodes and the separator are saturated using electrolyte solution. Supercapacitors are superior energy storage devices when compared to batteries, having the merit of faster charging and discharging speed, enhanced power density and extended cycle life. Supercapacitors have been classified as: Electrochemical Double Layer Capacitor (EDLC), pseudo capacitor and hybrid supercapacitor, a combination of EDLC and pseudo capacitor [70]. Nanocellulose has been used to fabricate and manufacture the basic components of a supercapacitor, i.e., electrodes, electrolytes, separators and substrates [71]. Nanocellulose is recognized as an effective reinforcement, given the unique features of flexibility, elevated Young's modulus and tensile strength, hydrogen bonding, thermal stability and non-toxicity, therefore its utility as an excellent matrix material appears to be a conducive approach for fabricating greener energy storage devices. Integration of nanocellulose with conductive materials efficiently resolves the issue of the inherent non-conductive nature

of cellulose. Best performing supercapacitors and other electrochemical devices call for fast ion and electron transport, and nanocellulose being porous and lightweight can be loaded with conductive materials resulting in better ion transfer. Nanocellulose has the following applications in various components of the supercapacitor:

3.3.4.6.1 *Nanocellulose-based electrodes*

Nanocellulose material being inherently non-conductive, it is pretreated and modified in order for it to make it conductive. Modification of nanocellulose can be done either by coating/deposition or blending of nanocellulose and conductive material using in situ polymerization. Conducting materials utilized in nanocellulose-based blends include conductive polymers, carbon materials and metal particles.

Conductive polymers which have p-conjugated polymer chains consisting of PPy, PAn, PA, polythiophene (PTh) and polyphenylenevinylene (PPV) have been extensively researched in sensors, electrochemical capacitors, fuel cells and field emission devices. Nanocellulose acts as the matrix in this binary system and the conductive polymer acts as the filler to enhance the conductivity of nanocellulose. Flexible and light weight paper electrodes have been prepared using chemically modified BC, increasing the conductivity of the manufactured nanopaper [72]. To produce stable hybrids, it is important that there is harmony among the nanocellulose and conductive polymer, and the active groups of the conducting polymer should associate with the hydroxyl groups in the nanocellulose backbone. A flexible electrode was designed by combining nanocellulose with flexible PPy/Graphene Oxide (GO) composite by Wang et al. [73], where the electrode possessed excellent mechanical properties, rapid charging and discharging cycles and volumetric capacitance of 198 F/cm³. PEDOT or poly(3,4-ethylenedioxythiophene) is another conducting polymer that can potentially be used in composites to increase the conductivity of nanocellulose matrix. PEDOT-based flexible electrodes have been fabricated with CNF as the building block. With difficulty finding solvents for a majority of conductive polymers, solution coating and deposition techniques are not feasible for preparation of high-performance nanocellulose (NC) conductive films and as a result, the technique of in situ polymerization is more suitable to introduce conductive polymers in the nanocellulose matrix. Nanocellulose precursor incorporates the advantage of easy manufacturing, lower cost and a uniform 3D structure in the electrochemical composite material.

With carbon materials being more conductive compared to conductive polymers, nanocellulose films with higher conductivity can be produced using carbon-NC composites. Nearly all conductive carbon/NC composites are composed of graphene or CNT in the nanocellulose matrix, with some research reporting the use of carbon black (CB) and nano carbon black (NCB) as well. Graphene being a carbon material having two dimensions

and microscopic width, has high electric conduction as well as elevated Young's modulus of 1 TPa, tensile strength of 130 GPa and a thermal conductivity valued at 5000 W/(mK). CNTs are highly thermally stable with thermal conductivity valued at 3500 W/(mK), high tensile strength as well as Young's modulus. With these qualities, graphene and CNT make perfect materials for incorporation of conductivity in nanocellulose matrix through blending or coating. Since the deposition of layers of these carbon-based materials is not a feasible technique due to the weak bonding of carbon atoms with the nanocellulose surface, mixing or blending of these conductive materials into the nanocellulose matrix can result in physically trapping more number of carbon atoms in the substrate. These composites exhibit high electrical conductivity even when stretched or bent. Using carbon material including CNT and GO, flexible electrodes for supercapacitors have been fabricated from CNF [74,75].

With the intrinsic conductivity of metallic particles being higher (~ 105 S/cm) than the preceding categories of materials, it is natural instinct to use them in combination with nanocellulose to enhance the conductivity of nanocellulose substrate. These conductive hybrid composites are manufactured either by depositing the metal nanoparticles onto the surface of the nanocellulose films/paper or by bonding these nanoparticles into the nanocellulose matrix. In this regard, conducting metal-organic frameworks (c-MOFs) have shown a significant prospect to be employed in the area of energy storage, owing to elevated electrical conductivity as well as increased surface area. Fabrication of c-MOF nanolayers upon CNF and the resulting flexible and conductive nanopaper electrode was reported by Zhou et al. [76], with the formation of nanofibrillar CNF@c-MOF. These hybrid nanofibres assembled into nanopapers exhibited electric conductivity of approximately 100 S/cm along with excellent mechanical properties and substantial electrochemical performance given the uninterrupted charge transfer through the electrolyte. MXenes have proved to be quite significant as materials for electrodes in supercapacitors given their amplified electrical conduction, similar to metals, therefore using MXene to make nanocomposites for enhanced capacitance and high electrical conductivity [77].

3.3.4.6.2 Nanocellulose-based electrolytes and separators

Electrolytes being a core element in the construction of electrochemical energy storage devices have a strong repercussion on the execution parameters of these devices like power density, capacity and safety. Electrolyte is a medium for the flow of electric charge across the electrodes, thereby a key component of an energy storage device, as higher voltages and higher specific energy can be expected with the suitable selection of the electrolyte material. Ideally, liquid electrolyte has higher ionic conductivity but due to safety hazards, gel or solid electrolytes are used. Solid electrolytes include solid polymer electrolytes (SPE) as well as inorganic solid electrolytes,

whereas gel electrolytes are produced by absorption of electrolytes in a polymer matrix. It has been researched that nanocellulose is suitable to be employed as a filler to amplify the strength of the SPEs. Gel polymer electrolyte (GPE) can be produced by absorbing large quantities of liquid electrolyte on to a polymer matrix, giving rise to a gel-like consistency. GPEs have better ionic conductivity, better thermal stability and an expansive electrochemical window [78]. Nanocellulose has proved to be an effective filler in electrolyte applications [79]. Willgert et al. [80] synthesized and characterized an array of four blended electrolytes. These biphasic electrolytes were made of pliable ionic conductive PEG and cellulose nanopaper was added for improving mechanical integrity. CNF was modified using acid chloride reaction so as to form acrylates on its outer layer. This modified CNF resulted in covalent bonds connecting these phases, resulting in ionic conductivity equivalent to $5 \times 10^{-5} \text{ S/cm}$ as well as elastic modulus of about 400 MPa. Another important component of a supercapacitor is the separator, which allows ions to be transferred through its cavities filled with the liquid electrolyte. Transport of ions through the separator is largely determined by its polarity and porosity, which influence the applications of the energy storage systems in high-power functions. In addition, the separator can also inhibit internal short circuiting across the electrodes by providing selective insulation. This enhances the safety of an energy storage system. Separators composed of polyolefin, primarily polyethylene (PE) and polypropylene (PP), are used. However, the separator is vulnerable to failure at high temperatures because of its low melting point and excessive thermal shrinkage. Nanocellulose-based separators have been researched because of renewability, higher thermal stability and better mechanical properties. These separators also have a highly hydrophilic nature, giving rise to high wettability which is a favourable advantage over current commercial separators. Nanocellulose-based separators were produced by Chun et al. using CNF in isopropyl alcohol (IPA)/water solvent [81]. As the composition of IPA-water solvent was fine-tuned to 95/5 (vol/vol%), this resulted in a nanoscale and unusually porous labyrinth structure with closely piled CNFs. The ionic conductivity of the separator was 0.77 mS/cm as compared to the ionic conductivity of conventional PP/PE separators (0.73 mS/cm) and in addition possessed better wettability and lower heat shrinkage.

b. Fuel Cells

Fuel cells represent the new and promising, highly efficient, environmentally friendly energy systems. Fuel cell converts the electrochemical energy from reaction between a fuel and an oxidizing agent into electrical energy, differing from a battery in the fact that fuel is continuously being provided to the fuel cell. Fuel cells are a clean source of energy conversion with high efficiency. Main elements of a fuel cell are anode, cathode, gas diffusion layer, bipolar plate and the electrolyte. Electrodes made from conductive material are embedded with a platinum catalyst surrounded by a porous

gas diffusion layer, through which the electrodes receive fuel and oxidant. The heart of the fuel cell is the assembly of two electrodes isolated by a proton-conducting electrolyte membrane (PEM), known as membrane electrode assembly. Hydrogen or methanol fuel is oxidized at the anode, generating the proton and electron pairs, where the electrons are transported towards cathode through external circuit and protons are transferred via PEM [82]. At the cathode, the protons, electrons and the oxidant O^{2-} combine to produce water. In order to transport the protons, the electrolyte membrane is required to have high and selective proton conductivity for the fuel cell to perform at its best. Superior barrier properties against the permeability of gases and a significant chemical stability towards redox reaction are some of the important attributes that a PEM is required to have. In proton exchange membrane fuel cells (PEMFCs) and direct methanol fuel cells (DMFCs), Nafion or perfluorinated sulphonc acid ionomer is commercially used owing to it being highly and selectively proton conductive at higher humidities. However, high manufacturing expenses, complex process for synthesis with toxic intermediate chemicals being produced and decreased conductivity at high temperatures are some critical drawbacks associated with Nafion and as a result, cost-effective PEMs which have outstanding proton conductivity and chemical stability are becoming increasingly important. One of the ways to materialize this change is to fortify the existing PEMs by making use of functional fillers, including nanocellulose. The extensive hydrogen bonding in cellulose is expected to provide a pathway for proton to hop from site to site and hence assist in proton transport. Nanocellulose has been utilized as reinforcement filler in the PEM so as to optimize the properties of PEM. The utilization of nanocellulose in various components of a fuel cell is discussed in the following sections.

3.3.4.6.3 *Nanocellulose as polymer electrolyte membrane*

Free-standing nanocellulose films have been investigated as proton exchange membranes for a broad range of temperature conditions given their elevated thermal stability. Nanocellulose has been doped with phosphoric acid, phytic acid, sulphuric acid, sulphosuccinic acid etc. to introduce phosphate and sulphate groups that would aid in proton conduction in the nanocellulose membrane [83]. Bayer et al. studied the high reliance of proton conduction on humidity in the nanocellulose films employing two different categories of nanocellulose, that is, CNC and CNF [84]. The maximum conductivities of CNF membrane and CNC membranes were 0.05 and 4.5 mS/cm, both at 100°C and the relative humidity of 100%, ascribed to Grotthuss mechanism of proton conduction mediated by water. Further, Bayer et al. successfully sulphonated the nanofibrillar cellulose in order to amplify the proton conductivity up to 2 mS/cm. This paper fuel cell membrane composed of sulphonated CNF (s-CNF) had a high current density of greater than 0.8 A/cm² and power density of 156 mW/cm². Although these

values are far from the conductivity parameters of commercial Nafion, these PEMs are cheaper to produce [85,86].

Composites of materials for various applications in the fuel cell have been a topic of interest for several years now. Certain materials which are promising for implementation in the fuel cell suffer various drawbacks including low thermal stability, loss of conductivity at higher temperatures and poor mechanical strength. To overcome these drawbacks, various composites with nanocellulose have been manufactured and tested for use in the fuel cell. Composites of nanocellulose with Nafion have been studied, aimed at improving the mechanical and thermal stability of Nafion [87]. PAEK or polyaryletherketones are a class of semi-crystalline polymers, which have favourable properties including amplified mechanical strength of approximately 100 MPa and thermal stability of greater than 200°C. This class of materials includes various polymers including particularly polyetheretherketone (PEEK) and sulphonated PEEK (SPEEK) including others. Quite recently, nanocellulose composites with these hybrid chemicals have been explored for applications in PEMFC and DMFC [88,89].

3.3.4.6.4 *Nanocellulose in fuel cell electrodes*

Recent research is focused on implementation of nanocellulose in the field of fuel cell membranes in particular. This includes embedding the noble metal nanoparticles in the fuel cell membranes based upon nanocellulose and these nanoparticles act as catalyst in oxidation of the fuel. In this regard, in situ incorporation of nano-sized platinum particles on bacterial nanocellulose membrane was reported by Yang et al., where the Pt/BC catalyst demonstrated enhanced catalytic activity in the oxidation [90]. The reported output power of the fuel cell was maximized at 12.1 mW/cm² for Pt/BC composite and 19.9 mW/cm² for Pt/carbon composite. Likewise, Sun et al. reported a flexible and independent membrane cathode composed of BC reinforced with PDA and nanosized silver particles (AgNP). The BC/PDA amalgam was prepared by self-assembly of the PDA on BC, followed by electroless metallization of the composite membrane by silver ions, reduced by the reducing groups available in the PDA molecules. The resulting film exhibited the conductivity of 2.72 S/cm and a maximum current of 66 μ A, sturdy up to 1000 cycles [91].

c. Solar Cells

Solar cell or a photovoltaic cell converts the inexhaustible solar energy into electric energy, by means of the photovoltaic effect. The electrical parameters of the cell rely on the exposure to light. Low efficiency of energy conversion and high manufacturing costs are the major drawbacks against the commercially used solar cells used in energy harvesting. To overcome these challenges, low cost, renewable and a non-toxic substrate is the need of the hour. The optical and mechanical properties of nanocellulose have attracted

interest in their research for photovoltaic applications. Optical transparency of the nanocellulose films results from the reduced spaces between the fibres, thereby nanocellulose films are able to exhibit homogeneous diffraction. Besides this, another property accompanying the transparency in nanocellulose is its haze. It was demonstrated by Fang et al. that the dimension of a nanofibre paper is responsible in altering the forward scattering angle. By combining nanofibres of varying dimensions, it was shown that haze could also be controlled [92]. This controllable haze is quite useful for solar cell applications, potentially allowing an increase in the path length of light into the functional layers of the device. Cellulose nanopaper-based solar cell was first demonstrated by Hu et al. [93], where they successfully deposited transparent and conductive materials onto the cellulosic nanopaper, which included ITO, CNTs and AgNWs. However, a maximum photoelectric conversion efficiency of 0.21% could be reached. To increase the conversion efficiency, Zhu et al. utilized CNC to make optically transparent nanopaper, possessing smoother surface. A tenfold improvement in the conversion efficiency (2.7%) was observed. Moreover, this research opened a pathway for an absolutely recyclable solar cell manufacture, where these cells could easily be segregated into their respective elements using low-energy processes [94]. Nogi et al. produced an optically transparent conductive paper made of CNFs containing AgNW, which exhibited high electrical conductivity without any post-treatments. Subsequently, organic solar cells were manufactured employing this conductive nanopaper, and a conversion efficiency of 3.2% was achieved, which is comparable to ITO glass-based solar cells [95]. Recently, much research has been undertaken upon perovskite solar cells (PSCs), particularly the flexible PSCs being more widely applicable as photoelectric conversion devices [96]. Biobased membranes have been developed using various forms of nanocellulose including CNF, TEMPO, oxidized CNF and BC for implementation as electrolyte holders in dye solar cells. These electrolyte holders also facilitated carrier transport while operating, besides improving performance and stability of the device. Despite substantial efforts being made in the fabrication of nanopaper-based solar cells, various issues still need to be addressed for practical applications of CNP-based solar cells. Among these issues is the amplified hydrophilicity of nanocellulose and the short service life of the CNP-based device.

d. Nanogenerators

Nanogenerators are compact devices converting mechanical or thermal energy into electric energy, thereby ideal to power portable electronic devices. It describes a small flexible electronic chip which is capable of generating electricity from body movements. The three main types of nanogenerators that exist are triboelectric nanogenerator (TENG), piezoelectric nanogenerator (PENG) and pyroelectric nanogenerator. TENG and PENG are the two recently developed energy harvesting systems. TENG works on the principles of triboelectric effect and electrostatic effect, similarly, PENG

works on the principle of piezoelectric effect. Wood cellulose has often been employed as an underlayer or a triboelectric material for TENG applications. A flexible and clear TENG material was developed by Yao et al., where cellulose nanopaper was used as the friction layer and was paired with fluorinated ethylene propylene (FEP) in order to build the TENG device [97]. This device exhibited performance comparable to the devices built using synthetic polymers. The film's nanoscale surface roughness created an extensive surface area for generation of charges. Upon further integration with a fibreboard, the assembly produced electric output of voltage of 30 V and a current of 90 μ A upon being tested using a human step. The CNF is used as a dielectric layer for the fabrication of TENG using AgNWs [98]. Moreover, the electrical performance of TENG depends on the morphology of the cellulose after the fabrication process. Higher pressure and more filtering passes improved TENG performance by increasing the film's effective surface area. Similar studies were performed on PENG. Sun et al. developed composite nanofibre membranes for application in the PENG, where Cellulose Acetate (CA)/CNC films were used to manufacture a nanogenerator driven by pressure alone. The addition of CNC served two purposes of enhancing the piezoelectric crystallization of cellulose I as well as strengthening the membrane. The content of CNC in the membrane was optimized at 20 wt% which yielded the output voltage of 1.2 V upon application of a force of 5 N. More recently, synthetic polyvinylidene fluoride (PVDF)/CA composite fibre membranes were created using the electrospinning approach by Li et al. [99]. A flexible nanogenerator was created using the PVDF/CA electrospun fibre membranes (EFMs). Under mechanical stress of 2 N and frequency of 1 Hz, the PVDF/CA fibres (mass ratio of PVDF to CA=9:1) demonstrated an output voltage of 7.5 V and a short-circuit current of 2.1 μ A, which were 2.5 and 2 times higher compared to their pure PVDF counterparts [100].

3.3.4.7 Microwave absorption and EMI shielding

Radiofrequency interference is defined as an electromagnetic field-induced disturbance brought on by various electronic equipment. These interferences impair or even cease the functioning of electronic devices. High proliferation of electromagnetic interference (EMI) in civil and military applications demands the use of efficient microwave absorbers in electronic applications. These absorbers are required to have powerful absorption and a wide frequency band. Dielectric and magnetic loss remain the two principal pre-requisites of a microwave absorber. A microwave absorber works by attenuating the microwave that strikes the material, this wave loses energy due to conversion to heat. The energy loss relies on the frequency of the wave as well as the dielectric constant of the absorber. Dielectrics and microwave absorbers generally use non-biodegradable or toxic polymer matrices which are fragile and stiff, therefore they cannot be used for flexible

or portable electronic applications. This includes materials such as TiO_2 , BaTiO_3 and ZnO . Dielectric matrices based on nanocellulose are becoming increasingly promising in this regard. The polarization centres in nanocellulose result from defects in the nanocellulose filler matrix, consequently, the dielectric attributes of these nanocellulose blends are a measure of the micro capacitances created by these fillers functioning as electrodes [101]. The improvement in the dielectric response in case of these nanocellulose composites was reported due to the Maxwell-Wagner-Sillars effect, where the frequency-dependent contribution to the dielectric response came from build-up of charge. This build-up occurs at the electrode-filler interface on a macroscopic level and on the phase separation interfaces in the composite on microscopic level. In both cases, this interaction leading to a separation of charges, often over a considerable distance, leads to a significantly large contribution to dielectric loss. Pottathara et al. fabricated film like xerogels along with porous cryogels by making nanocomposites of CNF and reduced Graphene Oxide (rGO). The dielectric characteristics and the electrochemical storage of these gels were subsequently investigated, leading to an elevated dielectric constant of approximately 85 and 164 in case of dense and layered xerogel films respectively, which were composted of 5 wt% rGO. The temperature-dependent performance of these films was investigated between the temperatures 270 and 370 K at frequency of 1 MHz, suggesting their feasibility for dielectric applications at high temperatures [50]. Similarly, films prepared using barium titanate and CNF have exhibited dielectric constant of 188.03 and excellent absorbing characteristics [102].

The term EMI shielding describes the process by which a substance absorbs and/or reflects electromagnetic radiation, thereby the material acts as an electromagnetic shield. In order to interact with radiation, shielding material should have enough conducting carriers, such as electrons or holes. Reflection is the principal technique of EMI shielding. The charge carriers within the insulating material engage in electromagnetic field interactions with the radiation during reflection. Adsorption is another shielding method where the shielding material should possess magnetic or electric dipoles that engage with the radiation's electromagnetic field in order for this sort of mechanism to work. Materials with a high magnetic permeability, like Fe_3O_4 , can generate magnetic dipoles, whereas materials with a high dielectric constant, like BaTiO_3 , can generate electric dipoles. While the absorption loss depends on the product of these two characteristics, the reflection loss is determined by the ratio of electrical conductivity relative to copper and the relative magnetic permeability. A third category of mechanism consists of numerous reflections. Given that there are several reflections occurring, this is quite efficient. In order for this to occur, the material has to have an enhanced surface and boundary area in order to reflect radiation. The primary materials that exhibit this type of shielding are porous foams and aerogels. The phrase "EMI shielding effectiveness"

(EMI SE) refers to a material's capacity to minimize electromagnetic radiation. EMI SE is commonly expressed in decibels (dB). Investigators in the field of EMI shielding materials based on nanocellulose have produced some astounding outcomes. Among these is an array of feather-weight, flexible and exceptionally conductive CNF nanopapers that Gopakumar et al. produced using the process of in situ polymerization of aniline into CNF, with the goal of suppressing electromagnetic radiations in the X band and the fabricated nanopaper demonstrated shielding efficacy of -23 dB ($>99\%$) at 8.2 GHz [103]. Using a straightforward vacuum filtering method, Cao et al. created very thin, flexible MXene ($\text{Ti}_3\text{C}_2\text{T}_x$)/CNF composite paper having a lamellar structure. The binary strength and robustness of nanocomposite paper are optimized by the interaction between two-dimensional MXene and one-dimensional CNF. This resulted in a fracture strain of up to 16.7% and a tensile strength of around 135.4 MPa. With a thickness of 47 μm , the membrane also demonstrated good specific EMI shielding effectiveness of 2647 dBcm²/g and strong electrical conductivity of 739.4 S/m [104].

3.4 CONCLUSIONS

There are several ways to manufacture nanocellulose; the decision is controlled by multiple elements such as availability, cost and environmental effect, all of which have a considerable influence on the production costs of nanocellulose. Novel sources and techniques for producing nanocellulose are anticipated to be developed as investigation and innovation in NC-based technologies continue, hence increasing the potential uses of this material throughout time. In general, the potential of nanocellulose to provide high-performance, sustainable and improved products across a broad range of sectors is what gives it its worth. Other research, however, has pointed out a number of significant financial hurdles to the broad use of nanocellulose, such as expensive raw materials, energy-intensive manufacturing processes and the absence of developed markets for goods derived from nanocellulose.

Recently, flexible, wearable and sustainable energy devices have been developed in response to a growing need from practical and environmental perspectives. Because of its numerous special qualities, like its high strength, low density, transparency and a high aspect ratio, NC has shown to be a potential contender. Nanocellulose being biodegradable and biocompatible can pave a way for implementations in various electronic components and devices in order to manufacture sustainable electronic appliances. These devices are easily recycled and therefore may reduce the electronic waste produced. Conductive components can be used to create NC-based conductive materials, where NC is used as a substrate or as nanofiller in a matrix. Nevertheless, the problem of how to use a basic, affordable and environmentally friendly

process to evenly distribute the nanosized fillers throughout the matrix and make them homogeneous still has to be solved. The quantity and homogeneity of active components inside the NC matrix determine the conduction of the prepared amalgams. Applications for NC-based conductive materials are numerous in the field of energy devices, including solar cells, lithium-ion batteries (LIB) and supercapacitors. In short, because of their enhanced permeability, increased strength, sparse density and malleability, NC films are utilized as electrodes or separators in solar cells and energy storage devices. Furthermore, NC is used in LIBs as an electrolyte and binder. It is possible to make SCs and LIBs more affordable, wearable, adaptable and ecologically friendly with the inclusion of NC. Nevertheless, there is still room for improvement in the NC-based SCs' and LIBs' performances going forward. Nanocellulose offers the ability to create extremely thin, highly transparent sheets used in the manufacture of solar cells.

Despite substantial work, academic research on the investigation in terms of energy consumption of NC-based materials is still in its infancy. In actuality, the large-scale manufacturing of nanocellulose is still rather difficult and energy-intensive. One obstacle to implementing the production of nanopaper on traditional paper machines is the intense energy consumption to manufacture nanocellulose. Low-cost and low-energy NC materials are anticipated to become commercially available, which will increase interest in NCs in energy devices research. Implementation of nanocellulose-based technology is a research topic of great importance in view of sustainable progress in the field of electronics.

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Sustainable dielectric materials

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4.1 INTRODUCTION

In the ongoing era of advanced technology, the sustainable systems move the society towards the smart world [1–3]. The sustainable materials have a lot of advantages such as eco-sustainability, biodegradability, low cost, high performance, portability, bio-electric devices and stability etc., which has been required for technological developments of future generation [2–4]. However, the large area of technological growth was mostly covered by electronics materials and devices, which cause to develop several electronics wastage that, in turn, affects human health, society, environment and the entire eco-system very badly [3]. To address these challenges, various enthusiastic scientific work has been done in recent days by several researchers on edible and biodegradable systems, which is more suitable in manufacturing of flexible electronics devices and enhancing the degree of biodegradability and eco-friendliness [3–6]. On account of the unique features, edible and biodegradable devices (dielectric) can play a crucial role in several biomedical tasks and useful treatment tools. Shah and Tahir [7] announced that the dielectric properties of vegetable oils are the same as the hydrocarbon oils, which have higher oxygen content, higher flash point, high viscosity, higher breakdown voltage, low instability, minimal harmfulness, nontoxicity and ameliorate biodegradability [7]. Some inorganic laboratory-based sustainable dielectrics have been developed remembering its low-cost value, minimum toxic effect, biocompatibility and eco-friendliness [8–10]. Sustainable dielectric systems have become the greatest attention among the research community in the age of modern technology and scientific research evolution, not only due to their exciting utilization in several solid-state devices, such as optoelectronics devices, IR transmission, fibreoptics, memory sensors, holography, laser technology etc., but also due to academic engrossment in thermo-electrical and structural transport properties [3,11]. The present work is on such lab-based sustainable dielectric made by some inorganic constituents. It also exhibits localized state which may be accountable for their semiconducting and dielectric nature [12]. Owing to the existence of various oxidation states, the oxide glassy system doped with several transition metal

ions (TMIs) (Iron, Vanadium, Tungsten, Cobalt, Copper, Molybdenum etc.) have become the main focus of the materials science research community [13–17]. The well-known transition metal oxides (TMO) are TeO_2 , ZnO , P_2O_5 , V_2O_5 etc. The thermally activated phonon-assisted electrons hopping (small polaron hopping) from the lower valance state to the higher valence state of TMIs (like between V^{4+} and V^{5+} states) can explain the conduction behaviour of such system. The contribution of polaron hopping to the electrical conductivity was established successfully by Mott's work [18]. The polaron concentration is expected to appear due to the existence of oxide constituents in such system [17–19].

V_2O_5 is one of the effective TMOs, which has an expressive utilization in several solid-state devices [17]. Various microstructural observations [16–18] evidenced that the small amount of V_2O_5 was responsible for densely distributing crystallites [20]. The density can be estimated for the microstructural compactness reported by Laila et al. [21]. They also observed from previous studies [21] that lead vanadate glassy system exhibited relatively higher conduction, broad glass-forming nature (i.e. network former) and stability. T. Cun et al. [22] concluded that zinc oxide (ZnO)-based glassy semiconductor has been extensively explored and analysed by several researchers due to its outstanding electrical properties, which include cost-effectiveness, wide availability and nontoxicity [23,24]. Apart from that ZnO shows an extensive bandgap of 3.370 eV and possesses a high exciton binding energy of 60 MeV, which may permit the device to operate at much higher voltage, frequency and temperature than the conventional semiconductors [25]. Doping of ZnO to vanadate glassy system in the composition exhibits its role as an excellent modifier [26–28]. L. Aquino-Meneses et al. [29] successfully show the concentration-dependent phase transition from crystalline to amorphous in CdO -doped vanadate glassy system. In their observation [29], evidence suggested that a larger concentration of V_2O_5 produced crystalline phases. As the concentration of CdO became higher [29], it was expected to produce amorphous phases.

The iron-doped ZnO binary system's dielectric properties were investigated by R. Leheru et al. [30]. This study [30] revealed that different dielectric parameters such as dielectric constant (ϵ'), dielectric loss factor (ϵ'') and tangent of dielectric loss ($\tan\delta$) as well as AC conductivity all decreased as the concentration of Fe rose. The $\text{Zn}_{1-x}\text{Fe}_x\text{O}$ binary system [31] shows that conductivity, ϵ' , ϵ'' and $\tan\delta$ decrease with iron concentration. But unexpectedly, σ_{ac} is found to grow [31] with Fe concentration, which remarkably specifies the presence of various defect states and different hopping mechanism.

Research on dielectric relaxation mechanism in metal oxide glassy systems has received a lot of attention lately for a variety of applications [18]. When compared to rare earth oxides, these compounds have higher ionic conductivity because of their greater polarizability [19]. Dielectric studies can be used to understand the conductivity of such materials [32]. Their capacity to hold charges explains their insulating behaviour, whereas their

ability to transport electric charges explains their conductive behaviour [32]. AC conductivity measurements [32] can be used to describe defect states and the nature of metal oxide nanocomposites. Complex electric modulus (M^*) can be considered to be one of the most important qualities to interpret dielectric features [33].

In the analogy of viscoelastic relaxation of polymer electrolytes, McCrum et al. introduced the concept of electric modulus formalism in 1967 [34]. Later, Macedo et al. [35] utilized electric modulus formalism to explore electrical relaxation phenomena in various ionic conductors.

The literature review demonstrates that the applications of sustainable dielectrics such as edible and biodegradable dielectrics have positive impact on modern technology as well as entire ecology. Considering the issue of dielectric degradation like various health problems, environmental distortion due to the use of conventional dielectrics, nowadays most of the enthusiastic research has been done on ingestible, edible and biodegradable dielectrics. The present work has been performed on sustainable dielectrics with varying Fe doping concentrations. Various structural and electrical transport properties have been analysed. This investigation of the current system has been accomplished to establish it as an efficient dielectric better than conventional one and efficiency is as comparable as edible or biodegradable dielectrics.

4.2 EXPERIMENTAL PROCEDURE

Iron-doped (TMO) glassy system, $x\text{Fe}-(1-x)$ ($0.5 \text{ V}_2\text{O}_5-0.4 \text{ CdO}-0.1 \text{ ZnO}$), where $x = 0.0, 0.05, 0.1, 0.2$ and 0.3 , has been developed using well-known melt quenching technique. In this process, all required constituents, after weighting, have been mixed thoroughly in a mortar for homogeneity. This mixture is taken in an alumina crucible and then it is placed in a high-temperature electric furnace (Jay Crucible made) starting from 100°C with a step of 50°C for melting. The temperatures were increased up to 800°C for $x = 0$ and 0.05 , it was 850°C for $x = 0.1$ and 0.2 and for $x = 0.3$ the sample melted at 950°C . The melts of a few millimetre thicknesses and a few square centimetre surface area were obtained by pouring the melts onto a flat stainless steel block in an air medium and quenching it right away. The samples were painted with silver paste on both sides in order to create electrodes for measuring electrical and dielectric properties. To accumulate electrical and dielectric measurement data (C , G and $\tan\delta$) at various temperatures in the frequency range of $42 \text{ Hz}-5 \text{ MHz}$, HIOKI (model no. 3532-50) made LCR metre was utilized. They were the subject of X-ray diffraction (XRD) pattern collection (Rich-Seifert XRD 3000P). JASCO made ultraviolet-visible (UV-Vis) absorption spectrometer (model no: V630 spectrophotometer) was used to measure the difference in optical transmittance (% T) between the wavelength of light incident on the present TMO-doped semiconducting glass-nanocomposite materials.

4.3 RESULTS AND DISCUSSION

4.3.1 X-ray diffraction analysis

The X-ray diffractograms of the as-developed samples have been presented in Figure 4.1. Standard JCPDS dataset have been utilized to explore their polycrystalline nature. Size of the crystallites has been computed from Scherrer relation [36,37]:

$$D = k\lambda/\beta_d \cos \theta \quad (4.1)$$

where k is the shape factor (varies 0.8–1.39), D is the mean crystalline size, λ denotes the wavelength of X-ray (1.5406 Å), β_d represents the full width at half maximum (FWHM) and θ stands for Bragg's angle [38].

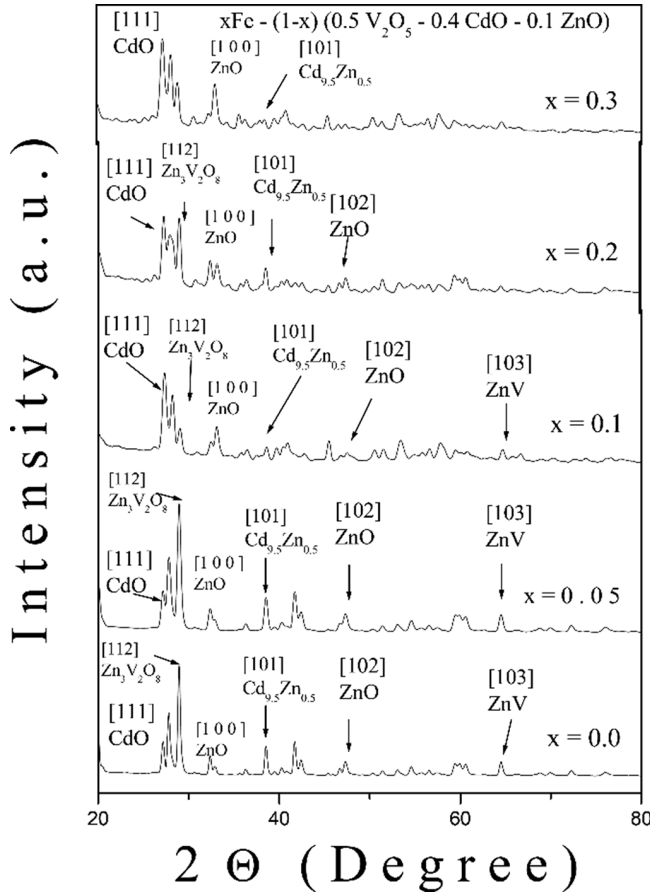


Figure 4.1 X-ray diffraction plots of system $x\text{Fe}-(1-x) (0.5 \text{ V}_2\text{O}_5 - 0.4 \text{ CdO} - 0.1 \text{ ZnO})$ where $x = 0, 0.05, 0.1, 0.2$ and 0.3 .

In the powder diffraction patterns, the presence of several diffraction peaks likes ZnO, CdO, $\text{Cd}_{9.5}\text{Zn}_{0.5}$, ZnV, $\text{Zn}_3\text{V}_2\text{O}_8$ etc. explores the formation of different nanocrystallites [39–43]. The similar observation for TMI (like Ni, Cu, Co, Mo and Mn etc.)-doped ZnO was reported by Ekambaram et al. [44]. The crystalline size is in the range of 14–25 nm given in Table 4.1. It is also observed that all the nanocrystallite sizes are found to decrease with Fe contents [44].

The dislocation density is determined using the relation [45]:

$$\delta = \frac{1}{D^2} \quad (4.2)$$

To explore about the crystal imperfection [46] lattice strain (ε) has been calculated using the form [46]:

$$\varepsilon = \frac{B}{4 \tan \theta} \quad (4.3)$$

where B denotes the peak breadth which may be due to micro-strain of nanoparticles and can be expressed as $B = 0.5 \beta_d \left(\frac{\pi}{\ln 2} \right)^{\frac{1}{2}}$ where β_d is FWHM [45,46]. The estimated values of strain increase with doping concentration of Fe which indicates more and more instability of the current system; that's expected to be favourable for better conductivity via polaron hopping process.

4.3.2 FT-IR spectra analysis

The Fourier transform infrared (FT-IR) spectra for all as-developed samples have been illustrated in Figure 4.2 in the frequency range of 4000–400 cm^{-1} . The absorption band near 860 cm^{-1} may be assigned as the characteristic vibration of Cd-O bonding [46,47]. The bands near 550–560 cm^{-1} can be caused due to the presence of Zn-O vibration [48].

The covalent Zn-O band's location gradually shifts from 600 to 700 cm^{-1} when the composition's Fe concentration rises from $x = 0.05$ to 0.20. Lower energy needed to cause the Zn-O band to vibrate should be correlated with a higher wave number in the sample with a higher Fe content. Our earlier work [45] makes it very evident that ZnO nanophases are involved in the acoustic phonon vibrations.

Table 4.1 Various parameters received from XRD study of system, $x\text{Fe}-(1-x)$ ($0.5\text{V}_2\text{O}_5-0.4\text{CdO}-0.1\text{ZnO}$) where $x = 0, 0.05, 0.1, 0.2$ and 0.3

X	Average crystallite size (nm)	Average dislocation density (nm^{-2})
0.0	24.6	0.00165
0.05	16.23	0.00379
0.1	15.18	0.00433
0.2	15.19	0.00442

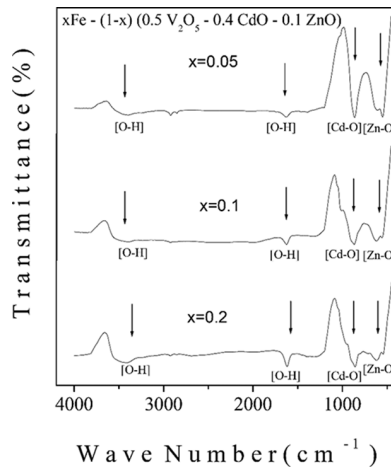


Figure 4.2 FT-IR spectra of $x\text{Fe}-(1-x) (0.5 \text{V}_2\text{O}_5-0.4 \text{CdO}-0.1 \text{ZnO})$ where $x = 0, 0.05, 0.1$ and 0.2 .

4.3.3 SEM and EDAX analysis

The features regarding surface morphology for $x = 0.0$ and 0.20 have been captured in scanning electron micrographs (SEMs), which are presented in Figures 4.3 and 4.4 respectively. The distribution of

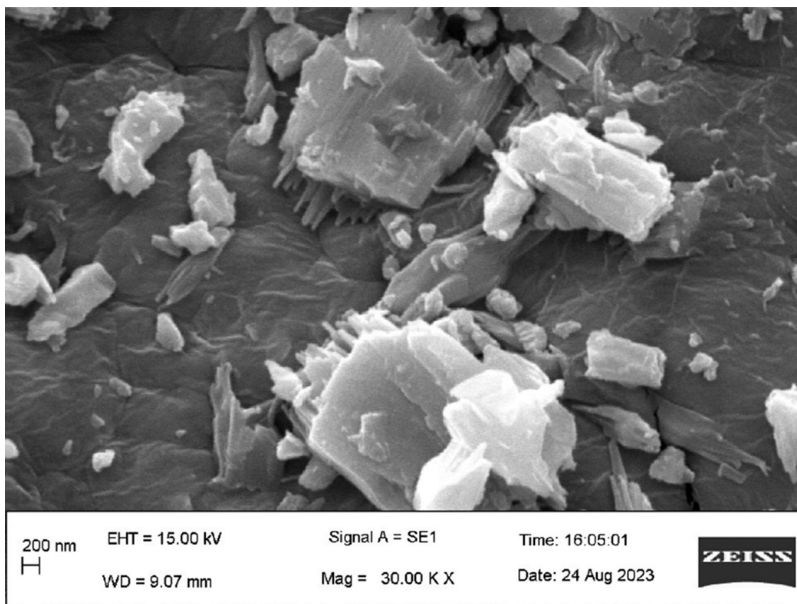


Figure 4.3 SEM scans for $x\text{Fe}-(1-x) (0.5 \text{V}_2\text{O}_5-0.4 \text{CdO}-0.1 \text{ZnO})$ system at $x = 0.05$.

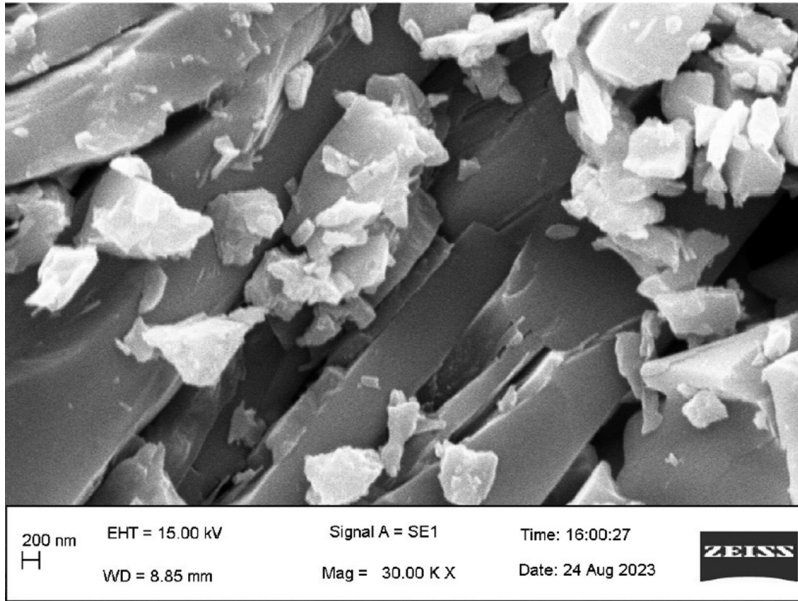


Figure 4.4 SEM scans for $x\text{Fe}-(1-x)$ ($0.5 \text{ V}_2\text{O}_5-0.4 \text{ CdO}-0.1 \text{ ZnO}$) system at $x = 0.20$.

spherical-shaped ZnO nanoparticles with the non-homogeneous size distributions are found in Figure 4.3 [49]. On the other hand, the rod-like ZnO structure [49] has been identified in Figure 4.3. With the inclusion of more and more Fe content in the compositions, the “heat of mixture” [50,51] in the compositions is expected to grow up. As a matter of fact, average particle size becomes broader and the boundaries between the neighbouring particles become distinct. In this regard, the agglomeration effect between the two or more nearest ZnO nanoparticles has been pronounced to form a larger one (rod-like ZnO structure) as evidenced from Figure 4.4.

The energy-dispersive analysis of X-rays (EDAX) depicts the presence of elemental compositions and a few representative patterns as shown in Figure 4.5.

4.3.4 UV-Vis spectra

Study of the system in a wide spectrum, the UV-Vis spectroscopy method has been used to find out the absorption of light intensity. The coefficient of absorption $\alpha(\nu)$ can be approximated as [52]:

$$\alpha(\nu) = \frac{1}{t} \ln \left(\frac{i_i}{i_t} \right) \quad (4.4)$$

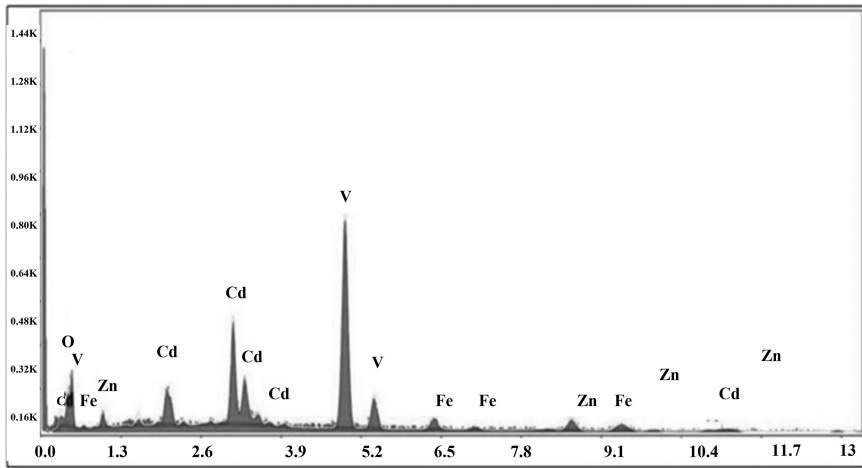


Figure 4.5 SEM scans for $x\text{Fe}-(1-x)$ ($0.5 \text{ V}_2\text{O}_5$ - 0.4 CdO - 0.1 ZnO) system at EDAX of $x = 0.05$.

where t indicates the thickness of the sample, i_i represents the intensity of incident light and i_t indicates the intensity of transmitted light. The optical band gap energy using Tauc's equation can be estimated as [53]:

$$h\nu = \left[A (h\nu - E_{\text{opt}}) \right] \quad (4.5)$$

where α represents the coefficient of absorption, $h\nu$ is the photon energy, E_{opt} represents optical band gap energy and A is a constant. The exponent γ has the numerical value of $1/2$, 2 , $3/2$ or 3 or more depending upon various transition mechanisms [54].

Evaluation of optical band gap energy in amorphous semiconductor has been depicted using Tauc's plot [53,54], shown in Figure 4.6 for the present system.

The calculated values of the optical energy band gap for as-prepared system are to be tabulated in Table 4.2. The nature of the current system in the range of E_{opt} indicates the indirect band gap-type semiconductor, which can be correlated with the conduction mechanism.

4.3.5 Electrical conductivity

When an electric field is applied, loosely bounded carriers of charge move synchronously, which causes a material's thermally activated electrical conductivity [55]. One of the key features of the material to be studied is its reaction to temperature and frequency, which is determined by the type of charged particles that drive the procedure of conduction, such as cations and anions or electrons and holes [56].

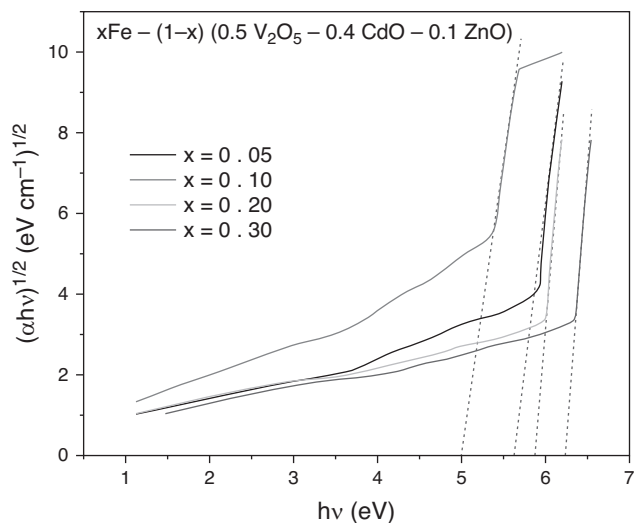


Figure 4.6 UV-Vis spectra of $x\text{Fe}-(1-x) (0.5 \text{ V}_2\text{O}_5-0.4 \text{ CdO}-0.1 \text{ ZnO})$ where $x = 0.05, 0.1$ and 0.2 .

Table 4.2 Optical band gap energy (E_{opt}) of system, $x\text{Fe}-(1-x) (0.5 \text{ V}_2\text{O}_5-0.4 \text{ CdO}-0.1 \text{ ZnO})$ for $x = 0.05, 0.10$ and 0.20

X	E_{opt} (eV) (± 0.10)
0.05	5.63
0.10	4.93
0.20	5.86

Estimated errors are also included.

The electrical DC conductivity of amorphous semiconductor has created a significant impact on the defect state density in the mobility gap [46]. The temperature-dependent DC conductivity of the as-prepared sample depicted in Figure 4.7 implies the thermally activated nature. The increasing nature of DC conductivity with temperature is confirmed by their semiconducting behaviour, as seen in Figure 4.7.

The common feature for all amorphous semiconductors is the dependency of electrical conductivity on frequency, which is used to determine AC conductivity by obeying Jonscher's power law [57] such as:

$$\sigma = \sigma_0' + A\omega^s \tag{4.6}$$

where σ_0' indicates the thermally activated nature of the conductivity near low-frequency regime (DC conductivity), s stands for the frequency exponent and A is the pre-factor that establishes the strength of polarizability.

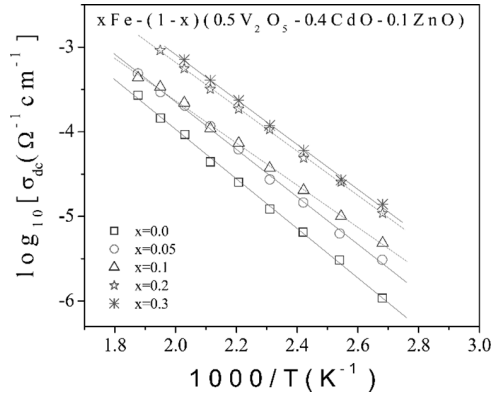


Figure 4.7 Variation of DC conductivity with temperature of system $\text{Fe}-(1-x) (0.5 \text{ V}_2\text{O}_5 - 0.4 \text{ CdO} - 0.1 \text{ ZnO})$ where $x = 0, 0.05, 0.1, 0.2$ and 0.3 .

The pure dispersive component of AC conductivity, denoted as $A\omega^s$, exhibits a power law characteristic with respect to angular frequency ω and exponent s ($0 \leq s \leq 1$), which should be regarded as the significant extent of interaction between polarons and the surrounding lattices. The conductivity spectra at various temperatures for $x = 0$ are presented in Figure 4.8.

As the frequency increases, the transition of AC conductivity above a critical frequency (ω_c) from a low-frequency plateau to a dispersive high-frequency region is observed from Figure 4.8. In a frame of feasible conduction channels, Papathanassiou et al.'s [58] modelling of electric charge flow under the influence of an external field shines most brightly. The distributions of potential energy determine the conduction path lengths [58].

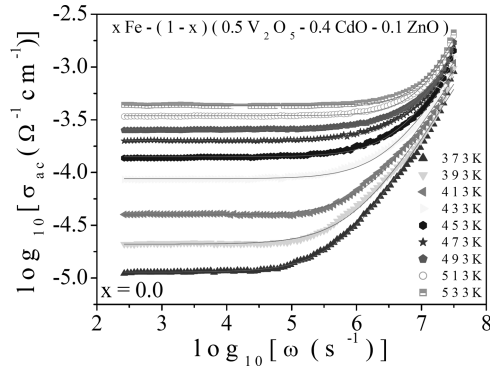


Figure 4.8 Conductivity spectra of $x\text{Fe}-(1-x) (0.5 \text{ V}_2\text{O}_5 - 0.4 \text{ CdO} - 0.1 \text{ ZnO})$, where $x = 0.0$ at different temperatures. Solid lines in plots indicate the fitting with Almond-West Formalism.

Figure 4.9 depicts the high-frequency region conductivity spectra at different temperatures (373 K–533 K) for $x = 0.0$, which implies the thermally activated nature. The slopes of linearly best fitted lines in Figure 4.9 provide the value of s . The similar fitted plot has been done for other values of x . Several conduction models have been efficiently implied by the different researchers such as quantum mechanical tunnelling model (QMT) [59], correlated barrier hopping (CBH) model [60], hopping over a barrier model (HOB) [46], non-overlapping small polaron tunnelling model (NSPT) [61] and many more [46].

S versus T for all values of x has been plotted and one of them ($x = 0.0$) is shown in Figure 4.10. In the present system, the values of S decrease with temperature for all values of x . S versus T plots for all x are properly fitted with modified CBH [60] model, which is expected to be effectively leading in conduction mechanism for the present system. It is noted that the concave and convex nature of S - T plots for the present system indicates the lattice distortions over an extended lattice site and hopping of large polaron inside the system respectively.

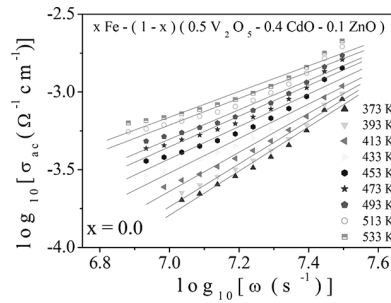


Figure 4.9 High-frequency conductivity spectra of respective system at $x = 0.0$. Solid lines indicate best-fitted straight lines, slopes indicate S .

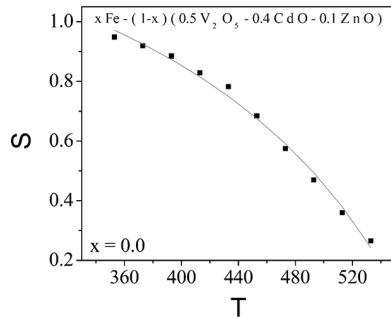


Figure 4.10 S versus T plots of that system at $x = 0.0$. Solid lines in the plots indicate the fitting with CBH model (modified).

According to the CBH model, the frequency exponent factor S can be presented as [60,62]:

$$S = 1 - \frac{6K_B T}{(Wm + K_B T \times \ln(\omega\tau_0))} \quad (4.7)$$

where T is the absolute temperature, Wm is the maximum barrier height, K_B denotes the Boltzmann constant and τ_0 denotes relaxation time [46,62]. The appropriately fitted model for present system has been slightly modified as [19,46,62]:

$$S = 1 - \frac{6K_B (T - T_0)}{(Wm + K_B (T - T_0) \times \ln(\omega\tau_0))} \quad (4.8)$$

where T_0 expresses the dimension of temperature defined as a glass transition temperature and T denotes operating temperature [19,46,62].

4.3.6 Dielectric relaxation

The investigation of the changes in frequency-dependent dielectric characteristics of materials at varying temperatures is of great interest as it offers vivid details about compound structures, grain boundaries and the materials' electrical energy storage capacity, among other things [34,63]. Dielectric materials act typically like insulators since they don't have any loosely bound charges that may drift through them. However, when an electric field is applied, they can become polarized (dielectric polarization) and exhibit conduction nature [64–67]. Thus, the two main electrical behaviour characteristics of dielectric materials are conduction and insulating behaviour. The movements of weakly bound charge carriers, such as expelled electrons or positive ion cores, are the primary cause of the dielectric characteristics of glassy conductors. In the iron-doped V_2O_5 -CdO-ZnO glassy system, the temperature and frequency-dependent dielectric constant (ϵ') has been studied. The frequency-dependent variation of ϵ' at various temperatures is shown in Figure 4.11, which makes it quite evident that ϵ' drops as frequencies increase in the low-frequency zone. ϵ' exhibits a flat character at higher frequencies, meaning that it is more prominent at lower frequencies. Additionally, it's observed that when temperature rises, it's going to increase.

In the low-frequency range, the variation of $\epsilon'(\omega)$ with temperature is greater. In polar material, the molecular dipoles in dielectric at low temperatures are unable to align themselves. The orientation of dipole is facilitated by increasing temperature of the as-prepared sample, leading to a high dielectric constant (ϵ'). At low frequency, the dielectric constant ϵ' gives a high value, due to high dipole ordering inside the material, the dipoles align along the direction of electric field and fully contribute to the electric polarization effect. Molecular dipoles' contribution to polarization

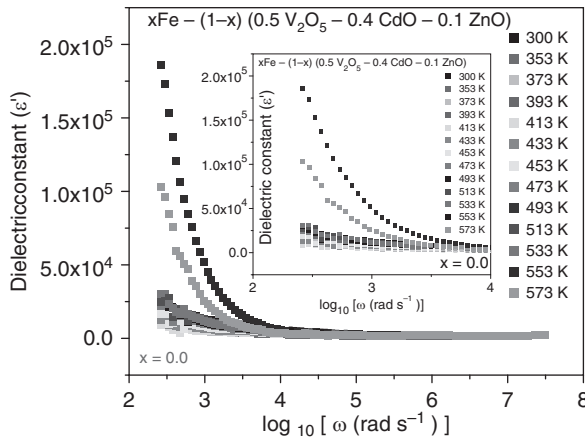


Figure 4.11 Dielectric constant frequency-dependent response of system $x\text{Fe}-(1-x) (0.5 \text{V}_2\text{O}_5 - 0.4 \text{CdO} - 0.1 \text{ZnO})$ where $x = 0.0$.

reduces as frequency increases because they can follow the electric field's fluctuation more quickly [68]. ϵ'' defines the dielectric loss factor as the loss of energy within the specimen which appears due to the phase difference at a particular frequency and is represented using the relation [68] $\tan \delta$ (tangential loss) $= \frac{\epsilon''}{\epsilon'}$. Figure 4.12 describes the frequency-dependent dielectric loss (ϵ'') of iron-doped V_2O_5 -CdO-ZnO oxide glassy system at various temperatures, which shows similar nature of $\epsilon'(\omega)$ as presented in Figure 4.11. To get the distinct nature of ϵ' and ϵ'' in the low-frequency regions, both the spectra are presented in the inset of Figures 4.11 and 4.12 respectively.

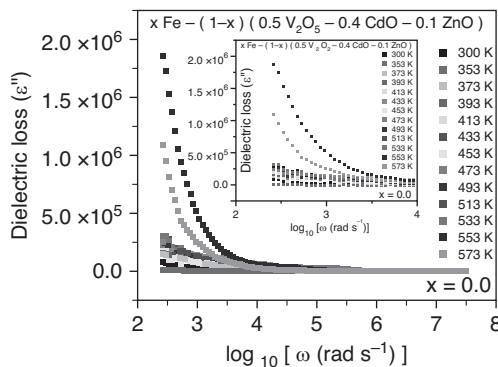


Figure 4.12 Dielectric loss frequency-dependent response of system $x\text{Fe}-(1-x) (0.5 \text{V}_2\text{O}_5 - 0.4 \text{CdO} - 0.1 \text{ZnO})$ where $x = 0.0$.

Thermally triggered relaxation of freely rotating dipoles causes dielectric loss. The loss is also anticipated as a result of electrical conduction at high temperatures brought on by hopping ions. The fluctuation of modulus with compositions (x) at particular temperature ($T = 413$ K) is depicted in Figure 4.13. The quality factor $Q = \frac{1}{\tan \delta}$ is plotted as a function of $\log(\omega)$ in Figure 4.14, which clearly indicates that the Q -factor increases with frequency. Similar nature is found for other as-developed samples.

At higher frequencies, it is discovered that both the Q -factor and electrical conductivity are high. The as-prepared glassy system is of good quality, as indicated by the lower dielectric loss values [69]. Furthermore, in order to expand the range of materials appropriate for use in photonics and electro-optics, low values of the dielectric constant at high frequencies are crucial [69].

As per Volger's proposition [70], conduction losses, deformational losses and losses from the mobility of ions or free charges can be expected to be the collective reason for dielectric loss. The hopping of charge carriers over

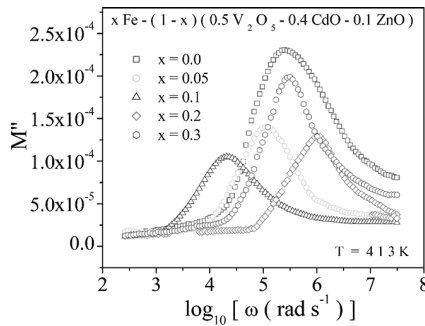


Figure 4.13 Frequency-dependent response of Modulus (M'') spectra of the system of $x\text{Fe}-(1-x)(0.5 \text{V}_2\text{O}_5-0.4 \text{CdO}-0.1 \text{ZnO})$ at 413 K.

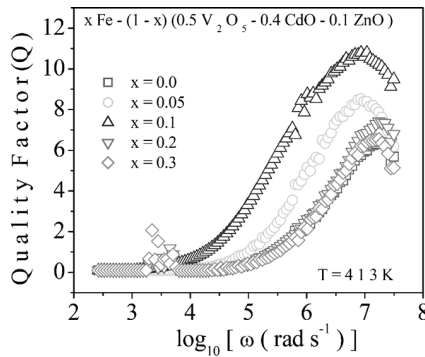


Figure 4.14 Frequency-dependent response of Quality factor (Q) of the system of $x\text{Fe}-(1-x)(0.5 \text{V}_2\text{O}_5-0.4 \text{CdO}-0.1 \text{ZnO})$ at 413 K.

lower potential barriers can be regarded as outcomes of the mobility of charge carriers over long distances. This procedure clarifies that the structural network shared the thermal energy of some weakly bound charges or ions, and consequently the energy losses in a cycle are proportionate to the AC conductivity as [71,72]:

$$\sigma_{ac} = \epsilon_0 \omega \epsilon'' \quad (4.9)$$

The dielectric loss ϵ'' exhibits a small value at lower temperatures, while the conduction loss frequency can be interpreted as follows: at low frequencies, higher values of ϵ'' can be found due to emigration of ions throughout the medium. The hopping of ions or ejected electrons may cause the mobilization of charge carriers and consequently the losses due to polarization may be pronounced in terms of decrement of ϵ'' with frequency. The oscillatory motion of charge carriers could be expected to be a valid source of dielectric loss at higher frequencies [73].

4.3.7 Electric modulus

Electric modulus (M^*) has been introduced as a matter of fact that it may be presented as the inverse of complex dielectric permittivity (ϵ_r^*) [34,35,74]. It should provide valuable information regarding dielectric polarization and charge transport properties of the electrolytes [35]. The idea of complex electric modulus [75] has been placed to analyse the electrical response of the present system by reducing polarization effect. The expressions of relative permittivity and complex electric modulus have been brought into consideration in mathematical form as [35,74]:

$$\begin{aligned} M^*(\omega) &= \frac{1}{\epsilon_r^*(\omega)} = \frac{1}{\epsilon' - j\epsilon''} = \frac{\epsilon'}{\epsilon'^2 + \epsilon''^2} + j \frac{\epsilon''}{\epsilon'^2 + \epsilon''^2} = M' + jM'' \\ &= M_\infty \left[1 - \int_0^\infty \exp(i\omega t) (-d\Phi/dt) \right] \end{aligned} \quad (4.10)$$

$$\text{where, electrical permittivity} \quad \epsilon_r^*(\omega) = \epsilon'(\omega) - j\epsilon''(\omega) \quad (4.11)$$

Here, M' is the real electric modulus, M'' is the imaginary electric modulus and ω is the angular frequency, $j = \sqrt{-1}$, ϵ' and ϵ'' are real permittivity and dielectric loss factor respectively.

Frequency-dependent modulus (M'') spectra at different temperatures for a specific sample $x = 0.0$ have been depicted in Figure 4.15. It is noticed from Figure 4.15 that at lower frequency, M'' is found to be nearly zero and increased gradually with increasing frequency and exhibited a single relaxation peak at

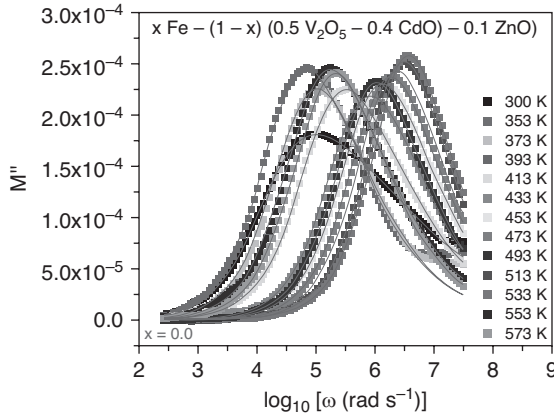


Figure 4.15 Variations of M'' with temperature of system $x\text{Fe}-(1-x) (0.5 \text{ V}_2\text{O}_5-0.4 \text{ CdO}-0.1 \text{ ZnO})$ where $x = 0.0$.

a certain frequency and after that it's going to decrease. The electrical conductivity data analysis is performed using the Dielectric Modulus Formalism. The extremely low value of $M''(\omega)$ in Figure 4.15 at low frequencies indicates that the electrode polarization effect has a minimal impact on $M^*(\omega)$ [76]. Figure 4.15 illustrates how, as temperature increases, the peak in the $M''(\omega)$ shifts to higher frequencies and the peaks in the corresponding spectra occur at different frequencies. This observation further suggests that the relaxation involves the localized motion of charge carriers and exhibits non-Debye-type behaviour [74]. The range in which charge carriers are spatially restricted to potential wells is found below $M''_{\max}$. The presence of a distribution and the shift from long-range to short-range mobility of polaron assembly are suggested by the asymmetric peak in the M'' spectra.

The frequency (ω_0) corresponding to $M''_{\max}$ can be related as $\omega_0 \tau_c = 1$ where the most likely relaxation time, shown by τ_c , indicates a drop in frequency and a transition from short-range to long-range mobility. The representative plot of the reciprocal of temperature with the conductivity relaxation time (τ_c) is shown in Figure 4.16. This plot follows the Arrhenius relation, $\tau_c = \tau_0 e^{\left(\frac{E_r}{kT}\right)}$, where τ_0 is the frequency factor and E_r represents the activation energy for conductivity relaxation [34,77,78]. The activation energies are evaluated in the two distinct temperature zones (E_{r1} for high temperature and E_{r2} for low temperature) using a least square fit of τ_c versus $\left(\frac{1000}{T}\right)$ plot demonstrated in Figure 4.16.

The activation energies corresponding to conductivity relaxation are presented in Table 4.3. This result highlights the issues on how the phonon-phonon assisted hopping of polarons takes place during relaxation to

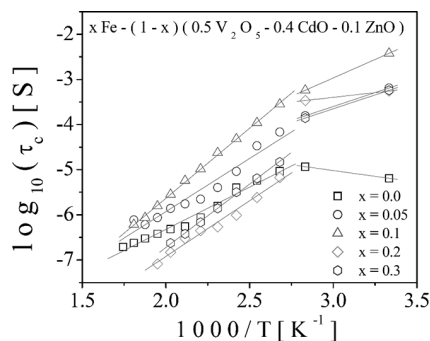


Figure 4.16 $\text{Log}_{10}(\tau_c)$ versus $1000/T$ plot of system $x\text{Fe}-(1-x)(0.5 \text{ V}_2\text{O}_5-0.4 \text{ CdO}-0.1 \text{ ZnO})$ for various compositions where $x = 0, 0.05, 0.10, 0.20$ and 0.30 .

Table 4.3 Activation energy corresponding to relaxation time and β_{ave} of system, $x\text{Fe}-(1-x)(0.5 \text{ V}_2\text{O}_5-0.4 \text{ CdO}-0.1 \text{ ZnO})$ where $x = 0, 0.05, 0.10, 0.20$ and 0.30

Composition (x)	E_{τ_1} (eV)	E_{τ_2} (eV)	β_{ave}	Q -value at 5 KHz (413 K)
0.0	0.370605	-0.1016	0.570307	1.13E+00
0.05	0.465423	0.243746	0.98838	2.45E+00
0.1	0.613889	0.324532	0.990655	5.85E+00
0.2	0.488161	0.082598	0.981483	1.19E+00
0.3	0.555639	0.243192	0.880645	1.02E+00

Estimated errors for β_{ave} are also included.

overcome the barrier height as per composition dependency in the high temperature. However, at the time of relaxation, the polarons must hop with the help of photons to get over the barrier height in the low temperature. Thus, from an application perspective as well as an academic interest, the relaxation processes in two different temperature zones are highly interesting.

Figure 4.16 reveals that the relaxation time (τ_c) is in decreasing nature with increasing temperature, which may indicate that the charge carriers move faster [68] with temperature. This characteristic feature should be associated with temperature-dependent relaxation time and hopping of charge carriers [69,79]. The variation of activation energy may be indicative factors for thermally activated nature of dielectric relaxation process of the present system [80]. The relaxation time (τ_c) with composition (x) for a particular temperature $T = 413 \text{ K}$ is illustrated in Figure 4.17. Several works of others researcher [13,24] have been included for comparison in Figure 4.17.

The activation energy corresponding to relaxation time has been shown in Figure 4.18. Here, similar results of others' work [13,24] have also been included in Figure 4.18 for comparison. Figure 4.17 reveals that the present

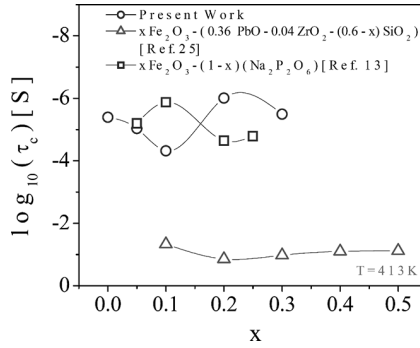


Figure 4.17 $\text{Log}_{10}(\tau_c)$ compositions (x)-dependent response of system $x\text{Fe}-(1-x)$ (0.5 V_2O_5 -0.4 CdO -0.1 ZnO). Comparison with others is also included.

system exhibits very small relaxation times in comparison with others' works [13,24]. The hopping of polaron assembly into a neighbouring void space and pass over a saddle point position is expected to happen in order to lose polarization energy. The dipole relaxation is sluggish as it involves the movement of polaron assembly as well as positions readjustment [51].

Almond-West Formalism [28] has been widely used to interpret the AC conductivity data [81]:

$$\sigma(\omega) = \sigma_{dc} \left[1 + (\omega / \omega_H)^n \right] \quad (4.12)$$

where ω_H represents the hopping or cross-over frequency, n indicates power law exponent and σ_{dc} can be considered as the conductivity at low frequency. The AC conductivity data were best fitted using Equation (4.12) to get the parameters ω_H , n and σ_{dc} .

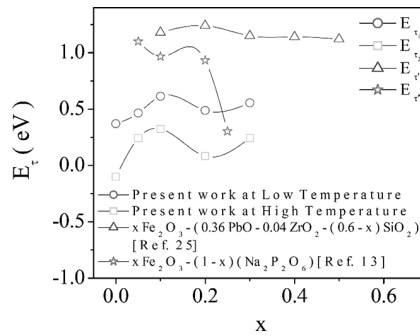


Figure 4.18 Relaxation energy (E_t) compositions (x)-dependent response of system $x\text{Fe}-(1-x)$ (0.5 V_2O_5 -0.4 CdO -0.1 ZnO). Comparisons with others are also included.

Additionally, all as-prepared samples have large values of exponent n , the constituent's dependency of power exponent n can be connected to the collective influence of the relaxation path allocation and on the structural mechanisms, such as the type of disorderliness and interaction degree [74]. n values that depend on composition are plotted in Figure 4.19. In the present system, percolated-type motion [74] of charge carriers is clearly shown by estimated n values (>1). As shown by Figure 4.19, the small relaxation times justify this percolated-type motion. A decreased rate of successful jumps could be the cause of higher values of n , which would ultimately lead to fluctuating high DC conductivity [29]. By deforming the electronic cloud, dielectric results from the predominance of polarization and the uncorrelated motions of electrons and polarons [28] can be used to establish their percolated-type motions up to an extent as evidenced from Figure 4.19.

One of the key methods for investigating a material's dielectric characteristics is relaxation dynamics [74,82]. In general, there are two forms of relaxation: non-Debye type and Debye type [82]. In an ideal situation (Debye-type relaxation), all freely rotating dipoles have been aligned towards an applied electric field and they could have been returned to the previous state after the applied field being withdrawn, exhibiting a single polaron relaxation. In such situation, stretched exponent factor or KWW is roughly equal to 1 [74,82,83]. On the other hand, non-Debye-type relaxation should involve the alignment of freely moving dipoles in the direction of the applied field, but not before all the dipoles are being returned even after the external field is withdrawn [83,84]. In such situation, β has a value of $0 \leq \beta < 1$. Keeping in mind the simplified version of KWW function [74,82,83]:

$$\Phi(t) = \Phi_0 \exp\left[-(t/\tau)^\beta\right] \quad (4.13)$$

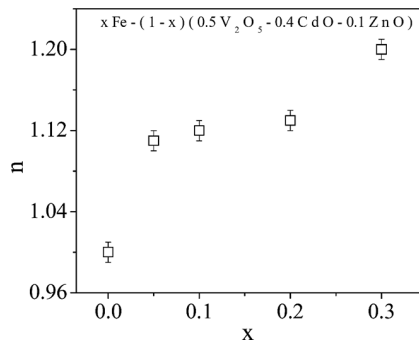


Figure 4.19 Plots of n (from conductivity power law) as a function of composition (x) of system $x\text{Fe}-(1-x)(0.5\text{V}_2\text{O}_5-0.4\text{CdO}-0.1\text{ZnO})$.

The corresponding FWHM of $M''(\omega)$ can be used to estimate β values [74,82,83]:

$$\beta = 1.14 / \text{FWHM} \quad (4.14)$$

The fluctuation of stretched exponent β as a function of compositions is displayed in Figure 4.20. Remarkably, Figure 4.20 shows that β has a low value for the Fe-undoped sample and increases gradually with Fe doping. Up to $x = 0.2$, β values exhibit nearly constant values as the Fe content enhances. For $x = 0.3$, β values are found to be slightly gone down. This result is directly used to conclude that in the final as-developed material, doped with more Fe, the relaxation process changes from non-Debye type to Debye type [82–85], or from an unstable to almost stable state. When the composition is further doped with more Fe, the relaxation process shifts back towards non-Debye type, but at a very slow rate.

Decoupling index [86] has also been introduced as a term to help understand the charge carrier relaxation mechanism in the current system. To get more insight about conductivity relaxation, the decoupling index [45,46] has been estimated. The decoupling index [45,46,86–88], $R_r(Tg)$, can be presented numerically as the ratio of the average structural relaxation time, $\tau_s(Tg)$, to the average conductivity relaxation time $\tau_c(Tg)$ at the glass transition temperature, Tg . $R_r(Tg)$ may be employed to explore the movements of assembly of charge carriers up to which extent in the glassy network of the materials, i.e. how much, the ejected electrons/polarons are coupled [87]. The value of $\tau_c(Tg)$ has been estimated by extrapolating the plots of Figure 4.15 at Tg . Assumption has been made to consider structural relaxation as $\tau_s(Tg) = 200$ [45]. The estimated values of $R_r(Tg)$ with composition are presented in Figure 4.21. It is significantly noted that with the initial doping of Fe content in the compositions, the decoupling index shows a decrement as evident from

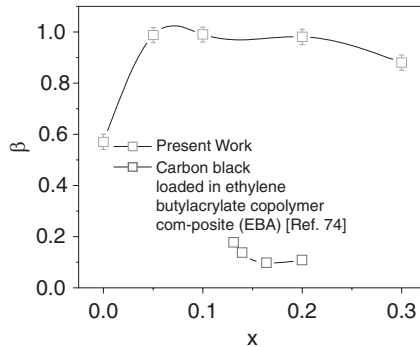


Figure 4.20 Plots of β (stretched exponent factor or KWW) as a function of composition (x) of system $x\text{Fe}-(1-x)$ ($0.5 \text{ V}_2\text{O}_5-0.4 \text{ CdO}-0.1 \text{ ZnO}$).

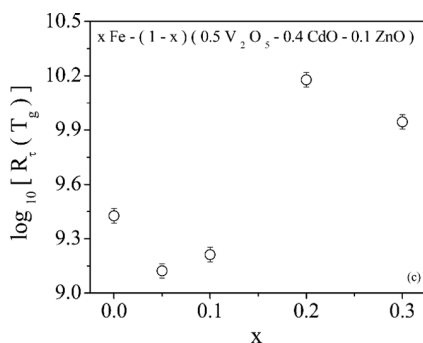


Figure 4.21 Plots of $\log_{10}[R_{\tau}(T_g)]$ as a function of composition (x) of system $x\text{Fe}-(1-x)(0.5\text{V}_2\text{O}_5-0.4\text{CdO}-0.1\text{ZnO})$.

Figure 4.21. Further increasing doping of Fe element in the compositions, $R_{\tau}(T_g)$ values are found to increase significantly up to $x = 0.20$ and then it is discovered to somewhat decline once more. It may be concluded from this result that the ejected charge carriers are predicted to be coupled more and more with the ion core during the initial stages of the Fe constituent doping. However, as the Fe content increases, they are found more and more decoupled from the viscous motion of glassy matrices [86,87] as evident from Figure 4.21. Additionally, it has been noted that a rising decoupling index denotes volume expansion in terms of free movement of charge carriers. As a consequence, the relaxation time reduces and electrical conductivity rises. The volume expansion with Fe content also points to an increase in electron-ion core, which should be linked to an improvement in polarization in terms of increment of capacitance values. Percolated motion of charge carriers is expected to fit for such high-capacitive glassy system [74].

According to a physical interpretation, the electric modulus represents the system's electric displacement at constant while the electric field is relaxing [31]. The amazing formalism for studying the relaxation process is electric modulus [31]. The range at which charge carriers are spatially restricted to potential wells is found below $M''_{\max}$. An asymmetric peak in the M'' spectra indicates that there is a distribution in the relaxation durations and that ions are moving from their long-range to their short-range mobility [63].

4.3.8 Edible, biodegradable dielectrics and integration with electronic devices

Owing to electromechanical and operational stability, low-cost effectiveness, low toxic effect and eco-friendliness, the edible, ingestible and biodegradable composite of nature becomes excellent dielectric candidates for flexible electronic devices among several researchers [2,3].

Various literature review demonstrated that such dielectrics have a lot of positive impact on the efficiency of modern electric devices as well as on the entire environment [3]. Konwar et al. [3] performed experiment for fabrication of flexible transistor using gelatin/chitosan dielectric constituents with ratio variations as 10:0, 10:1, 10: 5, 10:10 for tuning the dielectric capability. It was found that the edible gate device (with composition ratio 10:5) persists with an extensive level of bias-stress stability after imposing huge tensile force, and the stability is notably higher than pristine, which can be admirable candidates for future edible electronics [3]. Experimental investigations were carried out by Ishfaq et al. [2] to estimate the potential of biodegradable dielectrics (such as sunflower oil, olive oil, mustard oil, amla oil and coconut oil) at different C_p of Cu for sustainable machining. The findings of these study reveal that the economic assessment EWR ($2.69 \text{ mm}^3/\text{min}$) was decreased as well as the dimensional accuracy, i.e. over cut (0.33 mm), has been minimal; as a result, the powder mixed electric discharge machining (PM-EDM) with biodegradable dielectric assists to achieving more sustainable and dimensionally accurate machining [3]. Pucher et al. [8] reported that, albumen dielectrics combined with single-layer MoS_2 can be applicable as a bio-compatible device FET with semiconducting van der Waals materials. It was confirmed that the dielectric constant ($\epsilon_r = 11.2 \pm 1.9$) is higher than traditional SiO_2 -dielectric-based devices and the mobility value up to $\sim 90 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ raises several advantages introducing a new platform for biodegradable 2D applications [8].

4.4 CONCLUSIONS

Fe-doped-CdO-ZnO glassy dielectric systems have been developed and their electrical and dielectric properties have been explored extensively in terms of hopping of small polarons. Microstructure of the as-developed system has been revealed in terms of identifying various nanophases such as ZnO, CdO, $\text{Cd}_{9.5} \text{ Zn}_{0.5}$, ZnV, $\text{Zn}_3 \text{ V}_2 \text{ O}_8$. The electric modulus represents the system's electric displacement at a constant rate while the electric field is relaxing. The range in which charge carriers are spatially restricted to potential well is found below M''_{max} . An asymmetric peak in the M'' spectra indicates that there is a distribution in the relaxation durations and that ions are moving from their long-range to their short-range mobility. Owing to the electromechanical and operational stability, low-cost effectiveness, low toxic effect and eco-friendliness, the edible, ingestible and biodegradable composite of nature becomes excellent dielectric candidates for flexible electronic devices.

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Sustainable solar cells

Himanshu A. Patil and Aarti P. More

5.1 INTRODUCTION TO SOLAR ENERGY

Solar energy is a wonderful and increasingly important aspect of the modern world that serves as a source of renewable and sustainable electricity [1]. Attention to solar energy has increased due to rising energy consumption and growing environmental damage concerns [2]. Solar energy is one of the cleanest sources because it is environmentally benign and does not contribute to global warming. It takes the place of coal and oil [3]. This energy source captures the sun's heat and radiant light emissions and transforms them into heat or electricity for various uses. The sun emits electromagnetic radiation, which is the form of solar energy. With mechanical equipment, this electromagnetic radiation is transformed into useful thermal or electric power [4]. It supplies energy for photovoltaic (PV) water heaters, air conditioning, cooling, and solar household systems (including power for lights, TVs, washing machines, and other appliances) [5].

Solar cells, also known as PV cells, are a widely used method to harness solar energy [6]. These cells use the PV effect to turn sunlight into energy directly; they are usually made of semiconductor materials. When sunlight touches them, these cells release electrons from their atoms, creating an electric current [7]. Over time, solar energy has become a more competitive and feasible choice in the global energy landscape because of the enormous improvements in solar cell efficiency [8]. Solar thermal technologies and PV systems use the sun's energy to produce heat for various uses [9]. For example, concentrated solar power (CSP) systems direct sunlight into a tiny area, producing tremendous heat that may be used to drive turbines to generate electricity and manufacture steam. This technique can produce steady, dependable electricity and works especially well in areas with much sunshine [10,11].

5.2 IMPORTANCE OF SUSTAINABLE ENERGY SOURCES

The investigation of solar energy originates in prehistoric societies that used crude technology to harvest sunlight for warmth [12]. Our ability to harness the enormous potential of solar energy has grown throughout the ages, along with our grasp of science and technology [13]. The modern era's need for sustainable energy sources has led to an unparalleled upsurge in solar energy research, development, and application [14]. Solar thermal technologies, solar PV systems, and various cutting-edge applications exemplify how this surge has materialized [15]. The main goal is to mitigate the negative effects of climate change while reducing our reliance on fossil fuels, which are limited and costly for the environment [16]. The main attraction of solar energy is its accessibility. The sun is a ubiquitous celestial body that emits energy throughout the electromagnetic spectrum [17]. In contrast to limited resources such as coal, oil, and natural gas, solar energy has virtually infinite potential [18]. It is a globally available resource that transcends geopolitical boundaries and offers the possibility of achieving energy independence for all countries [19].

One strong argument for solar energy's broad use is its environmental advantages. When solar energy systems are in use, they have less of an impact on the environment than fossil fuels, which discharge dangerous pollutants and greenhouse gases [20]. Reducing greenhouse gas emissions agrees with international efforts to tackle climate change and move toward an energy infrastructure that is more robust and sustainable [21].

There are still issues, even with the amazing advancements in solar energy technology and usage. Because sunlight is sporadic and solar energy output depends on the weather and availability of daylight, energy storage is still a major problem [22]. Overcoming these obstacles and guaranteeing a steady and dependable energy supply require advancements in energy storage technology, such as high-capacity batteries [23]. Another difficulty is integrating solar energy into current electricity systems. Smart grid technology and efficient energy management methods are necessary to balance supply and demand due to the fluctuation of solar power output [24].

5.3 SOLAR CELLS

Solar cells, sometimes called PV cells, use the PV effect to convert sunlight into electricity [25]. The fundamental idea underlying solar cells is that certain materials, usually silicon-based ones, can produce an electric current when exposed to sunlight [26]. An electric field is produced by the semiconductor materials that make up these cells, which have positive and negative layers [27]. Photons from sunlight impact the solar cell and excite the material's electrons, causing them to break loose and produce an electric current. The electrical energy produced can subsequently be used for various purposes, such as supplying the electrical grid with energy for wider usage

or powering tiny electronic gadgets [28]. There are several types of solar cells, such as thin-film, polycrystalline, and monocrystalline solar cells. Each type has pros and cons related to production costs, efficiency, and other factors. The growing awareness of environmental issues and technological improvements that result in lower costs and increased efficiency has fueled the widespread adoption of solar cells [29].

5.3.1 Role of solar cells in harnessing sunlight

Through the PV effect, solar cells are essential for capturing sunlight and transforming it into useful electricity. Using the characteristics of semiconductors, PV cells, also called solar cells, are devices that directly produce electricity from sunlight [30]. An electric current is produced when photons from sunlight hit a solar cell's surface because they excite the electrons in the semiconductor material [31]. Without fuel or moving parts, this technique makes it possible to convert sunlight directly into electricity, which is essential for producing clean and sustainable energy [32]. In the larger scheme of renewable energy, solar cells play a critical role in reducing reliance on fossil fuels and mitigating climate change [33]. Solar cells play an even more important role in creating a greener and more sustainable energy landscape as the demand for clean energy rises. Their capacity to absorb solar radiation and transform it into electrical power lowers carbon emissions and helps create a decentralized and robust energy system [34]. Solar energy development as a common power source depends on solar cells, which offer a dependable and clean way to fulfill the world's growing energy needs [35].

5.3.2 Types of solar cells

PV cells, sometimes called solar cells, use sunlight to generate energy. There are various varieties of solar cells, each of which has unique qualities, benefits, and drawbacks. Here is a list.

5.3.2.1 Crystalline silicon solar cells

Crystalline silicon is the primary component used in approximately 90% of solar cells manufactured worldwide and is crucial to the PV industry. Monocrystalline and polycrystalline crystalline silicon solar cells are currently on the market. A crystalline solid whose crystal lattice is continuous and unbroken up to the borders is called monocrystalline silicon. A polycrystalline silicon, or polysilicon, comprises several tiny monocrystalline grains jumbled together in arbitrary orientations. Polycrystalline contains distinct, random grains that are discernible to the human eye, whereas monocrystalline has a single, uniform color. Because of fewer flaws and a longer recombination time for charge carriers, monocrystalline silicon solar cells are more efficient than polycrystalline solar cells. Figure 5.1 represents the structure of a crystalline silicon solar cell [36].

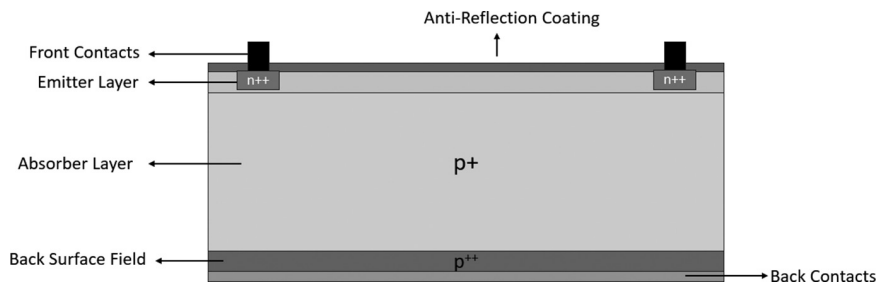


Figure 5.1 Structure of a crystalline silicon solar cell [36].

5.3.2.2 Thin-film solar cells

Thin-film solar cells are a broad class of solar cells distinguished by their adaptability and versatility. They are lightweight, flexible, and simple to integrate onto various surfaces because they use thin semiconductor layers. This group includes amorphous silicon (a-Si) cells, which are highly flexible due to their non-crystalline structure, making them ideal for applications requiring bendable solar panels. Because of their affordability, cadmium telluride (CdTe) thin-film solar cells are preferred for large-scale solar installations. Copper indium gallium selenide (CIGS) cells are an alternative that is valued for their effectiveness and ability to be integrated into flexible substrates [37–40]. Figure 5.2 represents the cross-sectional view of a CdS/CdTe thin-film solar cell [41].

5.3.2.3 Organic solar cells

Organic photovoltaic devices (OPVs) based on organic photoactive materials are used to convert solar energy into electrical power. OPVs are constructed with tiny molecules, thin polymer films, or both by low-cost spin coating, spray deposition, and printing techniques. Because of the typical solubility of organic semiconducting elements in organic solvents, liquid inks can be

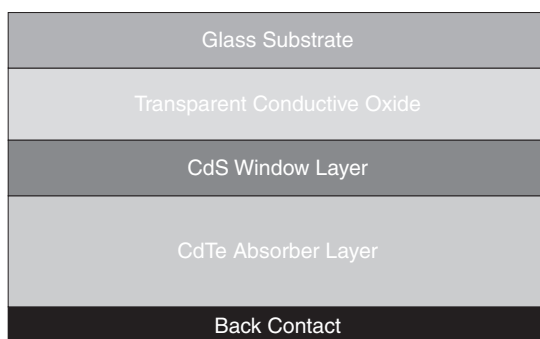


Figure 5.2 Cross-sectional view of a CdS/CdTe thin-film solar cell [41].

created and applied by printing them onto flexible polymeric substrates. This makes the application of OPV systems in large-area, flexible solar cells possible. Organic solar cells are economical to fabricate because their production technique is straightforward and inexpensive. Even though OPVs are inexpensive, simple to manufacture, and mechanically suitable, they are still regarded as a new generation of PV devices requiring significant scientific advancement. Small-molecule- and polymer-based solar cells are the two types of organic solar cells. Small-molecule solar cells have recently demonstrated comparable efficiencies due to technological breakthroughs despite polymer-based solar cells having achieved greater power conversion efficiency (PCE) than small-molecule solar cells [42]. Figure 5.3 represents the cross-sectional view of an organic solar cell [42].

5.3.2.4 Perovskite solar cells

The structure of the mineral CaTiO_3 , which serves as the light absorber, is the source of the name “perovskite” for solar cells. This structure is adopted by many compounds with ABX_3 stoichiometry, where X is the anion and A and B are 12- and 8-coordinate cations, respectively. Because of their strong electrostatic bonding and often divalent anions, perovskites’ large bandgaps render them unsuitable for solar PVs. Pb^{2+} , halide ions (I^- , Br^-), and organic ammonium ions (CH_3NH_3^+ or $\text{NH}=\text{CHNH}_3^+$) make up the most effective halide perovskite solar absorbers. $\text{CH}_3\text{NH}_3\text{PbI}_3$ absorbs light intensely and widely. It is an ambipolar semiconductor (n- or p-type), and solar cells built of it can have exceptional PCE because of its charge carriers’ long diffusion lengths and lifetimes. The capacity to process solutions at low temperatures, which lowers manufacturing costs, is another benefit of perovskite absorbers. Although several optoelectronic devices, including lasers, photodetectors, and light-emitting diodes, have been created using lead halide perovskite materials, the most extensively researched devices are solar cells derived from these materials [43]. Figure 5.4 represents the general structure of the perovskite solar cell (PSC) [44].

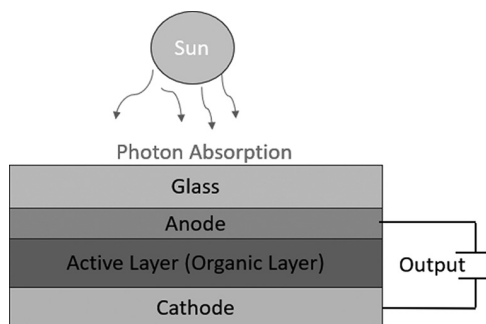


Figure 5.3 Cross-sectional view of an organic solar cell [42].



Figure 5.4 General structure of the PSC [44].

5.3.2.5 Multijunction solar cells

Combining solar cell materials with a variety of bandgap energies to absorb different wavelengths of sunlight is an efficient way to boost solar cell efficiency. The multijunction (MJ) approach reduces sub-bandgap loss caused by low-energy photons that cannot excite electrons in a material with a high bandgap. It also minimizes thermalization loss caused by high-energy photons absorbed by a small-bandgap material. By stacking materials with varying bandgap energies, more solar spectrum may be absorbed and converted to power, improving overall efficiency. This MJ type collects photons across a wider energy range than single-junction solar cells. Each layer enhances overall efficiency by maximizing absorption throughout a specific area of the solar spectrum. These cells, such as space satellites, are commonly used in specialized applications where optimizing energy conversion is critical. MJ cells are more expensive to build because of their complexity; hence, they are not extensively employed in terrestrial applications. Solar cells with different bandgaps are layered one on the other to ensure that the solar cell facing the sun has the biggest bandgap. This top solar cell captures all photons at or above its bandgap energy while transmitting less energetic photons to the solar cells below. Only MJ designs, out of all the so-called third-generation solar cell approaches, have surpassed the detailed-balance limitation of single-junction solar cells [45–47]. Figure 5.5 represents the diagrammatic representation of a MJ solar cell [47].

5.4 EMERGING TECHNOLOGIES IN SOLAR CELL DEVELOPMENT

Our world is powered by the sun, an endless supply of energy that also presents a viable answer to the rising need for sustainable and clean energy. Over time, the efficiency of using solar cells to harness this electricity has increased, although innovation is still needed. Emerging technologies promise to transform solar energy generation and pave the path toward a more positive future.

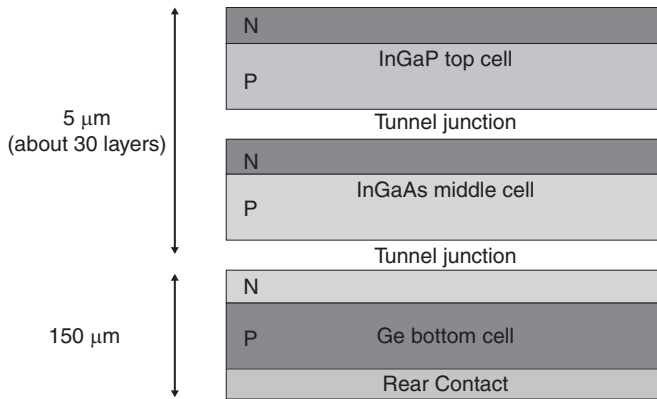


Figure 5.5 Cross-section of a multijunction GaInP/InGaAs/Ge solar cell [47].

5.4.1 Perovskites: emerging leaders in the photovoltaic field

Perovskite is one of the most exciting materials in the battle for next-generation solar cells. With remarkable light absorption, this intriguing material can theoretically achieve efficiencies higher than silicon, which is currently the industry standard [48]. PSCs are perfect for various uses beyond conventional rooftop panels because they are lightweight, flexible, and considerably less expensive [49]. However, issues such as long-term stability and lead contamination in some formulations must be resolved. However, these problems are being quickly addressed by research, and perovskites can potentially revolutionize the solar industry [50].

5.4.2 Quantum dots: tailoring light absorption for enhanced efficiency

Another intriguing option for increasing efficiency is using quantum dots, tiny semiconductor particles with special size-dependent optical characteristics. Through its integration into solar cells, scientists may accurately adjust the light absorption spectrum, thus catching a greater variety of wavelengths and increasing the total energy conversion [51]. Because of their ability to be integrated with current silicon technology and their remarkable performance in the lab, quantum dot solar cells are a possible option for commercialization soon [52]. A stack of quantum dot arrays, or quantum dot superlattice (QDS), is the fundamental component of this PV cell. The QDS may be used for Si/Ge or other material systems, such as GaAs, belonging to the III-Vs group. In a standard n-i-p (p-i-n) solar cell design, the QDS forms an intrinsic layer. The i-layer comprises variable-size quantum dots that confine charge carriers (holes and electrons)

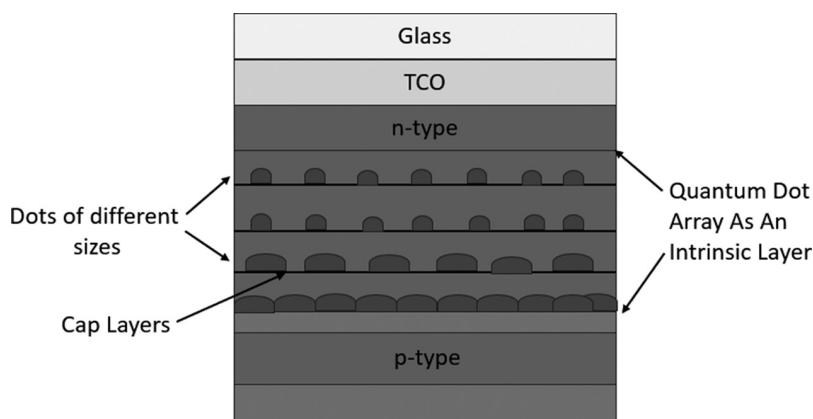


Figure 5.6 Schematic structure of PV cell based on quantum dot superlattice (QDS) [53].

quantum mechanically, increasing the material's effective bandgap. A multicolor quantum PV cell with an estimated efficiency of more than 50% may be produced by varying the size of the quantum dots to maximize absorption at various wavelengths [53]. Figure 5.6 represents the schematic structure of PV cells based on QDS [53].

5.4.3 Concentrating the sun's power: concentrated photovoltaics

Concentrated photovoltaic (CPV): CPV cells, commonly referred to as MJ PV cells, are a more contemporary option. MJ CPV cells are a more viable renewable energy solution due to their ability to convert a larger spectrum of electromagnetic wavelengths into power. CPV systems employ concentrating devices on the cell's surface, such as parabolic mirrors, to focus and increase solar irradiation by up to 1000 times (1000 suns). The focusing optics increase the intensity of sunlight striking the cell. The MJ construction of CPV cells allows for greater concentrated, wide solar spectrum absorption. MJ CPV cells can convert more solar energy into electricity than single-junction cells since they have a wider range of usable wavelengths. The newest and most sophisticated PV systems are CPV systems. Using reflectors such as mirrors or optical prisms, the sun may be focused into a solar cell according to the principle of operation. In areas where direct sunlight is plentiful, this concentration of sunlight is especially beneficial for maximizing energy conversion. CPV systems are frequently used in utility-scale solar installations because the sunlight concentration can cover the increased costs of concentrating optics. In CPV systems, sunlight reflects off mirrors or lenses, concentrating the rays on solar cells at the focus point. The reflectors collect sunlight and direct it toward the cells.

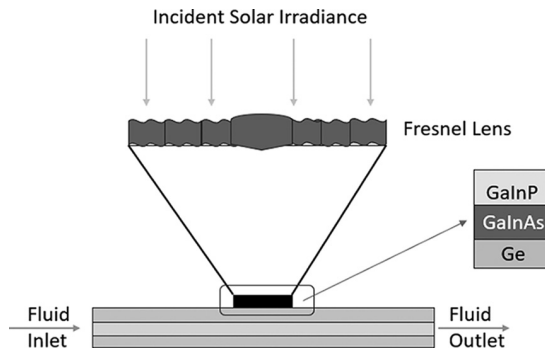


Figure 5.7 Concentrated PV cell [54].

To keep concentrated radiation on the panel, CPV systems with reflectors and cells must follow the sun's path across the sky [54–56]. Figure 5.7 represents the CPV cell [54].

5.4.4 Dye-sensitized solar cells: another promising path for solar energy

Dye-sensitized solar cells (DSSC): Out of all the renewable energy options, PV technology is the most appealing and environmentally benign. It is widely used to harvest solar energy because it immediately transforms sunlight into electrical energy. Because of their high cost, conventional silicon-based solar cells are highly constrained; instead, low-cost, green, and easily fabricated solar cells, including DSSCs, are employed. A photoanode made of a semi-conducting material, a counter electrode, an electrolyte, and a sensitizer (dye) make up the DSSCs. Because DSSC can operate in dim and overcast environments, it is a great option for interior applications. Typically, DSSCs are assembled in a sandwich-style configuration. Transparent conductive glass is often used as a substrate to produce metal oxide nanocrystalline thin films. When dye molecules are covalently bonded to the surface of the photoanode to produce photoelectrons, the metal oxide coatings become sensitized. Electrons are collected at the surface of the counter electrode, and dye molecules are regenerated using an organic electrolyte solution containing a redox couple. A counter electrode for DSSCs is a catalyst placed on a conductive substrate [57]. One of the distinctive features of DSSC is its use of a photosensitive dye to absorb light and produce electricity. Compared with conventional solar cells, these cells are distinguished by their lower production costs and simple manufacturing procedures. Because of its versatility, the DSSC technology is especially well-suited for low-light applications. They can be integrated into various surfaces. However, research into long-term stability and efficiency gains is ongoing in the DSSC technology

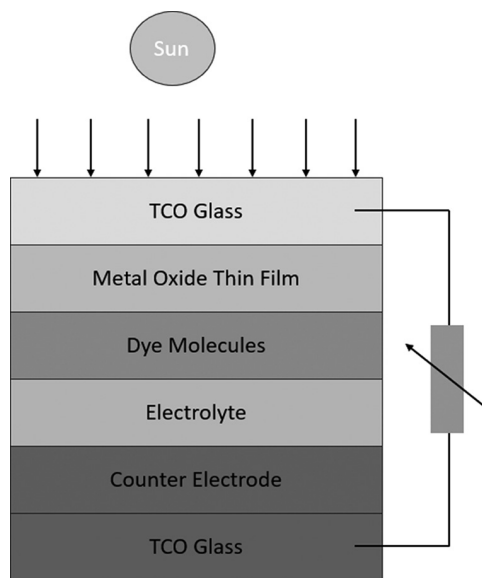


Figure 5.8 Device structure of a typical DSSC [57].

development process [58,59]. Figure 5.8 represents the device structure of a typical DSSC [57], and Table 5.1 represents the maximal efficiency achieved for different types of solar cells [60,61].

5.5 SUSTAINABILITY IN SOLAR CELL TECHNOLOGY

A key component of solar cell technology that tackles both the long-term sustainability and environmental effects of using solar energy to generate electricity is sustainability [62]. PV cells, another name for solar cells, are essential to the shift to greener, more sustainable energy sources [63]. Utilization of renewable raw materials in solar cell production is a major aspect of the technology's sustainability [64]. Many current solar cells are made from materials that are sustainable and have no environmental impact, such as silicon, CdTe, and CIGS [65]. Furthermore, research is being conducted to investigate abundant and environmentally favorable substitute materials that can lessen reliance on uncommon and possibly dangerous elements.

Improvements have been made to the manufacturing procedures used to create solar cells to reduce their environmental impact [66]. The overall environmental friendliness of solar cell technology is enhanced by sustainable manufacturing practices, including using cleaner production techniques, recycling initiatives, and a decrease in water and energy usage

Table 5.1 Maximal efficiency achieved for different types of solar cells [60,61]

<i>Solar cell type</i>	<i>Maximum efficiency reached (%)</i>
Crystalline silicon cells	
• Single crystal	25.3–27.6
• Multicrystalline	21.30
• Silicon heterostructure	26.60
• Thin-film crystal	21.20
Thin-film solar cells	
• CIGS	22.6–23.3
• CdTe	22.10
• Amorphous Si : H	14
Multijunction cells	
• Three-junction	37.9–44.4
• Two-junction	31.6–34.2
• Four-junction or more	38.8–46.0
Emerging photovoltaic	
• Dye-sensitized cells	11.90
• Perovskite cells	22.10
• Organic cells	11.50
• Organic tandem cells	10.60
• Inorganic cells	12.60
• Quantum dot cells	12.00
• Concentrated solar cells	15.00

during production. Moreover, the lifetime and robustness of solar cells play a major role in their sustainability [67]. Many solar panels can produce electricity for up to 25 years with little maintenance [68]. The lengthy lifespan of solar cell technology means that the initial environmental impact of manufacturing is amortized over an extended period, thereby improving the overall energy balance [69].

In the solar sector, the circular economy concept is becoming increasingly popular, highlighting the value of recycling and repurposing elements from used solar panels [70]. Efficient recycling procedures become essential as older solar panels are phased out to stop electronic waste buildup. The goal of efficiency improvements in solar cell technology is to increase the overall sustainability of solar power systems [71]. Increased efficiency makes solar energy more environmentally and economically feasible by requiring less area and resources to produce the same quantity of electricity [72]. Finally, a viable path toward sustainability is incorporating solar cells into commonplace items and building materials. Integrating solar technology into everyday objects such as windows, shingles, and devices shows a dedication to maximizing its impact and ubiquity [73].

5.6 MATERIALS AND MANUFACTURING PROCESSES

To inform the sustainable development of titanium dioxide nanotube (TNT) PSCs, Jingyi Zhang et al. (2015) conducted a life cycle analysis of TNT solar cells to assess their environmental impact. The functional unit is 1 square centimeter (cm^2) of the active cell area. Most of the environmental effects are caused by the manufacture of perovskite dye, which accounts for over 50% of all environmental consequences. This resulted from the huge amounts of solvents, such as diethyl ether, employed in dye manufacturing. Considerable solvents were used in the etching and cleaning processes during the production of the TNT film electrode, which had a considerable effect. The solvent consumption of these two components makes up about 30% of the materials and more than 60% of the overall embodied energy. Reusing these chemicals might have a significant negative influence on the environment. It is surprising to learn that the lead used in the perovskite dye has very low toxicity because other components dominate and require more energy and materials. The second largest component is the amount of power used in production operations such as drying and anodization; more effective techniques may reduce this. With comparable emissions and pay-back periods, PSCs exhibit potential compared to commercial silicon and cadmium-tellurium solar cells. PSC technology is ecologically sustainable for scaling up when considering predicted efficiency and lifespan increases, as well as recycling and more effective production practices. The report provides a thorough analysis, emphasizing the areas that should be prioritized for lifespan footprint reduction. This implies that TNT perovskite cells could represent a sustainable substitute for the current solar PVs [74].

L. M. Peter (2011) examines the potential and obstacles facing sustainable PVs in fulfilling the expected significant rise in global energy consumption, which is expected to double by 2050. Crystalline silicon cells continue to be the most common type of PV. However, thin-film technologies such as CdTe and CIGS are gaining ground quickly and driving down costs. First Solar, a manufacturer of CdTe, is now the leading PV manufacturer. However, immediate attention to sustainability problems such as material availability and cost is necessary for large-scale PV implementation. For instance, it would require more than 100 times the existing Cd cadmium reserves to use enough CdTe for 25 TW of electricity. This demonstrates why a wider variety of thin-film PV materials are required, emphasizing sustainability and low-cost, low-energy production. Copper zinc tin sulfide (CZTS) is a promising material that substitutes inexpensive, plentiful zinc and tin for rare and costly indium and gallium. This chapter investigates PV sustainability myths and realities after reviewing PV technology's fundamentals and popular varieties. PVs are not emission-free; however, thin-film technology offers significantly lower CO_2 emissions than fossil fuels and quick energy payback periods of less than 0.84 years, according to life cycle assessments. In summary, realistic PV contributions to the world's

expanding energy demands while addressing climate change will depend on innovation in sustainable PV materials [75].

Mahmoud Abdelfatah et al. (2015) look at producing and characterizing low-cost $\text{Cu}_2\text{O}/\text{ZnO}$: Al solar cells made from earth-abundant elements for long-term PVs. The Cu_2O thin films were created using electrodeposition, a low-cost, low-temperature chemical solution-based approach ideal for large-scale manufacture. Raman scattering indicated that the films were made entirely of crystalline Cu_2O , whereas Scanning Electron Microscopy images revealed a pyramidal grain structure. The effect of Cu_2O absorber layer thickness on solar cell attributes was investigated by manufacturing devices of varied thicknesses and analyzing performance data. Based on Gaussian fit curves, the ideal Cu_2O thickness for the highest efficiency, open circuit voltage, short-circuit current density, and fill factor was about 3 μm . Light absorption, minority carrier collection length, junction depletion breadth, and interface quality were all ascribed to this. Solar cells made of 3 μm Cu_2O had an efficiency of 1.09%, an open circuit voltage of 0.35 V, a short-circuit current density of 6.21 mA/cm^2 , and a fill factor of 50%. Measurements of electron beam induced current (EBIC), optical reflectivity, and external quantum efficiency shed light on carrier production and collection. According to C-V analysis, the top-performing cell's built-in potential and acceptor concentration were 0.35 V and $4.375 \times 10^{16} \text{cm}^{-3}$, respectively. Minority carrier collecting lengths of less than 1 μm in Cu_2O , voids creating shunts in thin films, and interface recombination in thicker films were recognized as key limits. The results show that Cu_2O thickness can be optimized for effective, low-cost solar cells made from earth-abundant minerals. Implementing buffer layers at the junction might further boost performance [76].

Kung-Shih Chen et al. (2012) present high-performance polymer solar cells made entirely of non-halogenated solvents, with a PCE of over 6%, equivalent to devices made entirely of halogenated solvents. The active layer is a bulk heterojunction mix of PIDT-phanQ conjugated polymer and PC71BM fullerene acceptor. The mix morphology demonstrates large-scale phase separation when cast from pure toluene or xylene solvents, leading to poor performance, with efficiencies below 0.05% for toluene. A tiny quantity (2%) of the high-boiling solvent 1-methylnaphthalene (Me-naph) added to toluene or xylene produces a finer phase-separated morphology and increases device performance by more than 6%. Atomic force microscopy and transmission electron microscope images show that Me-naph additive results in substantially reduced domain sizes on the order of 20 nm compared to over 1 μm without. Photoluminescence tests show that pure solvent films have modest exciton quenching but 100% quenching with the Me-naph addition. Photoinduced absorption spectroscopy reveals that charge production is minimal in pure solvent films but efficient in Me-naph processed mixes. The Me-naph improves the solubility of PC71BM in non-halogenated solvents, boosting blend compatibility and permitting finer mixing and phase separation on the length scale required for effective

exciton splitting and charge transmission. This study highlights the possibility of solvent additives for producing highly efficient solar cells from non-halogenated manufacturing that is sustainable [77].

Juan Carlos de Haro et al. (2021) describe the synthesis and characterization of new bioderived polymeric membranes for use as quasi-solid-state (QS) electrolytes in aqueous DSSCs by cross-linking preoxidized kraft lignin with poly (ethylene glycol) diglycidyl ether (PEGDGE). To improve the lignin's reactivity toward PEGDGE for effective cross-linking, a Fenton method was used to preoxidize it. Membranes were made by reacting oxidized lignin (OL) with various quantities of PEGDGE, and their characteristics were investigated. Because the flexible PEG segments improved molecular mobility, increasing the PEGDGE concentration lowered the glass transition temperature of the membranes. Thermal stability was improved following cross-linking but marginally diminished at higher PEGDGE levels. Fourier Transform infrared (FTIR) verified the covalent inclusion of OL into PEGDGE. The membrane's free swelling capacity made them appropriate as QS electrolytes. The OL/PEGDGE ratio was discovered to affect solar cell efficiency, mostly via short-circuit current density, since it altered the 3D macromolecular structure and, as a result, ionic diffusion and transport efficiency. The best device with an equivalent OL/PEGDGE ratio by weight obtained a PCE of 1.54%. Surprisingly, the lignin-based QS electrolyte demonstrated excellent stability under prolonged UV-vis light exposure for 5 weeks, outperforming reference cells with a carboxymethylcellulose (CMC) electrolyte and a liquid electrolyte, which can be attributed to lignin's UV absorption and radical scavenging ability. This is the first time lignin-based materials have been used as QS electrolytes to allow stable aqueous DSSCs. Overall, the adjustable membranes created by reacting lignin and PEGDGE offer a viable long-term method for customized QS electrolytes in the direction of enhanced aqueous solar cells [78].

Kunmo Chu et al. (2018) describe the creation of self-healing conductors based on liquid metal microcapsules (LMCs) that may be included in flexible electronics to repair electrical channels that have been destroyed. In situ polymerization of urea-formaldehyde onto liquid metal alloy colloids including Ga, In, Sn, and Zn yielded uniform and tiny LMCs (average diameter 5.5 μm). Because the LMCs were highly miscible with liquid prepolymers, it was possible to manufacture LMC/polymer composite passivation films in a single step using phase separation. Electrical self-healing was demonstrated on Cu and Au films passivated with LMC/polymer composites. After cutting the metal and passivation layer, liquid metal released from ruptured capsules quickly filled the damaged region within minutes, recovering the electrical pathway and reducing resistance to near initial values. The self-healing passivation film's potential was demonstrated in flexible PSCs with an LMC/polyurethane acrylate composite on the Au back contact. Because of the outflow of liquid metal that restored conductivity after cutting through the contact and passivation layer, the PCE recovered

to 99% of its previous value of 15.07%. The healed devices also demonstrated outstanding mechanical flexibility, with >95% of their initial performance retained after 500 bending cycles. The exceptional self-healing ability and cell performance recovery show the potential of LMC-based passivation films to improve the fault tolerance and reliability of flexible electronics subject to mechanical damage during manufacturing and usage. The innovative self-healing microcapsule idea has the potential to provide more sustainable electronic devices with longer lives and serviceability [79].

The development of entirely copper-based DSSCs as a sustainable alternative to cells employing costly ruthenium dye sensitizers and/or iodide/triiodide redox mediators is described in the study by Claudia Dragonetti et al. (2018). The authors created a novel heteroleptic copper(I) dye complex D with a 2,9-dimesityl-1,10-phenanthroline ligand for steric hindrance and an anchoring ligand of 6,6'-dimethyl-2,2'-bipyridine-4,4'-dibenzoic acid. When compared to the comparable homoleptic complex Cu(bpy-L)₂⁺, dye D displayed more light absorption and better molar extinction. The authors tested dye D in DSSCs using a standard I⁻/I₃⁻ electrolyte and two copper-based redox mediator couples: Cu(I/II) complexes E1/E2 with 2,9-dimethyl-1,10-phenanthroline ligands and E3/E4 with 2-*n*-butyl-1,10-phenanthroline ligands. Dye D obtained a PCE of 3.5% utilizing I⁻/I₃⁻, which is 40% higher than the typical N719 ruthenium dye. Replacing I⁻/I₃⁻ with the copper redox couples E1/E2 and E3/E4 resulted in decreased but significant efficiencies of 1.3% and 2.0%, respectively. The copper mediators' lower photocurrent is attributable to competing visible light absorption. Nonetheless, the promising performance of these completely copper-based DSSCs shows the use of copper complexes as sensitizers and mediators. The efficiencies compete with other metal-free organic dyes, outperforming previous copper dye cells. Copper is an appealing alternative to pricey ruthenium due to its ease, sustainability, and tunability. Higher efficiencies are possible with further optimization of the copper dye structure and redox electrolyte. Through the synergistic coupling of copper-based dyes and mediators, this groundbreaking proof-of-concept work paves the way for cost-effective and environmentally friendly copper solar cells [80].

5.7 LIFE CYCLE ANALYSIS OF SOLAR CELLS

Nieves Espinosa et al. (2013) examined the environmental viability of organic tandem solar cells using roll-to-roll techniques. They evaluated whether tandem architecture's added complexity is superior to single junction devices. With 2 active layers and 12 layers overall, the tandem solar cells optimize light absorption. According to the calculations, 1 m² of tandem modules would require a cumulative energy consumption of 43.86 MJ, just 19% more than single-junction modules. Most of this energy consumption is made up of materials, primarily supporting layers and encapsulation.

Assuming 3% efficiency, the energy payback period is 0.24 years. Based on module efficiency, the carbon impact is between 144 and 29 g CO₂ equivalent per kWh, more than ten times less than fossil fuels. The primary environmental hotspots are the PET substrate, silver electrodes, and power utilized in production. The tandem design works best at efficiency levels under 2%. Single-junction devices offer a lower payback period at 3%–6% efficiency if sufficient acreage is available. To make sense, tandem cells with extremely low embodied energy must have an efficiency gain of about 20% over single-junction cells. In summary, the research indicates that if material and process advancements can resolve certain issues with cost and efficiency, the organic tandem solar cell method holds more potential than single-junction devices. These devices with extremely low embodied energy broaden the range of circumstances in which tandem design is advantageous [81].

Although end-of-life management for PSCs has not received enough attention, they are a promising PV technology. Gonzalo Rodriguez-Garcia et al. (2021) examined the life cycle evaluation of recovering and recycling coated glass from PSCs at the end of its useful life. One square meter of the constructed PSC module serves as the functional unit. We examine two scenarios: recovering and discarding the coated glass for reuse or disposing of the complete PSC module in a landfill at its end of life. The investigation demonstrates that recovered coated glass enables savings in energy and raw resources used to manufacture new glass. However, the actual process of recuperation uses heat and power. Compared to landfilling, coated glass recovery lowers the potential for global warming by approximately 30% over its entire life cycle. Comparable decreases are observed for other effect categories, such as marine eutrophication and the depletion of fossil resources. The study concludes that recovered coated glass improves the environment in most effect categories examined. These advantages may be further enhanced by increasing the quality of the recovered glass, employing renewable energy at the recovery plants, and replacing additional virgin raw materials with reuse applications. Creating appropriate end-of-life management through coated glass recovery will be crucial to reducing environmental impacts and promoting a circular economy as PSC usage increases. This research offers a foundation for comprehending and refining the PSC recovery procedure [82]. Figure 5.9 represents the recovery of coated glass from PSCs [82].

Jie Xu et al. (2017) looks at a way for recycling the harmful lead component in PSCs to reduce environmental impact and production costs. Although methylammonium lead iodide PSCs are highly efficient, they contain hazardous lead. The scientists devised a method for thermally decomposing the perovskite layer into lead iodide and organic gases that can be recovered, allowing the lead iodide to be reused in future solar cell construction. They used thermogravimetric analysis to estimate the optimal temperature for full conversion to lead iodide by examining the thermal characteristics of the perovskite and organic components. By optimizing the thermal breakdown process, they fully converted the perovskite film

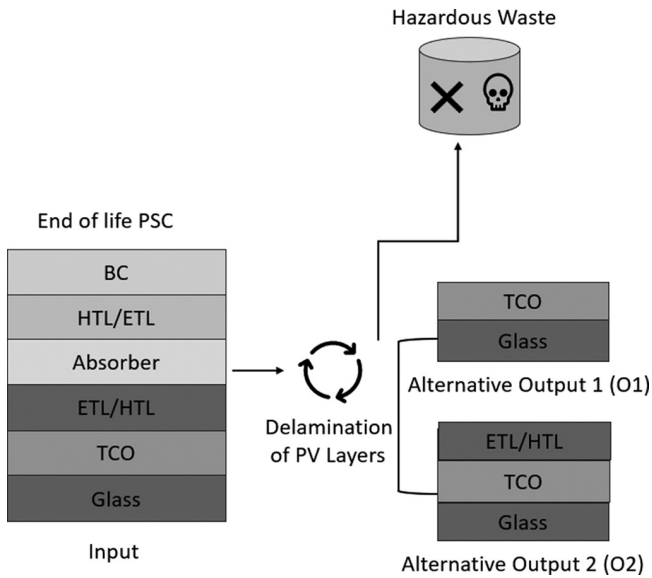


Figure 5.9 Recovery of coated glass from PSCs [82].

to a pure lead iodide layer with a mesoporous shape. In the second manufacturing process, utilizing a low-concentration methylammonium iodide solution to reconvert the lead iodide into perovskite, this mesoporous lead iodide scaffold supported effective perovskite crystal formation. The methylammonium iodide easily penetrated the porous lead iodide layer, allowing for complete conversion to perovskite within the scaffold and a compact capping layer on top. Solar cells built from recycled lead iodide had a 14.8% efficiency compared to 14.3% for control devices. This illustrates the viability of in situ lead iodide recycling for reducing hazardous lead emissions and saving money on materials. Recycling provides environmental advantages and decreases manufacturing energy usage by up to 90% since the clear electrode and titanium dioxide layers may be reused. The recycled lead iodide scaffold technique allows for perovskite layer shape control in high-efficiency devices. Overall, this in situ recycling technique overcomes toxicity challenges for PSC commercialization and moves the technology closer to sustainable large-scale production [83].

5.8 ENVIRONMENTAL IMPACT AND MITIGATION STRATEGIES

Melissa Davis et al. (2020) examined the latest developments in flexible halide PSCs, focusing on environmentally sustainable practices and scalable production methods. After over 10 years of development,

PSCs have proven to have high power conversion efficiencies of over 25%, making them a potential low-cost and high-efficiency PV technology. However, most high-efficiency devices use stiff glass substrates, which restricts their applicability and scalability. Switching to flexible plastic or metal foil substrates allows for high-volume roll-to-roll production and lightweight, portable devices; nevertheless, there are some obstacles to overcome, such as heightened temperature and chemical incompatibility. With more than 19% power conversion efficiencies, numerous scalable deposition processes for flexible PSCs have been examined, including blade/slot die coating, inkjet printing, and spray coating. It also requires adaptable encapsulation techniques to reduce oxygen and water intrusion. Research into lead-free compositions and recyclable device designs is underway because environmental concerns, including lead toxicity and a lack of recycling methods, might restrict the use of PSCs in the future in addition to scalability. Flexible perovskite PVs will be easier to integrate into the market and more widely used for distributed and portable power generation applications if efficiency, stability, and sustainability are further enhanced through compositional engineering and optimized scalable fabrication [84].

Giorgio Schileo et al. (2021) evaluate the toxicity and environmental effects of suggested lead-free replacements for lead-based PSCs. Hybrid lead perovskites have shown enormous potential for solar applications because of their high efficiency, simplicity of manufacture, and low cost. However, the toxicity of lead is a key worry for commercialization. Alternatives such as tin, bismuth, antimony, germanium, silver, and indium have been presented. Still, the study contends that they are not always superior alternatives in terms of availability, cost, toxicity, and environmental effects. Many replacements have annual worldwide production levels of 1–2 orders lower than lead. Most alternatives are more expensive and rely on lead refining as their principal source. Life cycle assessments demonstrate that suggested alternatives have larger environmental consequences than lead to energy usage, acidity, and toxicity. Toxicity data on alternatives is scant. However, compounds including tin, bismuth, antimony, indium, and tellurium are similarly hazardous to one's health. Given the lesser amounts and lower consequences compared to replacements, the benefits of utilizing lead likely exceed the dangers with adequate encapsulation and recycling. There are useful analogies to widely used lead-based technologies, such as lead zirconate titanate and CdTe solar panels, which are not subject to hazardous material laws. Finally, the article indicates that lead-free alternatives do not fulfill availability, economic effectiveness, and minimal environmental impact criteria. While research into lowering lead concentration is valuable, totally replacing lead in PSCs does not appear to be scientifically warranted when considering availability and life cycle implications [85].

5.9 ADVANCEMENTS IN ECO-FRIENDLY SOLAR CELL DESIGNS

Neeraj Kant et al. (2021) reviewed many generations of solar cell technologies, with particular attention paid to materials, manufacturing costs, efficiencies, designs, and the functions of organic and hybrid nanostructured components. Although they are more expensive, the first generation of solar cells made on crystalline silicon had a modest efficiency of 15%–20%. While a-Si, a second-generation thin-film technology, aims to reduce production costs, it also has modest efficiency, ranging from 13% to 16%. The third generation, which has significant prices, achieves high efficiency above 20% by using innovative materials such as perovskites and numerous junctions. Fourth-generation solar cells combine low-cost, flexible polymer thin films with stable inorganic nanostructures such as graphene, carbon nanotubes (CNTs), metal nanoparticles, and metal oxides to maintain the benefits of solution processability while enhancing charge transfer. Because of its outstanding mechanical, electrical, and optical qualities, graphene is recognized for its potential. It has demonstrated potential in polymer solar cells as a hole transport layer (HTL) instead of poly(3,4-ethylenedioxythiophene) : polystyrene sulfonate (PEDOT : PSS), as an interfacial layer between electrodes and the active layer, or as a part of the active layer itself, enabling effective exciton dissociation. Lithium doping of graphene has resulted in 11.8% cell efficiency. Comparably, CNTs have been investigated for use as active and transport layers in organic solar cells, with results to date of up to 8.6% efficiency. Nevertheless, there are still some issues of material quality, property tuning, and large-scale production to be resolved before CNT solar cells can compete with traditional silicon cells, which are now 25% efficient. With optimizable carbon nanostructures playing a key role, fourth-generation organic and hybrid polymer solar cells provide a promising research avenue for sustainable, solution-processable, flexible, and affordable PVs [86].

Seungjin Lee et al. (2020) examined the developments in creating environmentally friendly polymer solar cells, emphasizing the molecular design of photoactive polymer materials with enhanced performance and using green solvents for processing. It talks about substituting safer solvents, such as methyl acetate, with hazardous ones often used, such as chlorobenzene, so that ecologically benign devices can be made. Several novel donor polymers, such as PffBT4T-2DT, which process methyl acetate with 12% efficiency, are emphasized. This paper discusses the physics of the device and its operation, highlighting how careful molecular design can enable high PCE and environmentally friendly processing. The rationalization of critical optoelectronic features for ideal donor polymers includes wide absorption, high mobility of charge carriers, and appropriate energy levels

that facilitate effective charge transfer at polymer-fullerene interfaces. Green solvent processing presents opportunities and problems, such as the critical need for novel, high-efficiency acceptor materials. Economic viability's primary challenges are enumerated, including enhancing stability and scalability. Overall, the analysis presents a positive image of the rapid advancements in environmentally friendly performance and manufacturing occurring in this fascinating subject [87].

Swati Tripathi et al. (2020) studied hybrid buffer layers as a means of improving the efficiency of thin-film solar cells based on $\text{Cu}_2\text{ZnSnS}_4$ (CZTS) absorber material. CZTS is a new, non-toxic, and plentiful absorber material that can potentially replace CdTe and CIGS in solar technology. However, CZTS solar cells have lower efficiency than CIGS. One concern is the contact between the CZTS absorber and the buffer layer, which can produce significant recombination losses. The scientists used SCAPS-1D software to simulate several CZTS solar cell topologies. Three constructions were compared: (1) CZTS/CdS/ZnO : Al (2) CZTS/CdS/ In_2S_3 /ZnO : Al (3) CZTS/CdS/ZnS/ZnO : Al. The hybrid buffer layers CdS/ In_2S_3 and CdS/ZnS were studied as options to reducing the thickness of the hazardous CdS buffer layer. The band alignment between the various layers was investigated. It is preferable for CZTS and CdS to have a spike-like conduction band offset of 0–0.4 eV. The CdS buffer layer thickness was optimized to 80 nm, beyond which the efficiency declined due to parasitic absorption. Adding 40 nm In_2S_3 or ZnS layers lowered the CdS thickness to 40 nm while increasing efficiency from 15.68% to 16.52% (In_2S_3) and 15.81% (ZnS). The absorber layer thickness was altered because of enhanced light absorption and carrier production, which raised J_{sc} and V_{oc} . Increasing the density of CZTS absorber doping lowered efficiency due to increased bulk recombination. J - V curves revealed that the hybrid buffer layer devices had higher J_{sc} values, resulting in greater efficiencies when compared to the CdS reference cell. Finally, this study demonstrates that employing In_2S_3 or ZnS as hybrid buffer layers with a decreased 40 nm CdS layer may boost CZTS solar cell efficiency by more than 16%, offering significant insights for constructing high-performance and sustainable CZTS PVs via optimized device layer design. Device simulation was used as an efficient method to simulate and optimize the CZTS solar cell architectures [88].

Anup Bist et al. (2021), in their review paper, focus on DSSCs, which have sparked tremendous scientific interest as an alternative renewable energy source during the last two decades. DSSCs have several advantages over typical inorganic solar cells, including low cost, ease of production, and environmental friendliness. The photoanode, dye, electrolyte, and counter electrode are the main components of a DSSC. The photoanode generally comprises semiconducting metal oxide nanoparticles such as TiO_2 or ZnO on a substrate. The dye, frequently derived from natural

sources such as plants, absorbs light and injects electrons into the semiconductor. The electrolyte aids in electron transport and dye regeneration. The counter electrode collects the electrons from the external circuit. The study discusses recent developments in optimizing these components to improve DSSC efficiency. In one investigation, ethanol outperformed methanol for color pigment extraction. Anthocyanin dyes interacted with TiO_2 more than β -carotene. Light absorption was increased by combining colors like anthocyanin and chlorophyll. The efficiency of the TiO_2 semiconductor was improved by doping it with elements such as Na, Zn, or Nb. The use of single-walled CNTs enhanced TiO_2 . Light absorption was increased by using nanomaterials such as silver nanoparticles on TiO_2 . Replacing pricey platinum counter electrodes with less expensive alternatives such as graphene maintains efficiency while reducing fabrication costs. Overall, while DSSC efficiency remains lower than inorganic cells, current materials research to increase light harvesting, charge transfer, and interface performance continues to improve. The assessment emphasizes the importance of more research to make DSSCs economically viable renewable energy sources [89].

Fionnuala Grifoni et al. (2021), in their review paper, describes the development of DSSCs that selectively absorb in the near-infrared (NIR) wavelength region to achieve great transparency and colorlessness. It begins by detailing the theoretical limits of PCE and transparency for single-junction transparent PV devices that selectively absorb the NIR. Because of their molecular light absorbers that can be adjusted to absorb selectively in the NIR, very transparent electrode materials like fluorine-doped tin oxide (FTO) glass, and the possibility for tandem integration with UV converters, DSSCs are ideally suited for this application. Design criteria for NIR dyes, photoanode materials, redox couples, counter electrodes, and anti-reflective coatings for selective NIR DSSCs are described. Photovoltage and fill factor, on the other hand, require optimization by injection and surface recombination. For improved injection, the typical TiO_2 photoanode might be substituted by alternative high bandgap oxides such as SnO_2 , or aliovalent doping could be employed to modify the TiO_2 conduction band edge. If properly calibrated, fast one-electron metal complexes offer attractive redox couples for minimizing regeneration losses, with cobalt and ferrocene derivatives exhibiting low visual absorption. Highly transparent catalytic counter electrodes of graphene, conducting polymers, or metal chalcogenides have been created. However, they need to be optimized for the redox pair of interest. Antireflective coatings, such as nanoparticle films, boost performance even more. Overall, careful co-engineering of all selective DSSC components is essential to improve efficiency and transparency for NIR-absorbing devices simultaneously. A fully optimized selective NIR DSSC with over 70% average visible transparency might attain 8% efficiency [90].

5.10 CHALLENGES AND FUTURE PROSPECTS

5.10.1 Current challenges in the sustainable solar cell implementation

5.10.1.1 Material limitations

One of the most significant challenges to adopting solar cells is the limited availability of the ingredients utilized in their manufacturing. Conventional solar cells can contain expensive, rare materials like crystalline silicon, which can be harmful to the environment and hinder their ability to grow. The advantages of solar technology for clean energy are countered by the substantial carbon footprint resulting from the extraction and processing of these minerals. Researchers are working hard to build more affordable and sustainable solar cells by investigating alternative materials, including thin-film technology, perovskites, and organic polymers. However, these substitutes present a unique set of hurdles, such as problems with stability, toxicity, and attaining high-efficiency levels. For sustainable solar cell technology to advance, finding a balance between environmental impact, cost-effectiveness, and efficiency remains a major challenge [91].

5.10.1.2 Energy storage and grid integration

Solar energy is sporadic, which makes it difficult to generate power consistently, even if solar cells are excellent at turning sunlight into electricity. For a consistent and dependable energy supply, energy storage technologies must be efficient, especially at night or under low-light conditions. Batteries and other existing energy storage technologies have drawbacks in terms of cost, effectiveness, and environmental effects. The widespread use of solar power depends on the development of energy storage devices that are affordable, sustainable, and capable of storing and releasing solar energy. Technical difficulties with voltage swings, solar generation unpredictability, and grid stability also arise when incorporating solar energy into current power systems. For solar electricity to be seamlessly integrated into the larger energy infrastructure, these obstacles must be addressed via smart grid technologies and improvements in energy management systems [92,93].

5.10.1.3 Manufacturing processes and environmental impacts

One important component of a solar cell's overall sustainability is the effect that its manufacture has on the environment. Conventional manufacturing methods sometimes include resource- and energy-intensive procedures that result in considerable carbon emissions and environmental damage. Certain materials used in solar cells, such as silicon wafers, require specialized equipment and considerable energy usage during manufacture. The solar industry must shift to more environmentally friendly manufacturing techniques

to reduce the environmental impact of producing solar cells. This involves employing less hazardous chemicals, recycling and reusing resources, and switching to greener energy sources for production. Furthermore, there are issues with managing solar panels' end of life as many modern technologies are difficult to recycle, raising issues with electronic waste. It is essential to address the environmental impact of solar cell technology throughout its life cycle by creating effective recycling systems and developing solar cells with an emphasis on circular economy concepts [94,95].

5.10.2 Research and innovation for improved sustainability

The first 100% hydrogel electrolyte for aqueous DSSCs was developed by Federico Bella et al. (2017). It is made of water as the solvent, an iodide/triiodide redox mediator, and CMC sodium salt, a green biopolymer gelling agent. Electrochemical characterization shows that CMC successfully jellifies the aqueous electrolyte while retaining a high ionic conductivity of approximately 10 mS/cm over a wide temperature range, even at -10°C . This suggests that the cellulose matrix does not unduly impede the fast diffusion of the redox ions required to regenerate the oxidized dye effectively. Triiodide's observed diffusion coefficient was $5.2 \times 10^{-6} \text{ cm}^2/\text{s}$, similar to the values found for liquid organic electrolytes. Without any additional performance-boosting compounds or photoanode surface modifications, promising power conversion efficiencies of approximately 0.7% were achieved when integrated into lab-scale DSSCs with a metal-free organic dye sensitizer and 5.5 wt% CMC, indicating significant room for further efficiency improvements. The aqueous CMC devices underwent testing that revealed exceptional stability: they retained 93% of their efficiency after 29 days in the dark at ambient temperature, and they operated robustly for more than 800 hours during an accelerated thermal aging test that lasted 35 days at 60°C . The suggested system does not include organic solvents, petroleum-derived polymers, hazardous mediators, or corrosive co-additives compared with current record watery DSSCs. This eliminates the safety and environmental contamination issues associated with conventional devices and makes these solar cells sustainable, non-toxic, low-cost, stable, and highly transparent for integration into buildings when combined with the metal-free dye sensitizer and bioderived CMC gelling agent. To satisfy societal demands, this renewable cellulose-based electrolyte matrix marks a major advancement toward completely green, environmentally acceptable solar energy conversion technology [96].

DSSCs are a potential low-cost solar cell technology; nevertheless, significant advancements in stability, efficiency, and environmental friendliness are required for commercial viability. Nicole Mariotti et al. (2020) examined current developments in creating affordable, sustainable materials for DSSCs. Among the major innovations are materials for photoanodes,

organic dyes devoid of metals, electrolytes, and counter electrodes. The most common photoanode is metal oxides, such as TiO_2 . However, low-cost substitutes, such as metal sulfides, nitrides, and phosphides, and carbon-based materials, such as graphene and CNTs, are also being studied. Organic dyes without metals have demonstrated high stability and efficiency, and they are more environmentally benign than conventional ruthenium complexes. Using volatile organic solvents in common electrolytes has prompted studies into solid/QS and aqueous hole transport materials. Lastly, while platinum counter electrodes are expensive, readily available substitutes such as conductive polymers, metal sulfides, selenides, nitrides, and carbon compounds are appealing. New materials research has reduced DSSC prices and environmental effects while increasing efficiency. Notable unresolved issues include scalable production and improved stability. The depth of current materials research demonstrates how promising DSSCs are for achieving sustainability objectives [97].

Guoyu Ding et al. (2022) explored the trade-off between efficiency and toxicity to provide a thorough analysis of the development of sustainable PSCs. With their quick ascent to high power conversion efficiencies of over 25%, PSCs represent a potential new development in clean energy technology. Unfortunately, most raw materials utilized to create PSCs include dangerous compounds that can harm the environment and public health. Achieving a compromise between decreased toxicity and excellent performance is crucial for commercialization, even if eliminating toxicity would diminish efficiency. Lead is the principal metal that poses a toxicity problem. While replacing all lead with less toxic metals would significantly lower efficiency, there are ways to limit the danger of contamination, such as minimizing lead content and using industrial containment measures during manufacture and recycling. The use of organic solvents in fabrication is another significant source of toxicity; however, substitutes that balance solubility and danger levels for scalable green manufacturing, such as alcohols and dimethyl sulfoxide, have been found. Lastly, even if the halogens and perovskite cations used in PSCs have negligible toxicity compared with lead and solvents, sustainability is ensured by analyzing and choosing the best combinations through life cycle evaluations. Comprehensive processing innovations that optimize performance while reducing resource consumption, toxicity, and environmental effects are needed to realize truly green, efficient PSCs [98].

Incorporating mesoporous lead-adsorbing resin layers into the perovskite absorber layer is a sustainable technique described by Shangshang Chen et al. (2021) to stop lead leakage from damaged perovskite solar modules. Despite their high efficiency, PSCs are challenging to commercialize due to lead toxicity and leakage problems. Lead replacement attempts have not worked out, and encapsulation is more expensive. The researchers inserted blade-coated methylammonium lead iodide perovskite sheets with inexpensive, sulfonic acid-based cation exchange resins that tightly linked lead ions. These resins prevent exterior contamination and scratches while more

effectively trapping lead ions inside the perovskite layer after water infiltrates damaged modules, in contrast to earlier lead adsorbents placed on top of module glass. Remarkably, by passivating flaws, the insulating resin scaffold raises solar cell efficiency to 20.6% and mini-module efficiency of 60.8 cm² to 16.3% without compromising operational stability. The interior resin layers reduce lead concentrations to 4.5 ppm, nearly four times lower than glass-coated resins, according to acidic water dripping experiments on fractured mini-modules. Leakage is further reduced to 11.9 ppb by adding a thick resin coating on the metal electrode and replacing the cover glass with a more durable plastic. This always leads to concerns without compromising performance and offers a low-cost, scalable solution to avoid toxicity problems that impede commercialization. The sustainability solution represents a major step toward practical lead-based perovskite solar technology [99].

PSCs have become a potential PV technology because of their low manufacturing costs, easy fabrication techniques, and excellent power conversion efficiencies. However, lead is used in ordinary PSCs, which is hazardous to the environment. The study by Ga-Yeong Kim et al. (2022) examines the latest developments in lead-free or low-lead PSC technology to create environmentally benign and sustainable solar cells. Techniques include investigating substitute materials such as bismuth halides and copper-based perovskites and partially or completely replacing lead with less dangerous metals such as tin, germanium, bismuth, or antimony. In addition, device designs have been optimized through the use of interface engineering, inorganic cation replacements, and two-dimensional perovskites to increase stability and performance. According to life cycle studies, lead-free perovskite solar modules may have energy payback periods that are on par with those of silicon PVs used in commercial settings. Additional toxicity analyses are still needed to determine the stability of lead-free perovskite compositions. The study finds that lead-free PSCs may be a commercially feasible clean energy technology with negligible effects on human health and the environment if stability, efficiency, and scalability improve. Increasing the effectiveness and stability of lead-free formulations, accelerating the fabrication process, conducting additional lifetime and toxicity analyses, and guaranteeing recyclable materials or secure disposal at the end of life are the main difficulties that lie ahead [100].

5.10.3 Economic and policy considerations

Economic and policy issues heavily impact the adoption of sustainable solar cell technology. Government policies that are insufficient or inconsistent in some areas may impede the expansion of the solar sector. A lack of financial incentives, subsidies, or regulatory assistance may cause the switch to solar energy to proceed more slowly. On the other hand, nations with strong renewable energy development policies have witnessed faster adoption rates of solar technology. Another important consideration is the economic

sustainability of solar power. Even though the price of solar panels has decreased over time, many people and companies may still find it prohibitive to make the initial financial commitment to install solar systems. To increase the accessibility of solar technology, governments and financial institutions must provide financial support through tax credits or low-interest loans. Overcoming these obstacles and creating a supportive atmosphere for adopting sustainable solar cells requires balancing legislative support, public awareness, and commercial viability [101,102].

5.10.4 Future trends and evolution of sustainable solar cell technology

To recycle high-purity silicon and silver from silicon solar cells that are nearing the end of their useful lives, Rong Deng et al. (2021) proposed and assessed an ecologically sustainable chemical method. The technique achieves a 95% silver recycling yield by efficiently dissolving silver off the cell surface into an electrolyte solution and depositing it onto a cathode in a single step via reverse electroplating, a revolutionary circular process. Achieving stable silver deposits on the cathode and optimizing silver removal from the cells largely depends on the voltage and current density parameters. Following the selective recovery of silver, 4N purity silicon may be recovered at 99.6% yield using alkaline etching with sodium hydroxide, which eliminates the aluminum paste residue. Furthermore, silicon can be further purified to 5N purity using an acidic etch with hydrofluoric and nitric acid, which will require additional chemicals. However, compared to using alkaline etching alone to recover 4N quality silicon, life cycle assessment reveals that the extra acidic etch required to obtain 5N silicon has more environmental effects related to climate change, fossil fuel depletion, and acidification. Compared with a traditional nitric acid leaching procedure, the baseline chemical approach developed in this study—combining the novel reverse electroplating technology with alkaline etching—shows environmental gains in all effect categories examined. This is accomplished by reducing trash and chemical usage. In addition to removing silver quicker than acid leaching alone, the circular electroplating method eliminates the need for strong nitric acid. According to the investigation, recovering silicon with 4N purity seems more environmentally friendly than over-purifying it with a second etching phase using dangerous chemicals. In conclusion, this study's baseline chemical recycling method produces high material yields with minimal life cycle consequences [103].

5.11 CONCLUSION

Solar energy has immense promise as a sustainable power source to fulfill rising electricity demand while minimizing environmental impact. Solar PV cells play an important role in capturing the sun's plentiful energy by directly turning sunlight into electricity. Solar cell technology has advanced

dramatically, with efficiencies exceeding 20% for silicon cells and 40% for MJ cells. However, further progress is required before solar energy can be fully sustainable and cost-competitive. Developing abundant, non-toxic materials such as perovskites and organic polymers, improving manufacturing techniques to reduce emissions and waste, improving energy storage and grid integration to handle intermittent output, establishing effective recycling systems, and gaining policy support are all critical areas that require ongoing research and innovation. With careful management and system-level innovation, solar PV systems may greatly contribute to building energy security while boosting environmental sustainability. The solar industry has been strongly committed to pushing performance boundaries while reducing environmental impacts. However, translating scientific breakthroughs into commercial viability remains a challenge. Overall, solar energy can generate clean, renewable energy if challenges in materials, storage, manufacturing, regulation, and economics can be addressed systematically through collaborative efforts. With long-term vision and continual improvement, a world powered by solar energy may be within reach.

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Perovskite solar cells

A pathway to sustainable energy

Romana Yousuf and Gausia Qazi

6.1 INTRODUCTION

Every day the sun radiates limitless energy through heat and solar radiation referred to as solar energy [1,2]. The sun is a hot sphere of gas with a core temperature of 15 million Kelvin [3]. Nuclear fusion reactions take place within the core of the sun where helium is created by the combination of hydrogen nuclei, releasing enormous energy. Solar energy is a clean form of energy unlike fossil fuels and reaches common people in the community free of cost [4]. The dominance of solar technology compared to other traditional power generation techniques is that photovoltaic (PV) solar cells can transform sunlight into solar energy [5–7]. This chapter aims to briefly review the developmental stages in the field of solar PVs with emphasis on perovskite solar cells (PSCs). In a brief time of approximately 10 years, PSCs have demonstrated a marked advancement in power conversion efficiency (PCE) at a reduced fabrication cost, unlike conventional solar cells. This chapter familiarizes the reader with the different generations of solar cells, light absorbing materials used in each generation, losses in solar cells, and advantages and disadvantages of different generations with special focus on PSCs.

6.2 OVERVIEW OF DIFFERENT MATERIALS USED IN SOLAR CELL

Solar devices are used to convert solar radiation into electric energy with the help of PV effect [8]. Whenever photons of appropriate wavelength strike the semiconductor material, electrons are excited to higher energy levels followed by the separation of charges to produce electricity. Characteristics of the semiconductor material utilized in the solar cell regulate the interplay of photons with the material [9]. Semiconductor materials found in the periodic table from group II to group VI are best suited for solar PV applications. Such materials can be used either in the elemental form or in compound form where two, three, or four elements are combined, resulting

Table 6.1 Elemental and compound semiconductors used in solar photovoltaic applications

<i>Category</i>		<i>Material</i>	<i>Symbol</i>	<i>Bandgap (eV) at 300 K</i>
Elemental semiconductor		Germanium	Ge	0.66
		Silicon	Si	1.12
Compound semiconductors	Binary	Gallium arsenide	GaAs	5.65
		Indium arsenide	InAs	6.06
		Cadmium sulfide	CdS	5.83
		Cadmium telluride	CdTe	6.48
	Ternary	Aluminum gallium arsenide	AlGaAs	—
	Quaternary	Indium aluminum gallium arsenide	InAlGaAs	—

in flexible electrical and optical properties. Most commonly used elemental and compound semiconductors put to use in solar cell applications are presented in Table 6.1. The materials utilized for the manufacture of an ideal PV cell must meet the following criteria [10]:

1. Appropriate bandgap matching the solar spectrum
2. Direct band structure
3. High PV conversion efficiency
4. Strong absorption coefficient
5. Tolerance toward the defects
6. Small exciton binding energy
7. Longer carrier lifetime
8. Eco-friendly/non-toxic
9. Easily accessible
10. High stability

6.3 CATEGORIES OF SOLAR CELL

Researchers working toward the development of solar cell technology focus on the major challenges, i.e. low cost, high stability, high efficiency, and environmental harmony. Based on the materials that are being utilized in the construction, solar cells are classified into three different categories as outlined below [11]:

6.3.1 First-generation solar cells

Solar cells belonging to this category are fabricated using monocrystalline silicon, polycrystalline silicon, or gallium arsenide (GaAs) material. Monocrystalline silicon solar cells (SSCs) dominate most of the solar market and have an efficiency of about 25% [10,12]. Fabrication cost of the polycrystalline solar cells is typically lesser than that of the monocrystalline type; however, these are less energy efficient than that of the monocrystalline type. GaAs-based solar cells have advantage of higher efficiency and lower temperature sensitivity but are highly expensive. Absorption coefficient of GaAs is good; therefore, thin layer of GaAs is used to produce a strong absorption spectrum unlike SSCs [13]. However, arsenic being toxic is not considered good for human health.

6.3.2 Second-generation solar cells

Solar cells belonging to this category incorporate thin layers of one or more materials, offering a more cost-effective alternative compared to the initial generation. These are generally designated as thin-film solar cells. Thickness of these devices is notably reduced than that of the wafers employed in conventional SSCs. Therefore, less material is used in designing such solar cells and hence are cheaper [14]. These cells are fabricated using amorphous silicon (a-Si), cadmium telluride (CdTe), and Copper Indium Gallium Selenide (CIGS) materials [12,15]. However, these solar cells face the disadvantages of low efficiency and less availability of raw materials.

6.3.3 Third-generation solar cells

Solar cells belonging to this category strive to realize the maximum possible PCE by using different energy-efficient materials at a lower cost [16]. This generation of light-sensitive devices possesses the possibility to exceed the Shockley-Queisser limit, especially in the realm of single bandgap solar cells. Various types of solar cells within this generation include dye-sensitized solar cells, PSCs, organic solar cells, and tandem solar cells. To utilize the maximum solar spectrum to achieve maximum performance evaluation parameters (PEPs), different materials are stacked together to get high-efficiency solar cells [17]. For effective photoconversion, efficient technology promising a cheaper and accessible fabrication route is needed. To achieve this, perovskite material is considered as the best choice. Solar devices fabricated using perovskite material as an active layer are called PSCs. PSCs emerge as a serious candidate with remarkable improvement in PCE from 3.8% to 26% within a gap of 10 years, unlike traditional SSCs as shown in Figure 6.1 [18].

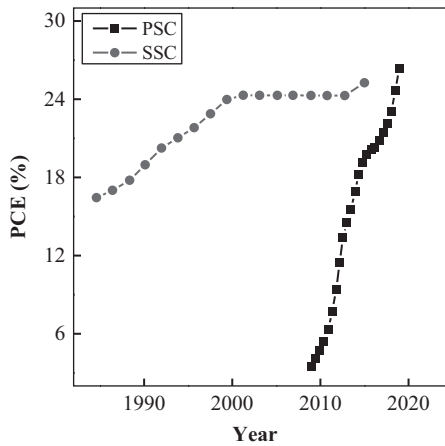


Figure 6.1 Development in PCE of silicon and perovskite solar cells [18].

6.4 PEROVSKITE MATERIAL

A mineral composed of calcium, titanium, and oxygen and having a chemical formula of CaTiO_3 is identified as the perovskite material. Organo-metal halide (OMH) perovskite materials have a cubic crystal structure and have a generic chemical formula of ABX_3 . Here organic monovalent cation is denoted as A, metal is denoted as B, and halide anion is denoted as X, as shown in Figure 6.2 [19]. Cations A are present at the corners of the cube and are represented as blue spheres, cation B, represented by yellow spheres, is present at the center of the cube, and halides X are represented by red spheres and form octahedra [19]. The extent of deviation of the perovskite material from its ideal structure is expressed as Goldschmidt tolerance factor (t) and is given by

$$t = \frac{r_A + r_X}{\sqrt{2}(r_B + r_X)} \quad (6.1)$$

where r_A is the radius of cation A (in pm), r_B is the radius of the cation B (in pm) and r_X is the radius of halide anion (in pm) [20].

The OMH perovskite materials have the capability to absorb more solar radiations because of unique properties of higher absorption coefficients ($>10^5 \text{ cm}^{-1}$), potential to tune optical bandgaps from violet to near infrared, and potential for long-range electron and hole diffusion length ($>1 \mu\text{m}$) [22–24]. Other intrinsic properties of perovskite material include low exciton binding energy ($<10 \text{ MeV}$), high carrier lifetime ($>300 \text{ ns}$), high electron mobility ($800 \text{ cm}^2/\text{Vs}$) [25], low surface recombination velocity, tunable bandgap, amiable grain boundary effect, and low bandgap. The exceptional

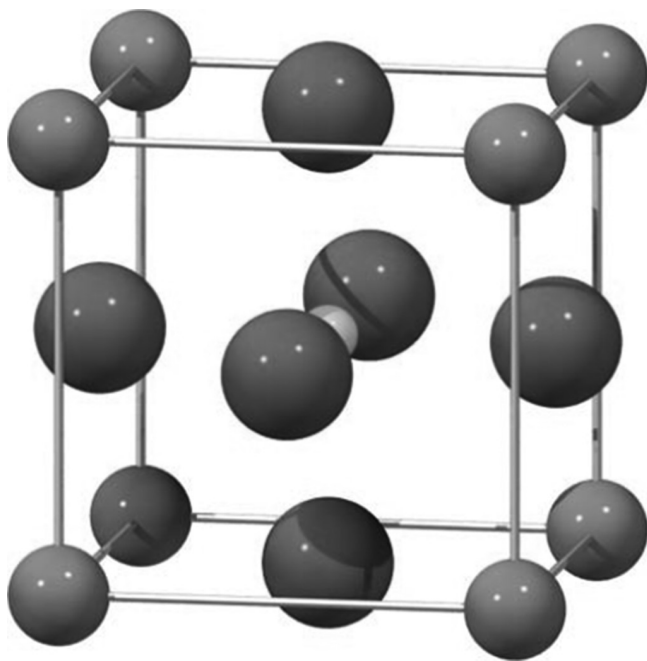


Figure 6.2 Cubic perovskite unit cell [21].

properties of the OMH perovskite materials have made them the perfect choice for various thin-film devices. Various OMH perovskite materials used as absorbers in solar cells include methylammonium lead tri-iodide ($\text{CH}_3\text{NH}_3\text{PbI}_3$), methylammonium tin tri-iodide ($\text{CH}_3\text{NH}_3\text{SnI}_3$), methylammonium lead tri-bromide ($\text{CH}_3\text{NH}_3\text{PbBr}_3$), mixed halide perovskite ($\text{CH}_3\text{NH}_3\text{PbI}_{3-x}\text{Cl}_x$), etc. [26].

6.5 ARCHITECTURE OF PSC

PSCs come up with a layered architecture as illustrated in Figure 6.3. The enhancement in PEPs of the PSCs is determined by the type of material chosen for each layer, deposition method utilized, and layer compatibility inside the device. Brief description of each layer is given below:

6.5.1 Metal electrodes

Metal electrodes function to collect the charge carriers produced within the cell, facilitating their transfer to an external circuit for the generation of electrical current.

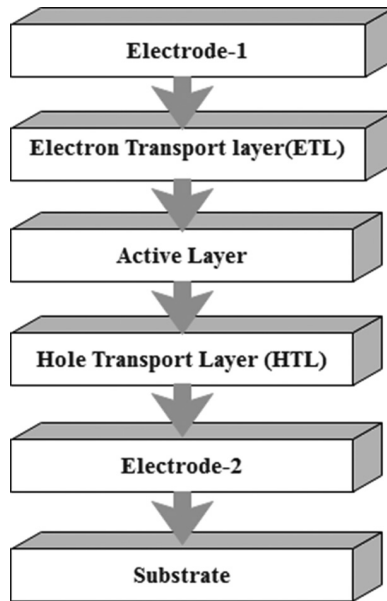


Figure 6.3 Basic layered structure of PSC.

The electrodes in solar cells must possess high conductivity to carry current efficiently. This conductivity ensures effective extraction and transport of carriers created within the light-sensitive absorber of the solar device. Materials like indium-doped tin oxide (ITO) or aluminum-doped zinc oxide (AZO) are chosen for their excellent conductivity properties, enabling the smooth flow of current within the solar cell structure. These electrodes are electrically conductive and optically transparent, exhibiting minimal light absorption within the visible spectrum while facilitating the transmission of photons into the solar cell [27]. The prevalently utilized front electrode in PV devices is ITO; however, it is brittle, expensive to fabricate, and rare material. Its brittleness limits the flexibility of solar cells. Typically, preferred back electrodes in PSCs encompass metal-based layers, with gold (Au), silver (Ag), and copper (Cu) being the favored choices. These metals serve as effective conductors for carrying current and facilitating the efficient retrieval of carriers generated in the light-sensitive material, contributing to the collective performance of the solar cell [28].

6.5.2 Substrate

End-use and sustainability of solar cell products are decided by the substrate fabricated from glass, paper, or plastics. Glass, a brittle material,

offers a good barrier to water and oxygen and is stable to heat. Paper substrate represents a lightweight, flexible, inexpensive, and environmentally friendly material [29,30].

6.5.3 Charge transport layers

Solar devices using perovskite as the light-sensitive material utilize two essential charge transport layers (CTLs): the electron transport layer (ETL) and the hole transport layer (HTL). These layers are essential in facilitating the migration of carriers within the device structure. CTLs are also used to block the opposite charges to allow the participation of a maximum number of carriers in the conduction process. A range of electron transport materials (ETMs) are employed in these devices including titanium oxide (TiO_2), zinc oxide (ZnO_2), zinc tin oxide (ZTO), etc. Additionally, some hole transport materials (HTMs) employed in the PSC include PEDOT:PSS (poly (ethylenedioxythiophene) poly (styrene sulfonic acid)), molybdenum oxide (MoO_3), vanadium oxide, cuprous oxide (Cu_2O), etc. [31].

6.5.4 Absorber layer

Absorber or active layer is regarded as the most crucial component of the solar device where absorption of electromagnetic radiation takes place. In PSCs, the perovskite material primarily serves as a light-absorbing layer; nevertheless, in certain instances, it can also function as a CTL [26]. The conventional perovskite material employed in these solar cells is methylammonium lead iodide ($\text{CH}_3\text{NH}_3\text{PbI}_3$) featuring a tunable optical band-gap reliant upon the halide content [31,32]. The efficiency of the PSC is influenced by various physical attributes which include thickness, doping density, defect density, etc. To bolster both the PCE and to ensure the stability of these solar cells, compositional engineering can be employed. This involves modifying the cations at sites A and B, as well as anions at site X, aiming to achieve more effective and desirable outcomes. Bandgap tuning is achievable through the substitution of an element or mixture of elements such as formamidinium (FA), cesium (Cs), rubidium (Rb), etc. at the A site. Additionally, enhancements in the forbidden energy gap ranging from 1.3 to 1.8 eV can be achieved by modifying the organic cations at the A site and halides at the X site [33]. Modifying the B site in ABX_3 structure also enhances the performance of PSCs. The toxicity associated with lead-based perovskites can be mitigated by substituting lead (Pb) with tin (Sn). However, stability concerns are commonly associated with the tin-based PSCs. Stabilization in such PSCs can be achieved by introducing formamidinium (FA) or cesium (Cs) at the A site. Substituting MA with FA leads to PSCs exhibiting improved efficiency and noticeable stability enhancements. The improved functionality of the PSCs stems from the considerable ionic radius of FA in formamidinium lead halide

perovskites, denoted as $\text{CH}(\text{NH}_2)_2\text{PbI}_3$ or FAPbI_3 . This characteristic contributes to improved light absorption and a reduced bandgap, contributing to the effectiveness of the solar cell. The optical bandgap of formamidinium-based PSCs can range from 1.55 to 2.3 eV [34], contingent upon the halide content at the X site, which may include iodide, bromide, chloride, or a combination of these.

6.6 WORKING PRINCIPLE OF PEROVSKITE SOLAR CELL

Absorption of electromagnetic radiations by the light-sensitive stratum stimulates the generation of excitons, which are electron-hole pairs (EHPs). Photons possessing energy beyond the bandgap threshold dissipate energy as heat when excited electrons release their energy through lattice collision, subsequently returning to the conduction band minimum. However, light particles possessing energy below the forbidden gap can still excite electrons through sub-gap transitions, either through deep defects or band tails. Nevertheless, the contribution of such transitions to the generation of charge carriers is typically negligible. Excitons can be classified as Wannier type and Frenkel type. Excitons present in perovskite material are categorized as Wannier type and are characterized by a low binding energy similar to that of the inorganic materials [35], facilitating quick dissociation. Frenkel-type exciton is associated with the organic absorber. To achieve free EHP at room temperature of 26 MeV, binding energy lower than that of the thermal energy is recommended. Higher binding energy requires external energy to produce free charge carriers. Having an exciton binding energy of 0.59 MeV [36], the excitons generated in the perovskite material can efficiently undergo thermal dissociation at the interfaces, resulting in the formation of electrons and holes. Subsequently, these generated charge carriers are then transmitted to the HTL and ETL through either drift or diffusion process. These layers serve the dual function of not only extracting the respective charge carriers but also blocking the opposite charges to prevent any undesired recombination of charges. Furthermore, the mobility of electrons and holes within transport layers plays a crucial role in effectively extracting electrons and holes, thus directly impacting the overall device efficiency [37]. Reduced mobility of charge carriers within the HTL or ETL results in the charge carriers being accumulated, both within the perovskite layer and at its interfaces. This further reduces the charge carrier extraction rate, leading to an increased prevalence of recombination within the device. This, in turn, causes a loss of a portion of the generated charge and consequently results in deterioration of efficacy in solar cells. The residual carriers are then guided through the external circuit to produce electrical power. In the PV process, the collection of charge carriers represents the final step,

wherein charge carriers are conducted and injected into current collectors. Here, the regulation in the compilation of photo-induced carriers is decided by the alignment of bands between the work function of the electrode and the active layer. Efficient interface engineering is thus essential for efficient charge extraction and blocking [38,39], which involves the introduction of a buffer layer, which is a thin CTL connecting the light-sensitive active material and electrodes. The primary role of these layers is to improve the overall device performance [40]. For efficient injection, contacts should be ohmic which involves optimized alignment of energy levels between the electrode and the transport layers. Imperfect matching results in the formation of an injection barrier, leading to charge carrier accumulation, an increase in trap-assisted recombination at the interfaces, and, therefore, poor charge injection. Thus, the injection barrier should be reduced to allow efficient charge carrier collection. Another function of the buffer layer is to avoid the adverse effect of humidity and oxygen on active layers. The processes of charge transport in PSCs are shown in Figure 6.4. The filled arrows symbolize the constructive approaches for energy conversion, while the unfilled arrow indicate the undesirable processes. The desirable processes involve the excitation of photons in perovskite (1), transfer of electrons to ETM (TiO_2) (2), and holes transfer to the HTM or, equivalently, movement of electrons from the HTM to the perovskite (3). Recombination of photo-generated species shown in (4) and back charge transfer at ETL and HTL interface (5,6) are considered undesirable processes between ETL and the HTL which may occur in the absence of perovskite layer in some cases (7). To achieve high PEPs, it is essential for processes (4)–(7) to occur on significantly slower time scales compared to the generation and extraction of charge carriers (1)–(3) [41].

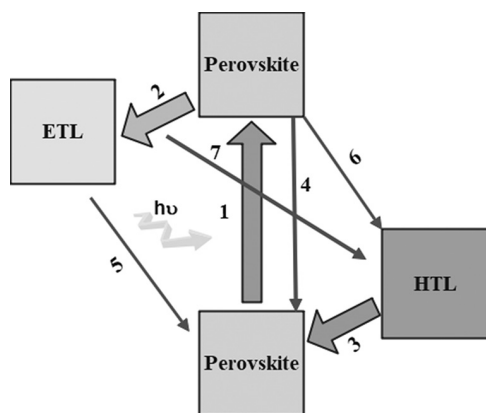


Figure 6.4 Transport of charge in PSC.

6.7 UNIFORM ABSORBER HOMOJUNCTION PSC

In this section a typical structure of homojunction PSC with a uniformly doped, lead-based photoabsorber layer sandwiched between WS₂ and molybdenum oxide (MoO₃) is discussed. Literature reported degradation of conventional ETM, i.e. TiO₂, when exposed to UV, resulting in unstable performance of PSC [42]. To address this issue, here oxygen-free WS₂ was adopted as an ETL. Furthermore, the solar cell efficiency is considerably impacted by the precise alignment of energy bands between the light-sensitive material and CTLs [43]. Therefore, to mitigate the mismatching in energy band alignment at interfaces, WS₂ and MoO₃ are employed as CTLs [42,44]. During the fabrication of spiro-OMeTAD, a widely used HTM in conventional PSC, high-density small-sized pinholes are created, which provide passage for penetration of moisture into the perovskite layer [45]. These pathways behave as channels encouraging the migration of iodine from lead-based perovskite to the electrode, resulting in deterioration of electrodes by corrosion and hence degradation of PSC [46]. Therefore, to realize moisture-resistant, high-stability, and high-performance PSCs, pinhole-free CTLs are proposed. The schematic representation of a uniform absorber PSC along with its corresponding band diagram is demonstrated in Figure 6.5a and b respectively [47]. Figure 6.5 distinctly illustrates the utilization of n- and p-type MAPbI₃ as an active material sandwiched between inorganic CTLs. The implementation of the MAPbI₃(n)/MAPbI₃(p) homo-junction aims to establish a built-in electric field, enhancing the carrier migration, and diminishing the EHP losses by mitigating the charge carrier recombination [48]. The heterojunctions introduced between absorber/ETM and absorber/HTM are also used to reduce the distance of the carrier

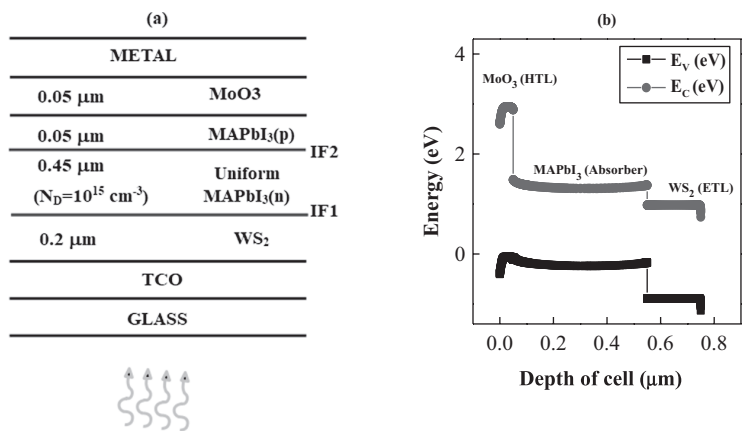


Figure 6.5 (a) Multilayered structure; (b) energy band depiction of PSC.

transport which further reduces the carrier losses. Here solar cell capacitance (SCAPS) has been employed as a numerical analysis tool to model PSC under study. The aim is to assess the impact of alterations in physical characteristics of the photoactive material on the performance metrics of the PSC under investigation. Extensive analysis is undertaken to ascertain the most optimal blend of performance parameters. The physical parameters changed during the optimization process include absorber layer thickness, doping density, working temperature, interfacial defects, bulk defects, and diffusion length. Once the optimal parameters are achieved, a significant improvement in PEPs is reflected in the results.

6.7.1 PSC device parameters

The summarized list of material parameters utilized in this investigation is outlined in Table 6.1 [49–53]. The initial level of defect density chosen for MAPbI₃(n) yields the lifetime of the charge carrier as 5 ns. Details regarding the defect characteristics of various layers and interfaces are defined in Table 6.2. The presumed distribution of energy levels for absorbers adheres to the Gaussian distribution. The defects observed at the interfaces are

Table 6.2 Distinct layer material characteristics

Design parameters	Tungsten disulfide (ETM)	MAPbI ₃ (n) (Absorber)	MAPbI ₃ (p) (Absorber)	Molybdenum trioxide (HTM)
Thickness (μm)	0.2	0.450	0.05	0.05
Bandgap (eV)	1.87	1.5	1.5	3
Electron affinity (eV)	4.3	3.93	3.93	2.5
Dielectric constant	11.9	25	25	12.5
Conduction band effective DOS (cm ⁻³)	1×10^{18}	2.2×10^{18}	2.2×10^{18}	2.2×10^{18}
Valance band effective DOS (cm ⁻³)	2.4×10^{19}	1.8×10^{19}	1.8×10^{19}	1.8×10^{19}
Electron thermal velocity (cm/s)	1×10^7	1×10^7	1×10^7	1×10^7
Hole thermal velocity (cm/s)	1×10^7	1×10^7	1×10^7	1×10^7
Uniform donor density (cm ⁻³)	1.1×10^{19}	1×10^{15}	0	0
Uniform acceptor density (cm ⁻³)	0	0	5×10^{17}	2×10^{18}
Mobility of electrons (cm ² /Vs)	260	10	10	25
Mobility of holes (cm ² /Vs)	51	10	10	100

Table 6.3 Parameters describing defects in materials used in PSC

Design parameters	Defects			
	MAPbI ₃ (n)	MAPbI ₃ (p)	HTM	ETM
Defect type	Neutral	Neutral	Neutral	Neutral
Capture cross-section of electrons (cm ²)	2×10^{-15}	2×10^{-15}	1×10^{-15}	1.2×10^{-14}
Capture cross-section of holes (cm ²)	2×10^{-15}	2×10^{-15}	1×10^{-15}	1.2×10^{-14}
Energetic distribution	Gaussian	Gaussian	Single	Single
Reference for defect energy level (eV)	Above E_v	Above E_v	Above E_v	Above E_v
Total defect density (cm ⁻³)	1.0×10^{16}	1.0×10^{16}	1×10^{14}	1.2×10^{11}
Characteristic energy (eV)	0.1	0.1	–	–

considered single and neutral [54]. The work function for transparent conductive oxide (TCO) remains constant at 4 eV, while that of the back metal is established at 5.1 eV (Table 6.3).

6.8 INFLUENCE OF PHYSICAL PARAMETERS ON PEPs OF PSCs

This section delves into examining how different physical parameters of the photoactive layer influence the evaluation parameters of PSCs. Through this exploration, we aim to identify the optimal parametric values necessary for achieving optimized PSC performance. The optimized physical parameters of the active layer discussed here encompass absorber thickness, diffusion length, lifetime, temperature, doping, and defect density, both within the bulk and at interfaces. All these parameters are recognized as significant factors in the design and optimization of PSC performance.

6.8.1 Influence of thickness

Identification of the thickness of the lead-based optically sensitive layer is a crucial aspect while designing the optimum PSC. In the pursuit of determining the optimal thickness, all the device parameters are maintained at a constant value, with the variation solely focused on the thickness of MAPbI₃(n), and the impact of this variation on various PEPs is examined. Figure 6.6 illustrates the variation in PEPs corresponding to alterations in the absorber thickness (t_{abs}). Results indicate the short-circuit current density experiences an initial increase, reaching to saturation at a thickness of 1.5 μm , followed

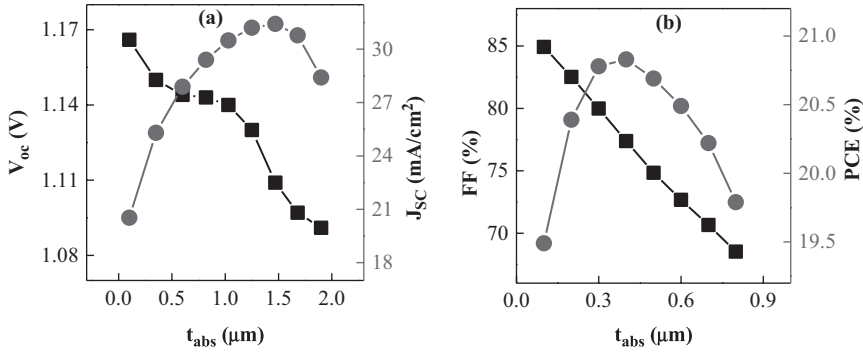


Figure 6.6 Change in (a) V_{oc} and J_{sc} and (b) PCE and FF wrt the thickness of the active layer in uniform absorber PSC, all other parameters are specified in Tables 6.1 and 6.2.

by a subsequent drop, on expanding the thickness of the photosensitive layer. The findings are supported by the observation that an increment in the thickness of the active layer leads to enhanced absorption of photonic particles. This, in turn, contributes to an increased concentration of charge carriers, thereby resulting in a higher short-circuit current. The outcome is elucidated by Equation 6.2 where A_c denotes the area of the cell, G stands for generation rate, and W_{eff} signifies the effective thickness of the solar cell.

Figure 6.6 depicts a decline in the fill factor (FF) of the examined solar cell, diminishing from 84.93% to 68.52% on increasing the thickness of the photon-reactive material. The enhancement in the thickness of the optically sensitive material raises both the R_s and internal power depletion within the cell. The highest FF of 84.93% observed at a thickness of 0.1 μm is attributed to reduced recombination rates, an extended lifetime of the minority carriers, and consequently a lower I_o . At a larger absorber thickness of 0.8 μm, FF of the PSC decreases to 68.52%. The observed decrease can be attributed to the increased absorber thickness, which, despite the consistent level of photoabsorption, results in reduced collection efficiency. The outcome of altering the thickness of the photosensitive layer on open-circuit voltage can be elucidated by referencing Equation 6.3, which illustrates an inverse correlation between open-circuit voltage and dark saturation current.

$$J_{\text{sc}} = \frac{I_{\text{sc}}}{A_c} = qGW_{\text{eff}} \quad (6.2)$$

$$V_{\text{oc}} = \frac{\eta kT}{q} \ln \left(\frac{I_L}{I_s} + 1 \right) \quad (6.3)$$

With the enhancement in the $\text{MAPbI}_3(\text{n})$ thickness, electron-hole recombination becomes more pronounced.

This subsequently raises dark saturation current resulting in a decrease in the value of V_{oc} , as outlined in Equation 6.3 and demonstrated in Figure 6.6a. Additionally, Figure 6.6b demonstrates that maximum PCE attained is 20.83% when the absorber thickness is set at 0.4 μm . Nevertheless, it has been observed that a continuous increment in absorber thickness leads to a reduction in PCE. This reduction can be attributed to the diminishing electric field, impacting the recombination dynamics of active layer carriers of the PSC. The efficacy of PSC relies on two pivotal factors: the absorption of photons and the efficient transport of electrons and holes. This dual influence becomes a crucial consideration in determining the optimal thickness of the $\text{MAPbI}_3(\text{n})$. Setting the thickness of $\text{MAPbI}_3(\text{n})$ at 0.4 μm and fine-tuning other PSC parameters leads to the proposed optimized PSC. On the contrary, changing the thickness of p-type optically active layer from 0.01 to 0.06 μm maintains the PCE of the PSC consistently at 20.83%.

6.8.2 Influence of temperature

Typically, solar devices operate at high temperatures, which can detrimentally affect their performance. Elevated temperatures contribute to stress and strain within the devices, escalate the prevalence of defects at interfaces, and diminish overall stability over time. The formation of defects at the interfaces promotes an increase in series resistance, reduces carrier lifetime, and consequently diminishes the open-circuit voltage. Furthermore, elevated temperatures also increase J_0 , further contributing to the decrease in V_{oc} . The impact of temperature on the uniform absorber PSC is depicted in Figure 6.7. The inverse correlation between the change in open-circuit

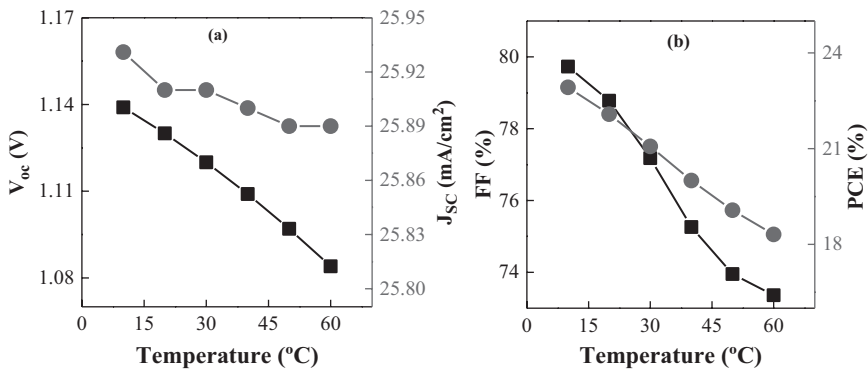


Figure 6.7 Change in (a) V_{oc} and J_{sc} and (b) PCE and FF wrt temperature at a $\text{MAPbI}_3(\text{n})$ thickness of 0.4 μm .

voltage concerning temperature is depicted in Equation 6.4, where T (K) represents the operating temperature, E_g (eV) denotes the bandgap, and q (C) signifies electric charge [55]. As temperature rises, the formation of deep trap states occurs, leading to increased charge trapping. Consequently, the diffusion length of light-generated carriers in the solar device decreases, leading to a reduction in J_{sc} [56–60]. This effect is depicted in Figure 6.7a.

$$\frac{dV_{oc}}{dT} = \left(\frac{V_{oc} - \frac{E_g}{q}}{T} \right) \quad (6.4)$$

6.8.3 Influence of doping density

With the rise in doping density of the active layer, PCE of the PSC also increases. This can be elucidated by noting that rise in doping density leads to an enhanced conductivity of the absorber layer. The graphical representation of this effect can be observed in Figure 6.8, where the peak efficiency is achieved at N_d of 10^{13} cm^{-3} , accompanied by a decrease in V_{oc} . For an absorber doped with the n-type dopants, conductivity can be expressed as Equation 6.5, where n (cm^{-3}) is the electron concentration, μ_n ($\text{cm}^2/\text{V s}$) is the mobility of electrons.

When the doping concentration is low, we have $n \approx N_d$, where N_d (cm^{-3}) is the ionized dopants. Equation 6.5 can hence be rewritten as:

$$\sigma = qn\mu_n \quad (6.5)$$

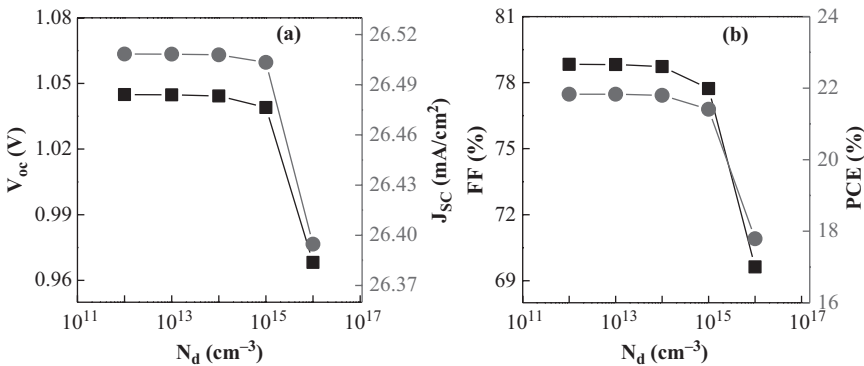


Figure 6.8 Change of (a) V_{oc} and J_{sc} and (b) PCE and FF wrt N_d at a $\text{MAPbI}_3(\text{n})$ thickness of $0.4 \mu\text{m}$.

Equation 6.6 highlights correlation between σ and N_d . When the perovskite layer has a low doping concentration, μ does not vary significantly. Nonetheless, in the presence of substantial doping, the efficacy of PSCs declines as a consequence of the Burstein-Moss effect [61].

$$\sigma = qN_d\mu_n \quad (6.6)$$

6.8.4 Influence of defect density and diffusion length

The operational efficacy of the solar device is greatly influenced by generation and annihilation of charges within the absorber material. The diffusion distance and lifespan of carriers produced in photosensitive layer need to be substantial to ensure the effective capture of charge carriers by their corresponding electrodes. Due to the development of poor film quality, defect sites emerge within the material, leading to the recombination of charge carriers. These defects, found within the energy gap of material, serve as Shockley-Read-Hall (SRH) recombination sites, which are responsible for electrons and holes annihilation [62,63]. The modeling of charge carrier recombination via deep traps is commonly accomplished using SRH model [64–66]. Equation 6.7 provides a means to express net recombination rate ($\#/cm^3\cdot s$) caused by traps, occurring both within the bulk and at interfaces [31,32], where K_B is the Boltzmann's constant (J/K) and T (K) represents the temperature, n and p are the electron and hole densities (cm^{-3}), n_i is the intrinsic carrier concentration (cm^{-3}), E_i is the intrinsic Fermi level (eV), E_t denotes the trap energy level (eV).

$$R_{SRH} = \frac{(np - n_i^2)}{\tau_p \left(n + n_i \exp\left(\frac{E_t - E_i}{K_B T}\right) \right) + \tau_n \left(p + n_i \exp\left(\frac{E_i - E_t}{K_B T}\right) \right)} \quad (6.7)$$

Minority carrier lifetimes, $\tau_{n,p}$ (s), is expressed by Equation 6.8, which is a function of trap type and volume density of traps, where v_{th} is the thermal velocity (cm/s), N_t is the defect concentration (cm^{-3}), and $\sigma_{n,p}$ is carrier capture cross section (cm^2) [67].

$$\tau_{n,p} = \frac{1}{\sigma_{n,p} N_t v_{th}} \quad (6.8)$$

The lifetime of minority carriers also affects the diffusion length of the carriers, which is the average distance traveled by an excited carrier before recombining and is defined by Equation 6.9, where D is the diffusion coefficient and $\tau_{n,p}$ is the minority carrier lifetime [68].

$$L_{D(n,p)} = \sqrt{D\tau_{n,p}} \quad (6.9)$$

Table 6.4 Influence of variation in N_t of MAPbI₃(n) on L_D and τ

N_t (cm ⁻³)	10^{12}	10^{13}	10^{14}	10^{15}	10^{16}
L_D (μm)	36	11	3.6	1.1	0.36
τ (ns)	5×10^4	5×10^3	5×10^2	5×10^1	5×10^0

According to Equations 6.7–6.9, it becomes apparent that an increased defect density accelerates the annihilation of charge carrier. This, subsequently, diminishes the lifespan of the charge carriers, consequently affecting the diffusion lengths. For the PSC under study, the diffusion distance decreases from 36 to 0.36 μm when the N_t of the n-type absorber changes from 10^{12} to 10^{16} cm⁻³. Table 6.4 demonstrates enhancement in both L_D and τ arising from the decrease in defect density. This extended diffusion length allows designers to extend the thickness of light-sensitive layer up to the L_D of charge carriers, providing greater design flexibility. This extension enhances absorption and, consequently, boosts the efficiency of the PSC. The influence of alteration in N_t is examined across various PEPs of PSC under investigation. Varying the N_t from 10^{12} to 10^{16} cm⁻³, FF of devices reduces from 88.66% to 78.85%. To enhance the FF, a high-grade active layer is essential, as it contributes to the improvement of both carrier diffusion and carrier collection. Figure 6.9 illustrates the impact of varying N_t of MAPbI₃(n) on PEPs of the PV device. Figure 6.10 illustrates the correlation between the PCE and MAPbI₃(n) thickness for various diffusion lengths. Increase in diffusion length demonstrates a rise in PCE of PSC. Figure 6.11 illustrates the relationship between lifetime of carriers and defect density of MAPbI₃(n). Additionally, Figure 6.12 displays the JV characteristics

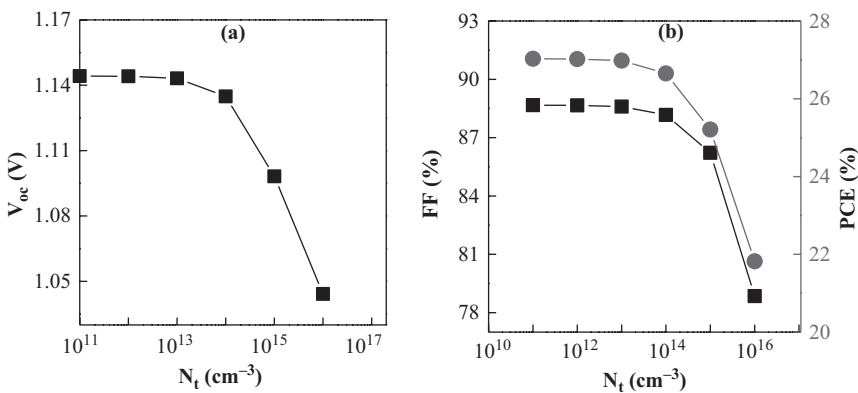


Figure 6.9 Deviation of (a) V_{oc} and (b) PCE and FF wrt N_t in PSC under study.

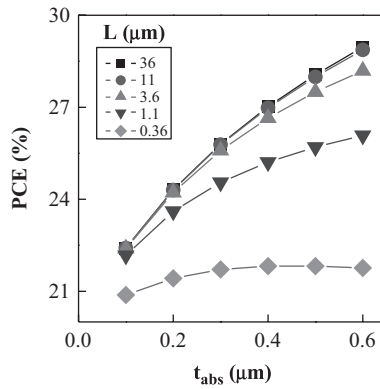


Figure 6.10 Change in PCE wrt absorber thickness for different L_D .

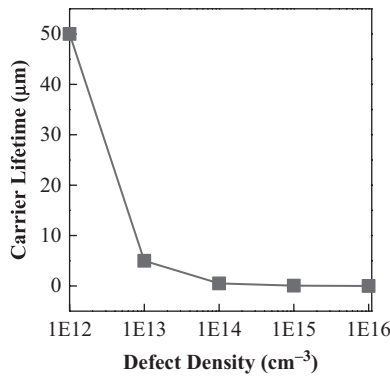


Figure 6.11 Variation in carrier lifetime wrt N_t .

for different defect density values of $\text{MAPbI}_3(\text{n})$. This graphical representation further confirms that a higher density of defect results in the degradation of JV curves.

6.8.5 Influence of defect density at interfaces

The defect density within the interface layers significantly impacts the enhancement of solar cells' performance. Increased density of defect at interfaces leads to increased trap states and higher recombination rates. Consequently, this diminishes the PEPs of the PSC [69]. Here impact of interfaces on the PCE of PSC has been investigated.

The findings are presented in Figure 6.13. The result indicates that as the defect density at interfaces increases, there is a proportional decline in PCE.

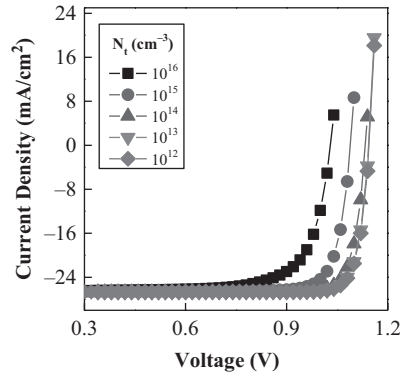


Figure 6.12 Variation in JV characteristics with varying defect density of MAPbI₃(n) at MAPbI₃(n) thickness of 0.4 μm and N_d of $1 \times 10^{13} \text{ cm}^{-3}$.

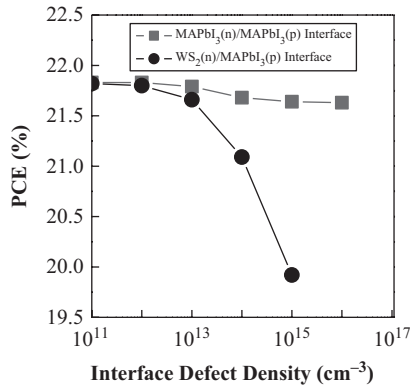


Figure 6.13 Change in PCE with varying interface defect density at N_d of $1 \times 10^{13} \text{ cm}^{-3}$.

Nevertheless, the observed decrease in PCE is more pronounced at the ETL/absorber interface. This is ascribed to the increased density of carriers created at this interface, subsequently causing a higher recombination rate. Therefore, the efficacy of the absorber material becomes the paramount factor in realizing high-efficiency PSCs.

In Section 6.8, a comprehensive assessment analysis and examination are conducted on all the pertinent factors contributing to the enhanced performance of uniform absorber PSC, thoroughly scrutinizing and deliberating upon each. Subsequently, these parameters are further refined to attain optimized outcomes. By incorporating optimal design parameters and iteratively conducting simulations, a modified version of the proposed uniform absorber PSC, featuring an exclusive set of design parameters,

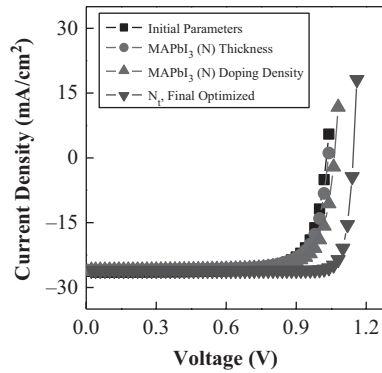


Figure 6.14 Comparison of JV curves at MAPbI₃(n) thickness of 0.4 μm and N_d of 10^{13} cm^{-3} .

was successfully developed. The structure identified as the proposed optimal uniform absorber PSC demonstrates a 6% improvement in PCE when compared to the standard uniform absorber PSC. The design demonstrates top-notch performance benchmarks, featuring V_{oc} of 1.15 V, FF of 87.9%, J_{sc} of 26.6 mA/cm^2 , and a PCE of 26.81%. Figure 6.14 depicts the JV characteristics of the proposed uniform absorber PSC across each iterative optimization. Enhancement in the PCE and FF of proposed PSC structure requires further refinement of JV curves. This improvement can be attained by reducing the reverse saturation currents, a consequence of diode action inherent in the circuit model of the PV cell. This is realized by incorporating appropriate non-uniform doping levels in the MAPbI₃(n) layer, leading to development of a non-uniform or graded absorber PSC.

6.9 CONCLUSION

The work outlined in this chapter concentrated on the design and investigation of proposed structure of PSC. Initially, lead-based, uniform absorber homojunction PSC variant having a primary architecture of TCO/WS₂/MAPbI₃(n)/MAPbI₃(p)/MoO₃/metal was proposed, which was further optimized to give improved performance evaluation metrics. The PSC structure explored in this work identified fundamental physical parameters as strong competitors in PSC design. These attributes perform a crucial role in defining the effectuality of solar cell. By optimizing these parameters, the performance evaluation metrics of the proposed optimized PSC were improved with V_{oc} of 1.2 V, FF of 87.9%, J_{sc} of 26.6 mA/cm^2 , and PCE of 26.8%. The optimized structure exhibited a 6.03% improvement in the overall PCE.

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Role of electronic textiles in health care

A sustainable approach

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7.1 INTRODUCTION

The term “dementia” is used to describe a disease which is characterized by memory loss, difficulty in making decisions for routine activities, and gradual decline of rational thinking. It has been commonly noticed among the older population owing to the age factor. Patients will experience moderate cognitive issues before attaining the dementia disease which is referred as mild cognitive impairment [1,2]. A serious concern of the disease is the percentage of patients with dementia disease increasing from the stage of mild cognitive impairment. Around 10% population of people with more than 60 years have the aforementioned disease. The severe or next stage of dementia is Alzheimer’s disease [3–6]. Hence, it is essential to carry out a methodological approach for addressing the issue of steep increase of people with diseases and assisting the other stakeholders associated in the health care sector [7]. Therefore, patients’ comfort and their health quality can be improved by using appropriate wearable products for monitoring them and their environment [8]. The skin in our body and in other animals is used to regulate the body temperature, inhibits unnecessary hydration loss, and shields the internal organs such as brain, heart, lungs, liver, and kidneys from external microorganism. Skin exhibits functional irregularities in controlling transepidermal water loss (TEWL) when it becomes damaged by inflammation, scarring, and conditions such as xeroderma, psoriasis, and atopic dermatitis [9,10]. Thus, health quality can be examined by assessing the moisture condition of the skin [11]. Moreover, the moisture content of the skin influences its resilience and suppleness, serving both social and aesthetic purposes. Therefore, there is a growing academic and commercial focus on the surveillance of skin hydration levels in the present environment [12–14].

7.2 INTELLIGENT TEXTILES FOR COGNITIVE EVALUATION AND LIFE EXTENSION

7.2.1 Dementia and mild cognitive impairment

Wearable textiles are also referred as “electronic textiles” and “e-textiles” [6,15–17], where the textile product has the ability to engage in interactions with an external stimuli, including the physical structure like arms, legs, etc. “Smart textiles” is the word that is being used to describe the textiles that perform activities which are unable to be carried out by conventional textiles [6,18–20]. Textiles without technology integration are being used for people with dementia to instigate and engage the individual with activities for a considerable amount of time [22]. Recently, there is a strong growth observed in wearable technology due to the availability of inexpensive sensors [22,23]. Though several applications are associated with physiological sensors, none of them are specifically designed for evaluating the life quality of people with Alzheimer’s disease. The interest in manufacturing sensors has been growing in the medical and electronics field as they are tiny and less visible. Thus, it has resulted in the production of smaller computers. There have been a number of studies that have revealed the various methods of incorporating wearable or portable sensors like interlacing the textile material or placing it between two layers of cloth material. The sensor-integrated fabric materials will then be taken for garment manufacturing process [24,25]. In this chapter, the technical and design considerations for manufacturing wearable textile are discussed [26]. The said products can be utilized by aged people or those living in professional care facilities. In addition, it provides an illustration of product development and an integration of electronics in the textile manufacturing process, along with the development of tools for the evaluation of cognitive capacities. Hence, an innovative design is used for the product development for meeting the aforementioned requirements and achieving a balance between personalization and product’s performance. The difficulties associated with scaling up the production of personalized solutions constrains the implementation of textiles [27]. The lab-based prototype is developed with a loosely connected architecture for ensuring the flexibility that is essential for a scalable solution.

7.2.2 Personalized textiles for enhancing the healthy life

People who are living under professional assistance may benefit from therapeutics to provoke their senses and cognitive impairment. These therapies have the ability to assist in alleviating a wide range of dementia-related difficulties [28,29]. The techniques that are utilized in therapy are extremely diverse in nature like dance or movement, music, aroma, and multisensory

and comforting fabric artefacts [30–33]. Quilts and other smaller textiles that are placed on patients when they are sitting or sleeping are included in this category of artefacts. Similarly, aprons used for the neck and back are also included in the artefacts category. These artefacts can be integrated by a variety of characteristics such as playing or fiddling for stimulating the senses. Thus the blankets are also referred as “fiddle blankets”. The features can be integrated through accessories like zippers and fabric pieces. Recent developments include the use of integrated microelectronics, which increase the sensory experience by providing output as light, sound, and other element form [17,21,34]. Further to the above, the customization of the product by adding significant memories of the user in the products which may be associated with people, thing, etc. can further enhance the enjoyment of the user and thus provide a comforting lifestyle.

7.2.3 Study on the application of gamification

At present, mild cognitive impairment cannot be evaluated by any specific test [35,36]. Conventional diagnostic methods based on “neuropsychological battery test” are used [36,37] where there are possibilities for error [38,39]. Moreover, the present methods can only be administered by a trained professional in the clinic which has resulted in higher cost due to employing health care professionals. The majority of research that has been reported for using a clinical consensus method [40] involves multiple clinicians. Hence, numerous research has been conducted on smart textile products for monitoring the physiological parameters associated with wellness [36,37]. In addition, research studies cover various aspects like flexibility and size of the products, i.e. product should be smaller and unnoticed in nature [24,36]. Recently, games have been designed to collect data from patients where the requirements of trained health care professionals can be avoided [38–40]. Games have been developed for providing treatment for several medical conditions [36,37]. These games make use of wearable sensors for assessing the health condition of the playing person. So, these wearable products have the potential of retrieving not only the physiological information but also the mental ability of the person. Moreover, the data is collected continuously with no interference and trained professionals [38]. It has resulted in more accuracy and less bias. The aforesaid wearable devices can be used to collect the health condition of the people with dementia disease or mild cognitive impairment throughout the year or for a specific time period as prescribed by a health care professional. The memory evaluation is conducted using the “Wisconsin Card Sorting Test” where light-emitting diodes (LEDs) and other required electronic parts are placed below the fabric layer [41]. Similarly the other game “master mind” is designed with LEDs and switches for assessing the memory recall evaluation [42].

So, the information can be collected for a specified time period continuously for examining the mental ability of persons with dementia disease, aged people, and people living in care homes [26]. Besides, the elderly residents in care homes are being entertained by designing a personalized, interactive, and amusing cloth.

7.3 GROWTH IN TECHNOLOGICAL CAPABILITIES

In recent years researchers have developed electronic components in miniscule level with the help of microelectronics [26]. It has facilitated researchers to design the circuit in smaller size with the requisite functions like sensing, recording and amplifying the signal, and transmission, etc. The above-mentioned advancements in electronics and material science have paved the way for the development of wearable textiles. Electronic components such as electronic thread, LEDs, microcontroller, and miniscule switches have converted the garment into a mobile workstation like laptop. These integrations are assisting in the collection of various physiological data during the movement or specified activities of either individuals or aged people or people with chronic diseases in medical care facilities. This part provides a review of the relevant literature, delving into topics such as applications of assistive technology, wearable technology, electronic textiles, wearable sensors (biomedical), utilization of wearable textiles for the purpose of evaluating cognitive abilities of the aged or dementia diseased people, and effect on their life quality, as well as games for memory recall assessment.

7.3.1 Study on assistive technology

People with mid cognitive impairment or aged people living in home care environments are being supported with artificial intelligence for assisting their activities along with monitoring [7,8,26]. Further to the above, memory aid devices have been used for improving their living environment and regular day-to-day activities [43,44]. Similarly, products have been designed based on games for entertaining them along with memory recall assessment [45].

7.3.2 Wearable technology

After the commencement of the Smart Modules Programme by the Defence Advanced Research Projects Agency (DARPA), armed forces in the United States have been given wearable textiles for remote monitoring and assistance [46]. Wearable textiles have been widely used for online assistance of patients and people in isolated locations with the help of revolutionized sensing devices, microcontrollers, miniscule level of electronics, and

data analytics [26]. Mostly, the wearable technology is employed for people with physical or cognitive impairment and their treatment and evaluation. Besides health monitoring of an individual, it is used for early disease detection, comfort and safety, etc [25]. Most of these applications are used to monitor the parameters associated with biological systems like heart, lungs, and muscles for maintaining good health [47]. Further, motion detection is employed in the “fall detection system” [48] where the elders are more likely to sustain injuries, both fatal and non-fatal, as a result of falls, which can result in significant financial burdens for medical care. These systems have facilitated people who are chronically ill or aged to live independently for longer periods of time [49]. Body sensor network system has been designed to monitor patients in remote location and providing the necessary wellness assistance, retrieval of their physiological data, and enhancing their memory level. It is referred to as a body sensor network when it is applied to an individual. It also assists the individuals by delivering a variety of health care services like continuous health care monitoring, access to medical data, communication in the event of an emergency, and control of home appliances [50]. The aforementioned services have benefited individuals with varying degrees of physical and mind impairment through the use of implantable body sensor networks [49,51]. Various wearable biomedical systems have been developed for examining the specific functions such as the cognitive stress level in the office, language function by assessing the electrical characteristics, and magnetic characteristics in the brain [50,51]. Smartphone is widely used for deriving the trends based on the collected data [52]. The major design concerns like inconspicuous, mass production, efficient energy consumption, and safety need to be considered during the development of wearable devices [37]. Wearable products such as wrist watch, spectacles are the main products available in the market as they can be fastened to the body easily. Hence, the textile wearable computing products are not yet considered as mainstream devices. Therefore, there is still a requirement for additional research and development in the field of electronic textiles. For the purpose of enhancing human cognition in regular activities in the personal and official environment, a new category of augmented reality application known as Wearable Cognitive Assistance (WCA) has emerged [53]. These applications are highly interactive and sensitive to the context in which they are presented. It is useful to the person who is having mild cognitive impairment due to ageing or brain damage. It is possible for cognitive decline in a variety of ways, such as lack of ability to identify the people, places, things, memory loss for short-time duration and long-time duration, as well as changes in etiquette and appearance. “Google Glass” is one of the assistive systems which helps to perform the difficult task by taking the user view and processing it for tangible intervention [54,55]. WCAs will become an application class that will be widely employed [56] along with the new network infrastructure, namely “5G”,

for computing operations. The other most advancement technologies in various areas such as transmission, sensing, and data analysis are used in the wearable technology [33].

7.3.3 Study on smart textiles or wearable textiles

Smart textiles are produced by using conductive materials, pressure-sensitive fabrics instead of using conventional materials like switches, key-pads, adjustable knobs, and buttons [26]. Fabric will conduct electricity while applying pressure to the materials. This could be due to the reduction in fabric resistance and can attain the level of metal conductivity. Conductive threads are used to produce embroidered electrical circuits. “Wearable textiles” or “smart textiles” or “electronic textiles” or “interactive textiles” indicate the incorporation of electronic components into the textile products [57]. The main purpose of integrating the electronic components to the textile structure is to enhance the interaction of textile products with the external stimuli which is highlighted in the phrase “interactive textile” [58].

Wearable textiles have been categorized into three types based on interaction level, namely passive smart type, active smart type, and very smart type [59]. The passive category products are able to perform sensing operation in the surroundings by using the sensor. The active smart types are having the characteristics of sensing impetuses from the surroundings and integrating an actuator function. Textiles that are very smart are characterized by the ability to sense, react, and modify their behaviour in response to the conditions in the given environments. This classification is helpful for investigating a variety of topics, such as the level of interaction being provided. The field of smart textiles is undergoing rapid development and is located at the crossroads of a number of different engineering fields, including electrical, electronics, computer science, and fashion.

The employment of wearable textiles has revolutionized the health care sector in terms of monitoring the patients, providing treatment, assessing the treatment efficiency, and remote assistance to the patients in care homes or aged people [20]. Recently, wearable products are gaining more importance in mild cognitive impairment treatment [60]. Wearable textiles have been designed based on the customer requirements such as appealing, comfort, monitoring, and safety. Further to this, the performance is achieved by designing the interaction between user and electronic devices. This could lead to connecting the people in a distinctive manner and potentially enhancing existing relationships or accelerating the connection between lonely older persons [61]. These wearable textiles are used to generate large amounts of information and details concerning the lives and bodies of patients.

7.3.3.1 Study on sensor integration

The term “sensorized garments” refers to a subset of e-textiles which has electronic devices. These electronic and sensor components are affixed as well as assimilated with the garment [61,62]. While wearing the garments, few important concerns such as the resistance of conductive substance, flexibility and mechanical deformations that result from stretching need to be considered [19,26]. Continuous monitoring of this kind would be beneficial in a variety of domains, including health care, fitness, and the workplace, among others. One variation of this strategy involves coating various fibres like cotton, nylon, etc. with metallic substances like copper and silver. These fibres can be utilized in the knitting, weaving, or embroidery of garments and thus producing garments with electrical conductive characteristics. In addition to the above strategy, a conductive layer can be printed or coated onto a non-conductive substrate for making it conductive [25]. Textiles are manufactured with sensing structures or measuring devices through processes which are suitable to the textile industry [61,63]. Measuring device should be included into the textile as an integrated part of the garment which may use maximum region of the fabric and clothing properties. These sensing devices can perform the activities like capacitor, inductor, and biopotential electrodes. The emphasis is placed on sensor structures inside the textile, rather than solely communication [64]. It is essential to envisage a distinct division between the products like fabric, apparels, electric and electronic platforms, applications, and sensing devices. In this study, unstructured sensor layer is incorporated with the textile material during the manufacturing process. It can be illustrated by imparting surface finish to the whole materials in the finishing process. In another illustration, two-dimensional grids of metallic threads are interlaced alone or with other insulating threads during the fabric formation. In addition to the weaving technique, the sensing materials can be integrated to the textile by printing technique. In all illustrations, the sensing materials do not have any specific constraint.

7.3.3.2 Study on conductive grid

In the earlier research, electronic components and monitoring devices were added to the fabric during the manufacturing process. Though the concept mentioned in this chapter is substantially older than the recent advancements, it has been discussed as the work mentioned in this chapter is similar to the concept that is being presented [26,65,66]. “Wearable motherboard™” or “Smart shirt” has been designed for the continuous detection of physiological parameters of a person either in person or remotely using a “platform” for sensing devices [67,68]. This product has been designed for health care applications in the midst of war when soldiers sustained injuries

or bullet wounds [69]. In this structure, fabric is manufactured by using the fibres like polyester, cotton, or its blend. This material is used to provide a base for placing the required electric and electronic components for the “Wearable motherboard”. In addition, the optical fibres or any specified fibres have been used to communicate the data from the user to the sensing devices. Breathing rate has been observed by using the specified monitoring device which is integrated with the fabrics. Microphone is used to record the vocal sound and other important parameters like beating level, breathing level, pulse oximetry (SpO_2), and electrocardiogram (ECG). Certain “islands” can be designed on the garment that can hold sensors, and those sensors can be attached to and removed from those islands. Hence, the sensors can be changed according to the product customization which is the highlight of this development [65].

7.3.3.3 Impact of smart textiles on life quality

It is crucial to note that sensory stimulation is used to enhance life quality and assisting the aged people, particularly those living with dementia [21,26]. The patients are engaged and entertained by “comforting fabric artefacts”, which are supplemented by electronics in terms of music, lights, etc. It is necessary to come up with new ideas in order to minimize the expenses and reduce resource consumption [34]. These e-textiles have been produced by incorporating various features like playing of music with on/off provision in the fabric, LED-based games, flexibility, and free from electrophoresis [70].

For many years, music has been recognized as a treatment (intervention) for individuals with dementia [32]. The results of this study revealed six primary reasons for the continued use of music as a form of therapy. It has been observed that music has a role more than just reducing behavioural and psychological issues. It also enhances the life quality and cognitive performance in patients with dementia [31]. The identification of cognitive impairment is the most appropriate point at which to initiate the investigation of preventative therapy. Testing for mild cognitive impairment is a laborious process that necessitates the administration of the test by a physician or psychologist in order to obtain original data. This entails the introduction of bias and an increase in expense.

Among the tools that have been utilized in the past for the purpose of examining dementia are the “Memory Impairment Screen, the General Practitioner Assessment of Cognition, The Montreal Cognitive Assessment, Mini-mental state, Telephone Interview of Cognitive impairment, and the Cog State Brief Battery” [61–63,71–73]. Before the aforementioned techniques, patients with dementia were assessed by the health care professionals through observation and interrogation, and family member’s observation [74]. In addition, other tests used for the assessment are

“Wisconsin card sorting test” and clock drawing test where people have been asked to sketch the clock in a given time [75,76]. Both of these tests are memory-based exercises. Utilizing the technology is more important during the test administration to the patients. CogState Brief Battery questions is the example for assessing psychomotor functions [63].

7.3.4 Study on games in cognitive tests

Wearable sensors have been used in the creation of games that have been used as a treatment for a variety of medical conditions [75]. These sensors have been used for observing the player of the game [26]. It has been revealed from the findings of the research that memory game has been considered as worthwhile treatment for dementia disease [69] because this tool can be used in assessing the decrease and improvement of cognition ability of an individual. It assists the aged or dementia diseased people in terms of more engagement, decreasing the incidence of dropouts, increasing the interest for continuing the game by participation, increasing mental ability and enthusiasm, and precise data collection without any intervention, which are all outcomes that can be improved by the use of gamification in cognitive activities [77]. On the other hand, it is essential to confirm that the data collected through games should be aligned with the scientific value of the subject matter [71]. Generally, the methodologies for assessing the user are followed by creating happiness and enjoyment to the user. Moreover, trained health care persons are not required to administer or monitor the activity which would incur additional costs. On the other hand, it is necessary to understand that there will still be a cost associated with the analysis for the collected information.

7.3.5 Study on wearable technology characteristics requirements

It is essential that wearable technology should be both functional and economical. The cloth used in the product should have less weight and be flexible which has resulted in producing thin circuit and flexible one. Accordingly, circuit layouts or “circuit board fabrics” should be designed with screen, sensors, and power source, etc. Power source is preferred to be in movable and rechargeable type in order to use the product in a flexible manner. Hence, the size of power source or cell, method of charging, and charging time are some of the important areas of concern. As e-textiles have been used for long hours, some of the wearability characteristics like comfort, including weight and other characteristics such as ability to connect, long lasting, dimension retention, caring with less effort, production feasibility and cost-effectiveness, are to be considered in designing. Similarly, the other electric and electronic components should have

adequate resistance to thermal conductivity, electrical conductivity, bending rigidity, and ease of handling and fixing in the circuit with the other components like computer and processors [74]. It has been observed from the market understanding that the available e-textiles have been produced with low volume and special purpose only. It could be due to the limitation of material and expensive technology used for the production. Hence, the wearable textiles need to be mass-produced in order to be economical which is a main concern in terms of the cost of materials and manufacturing process. Moreover, it must be compatible with the general machinery used in manufacturing. This presents a challenging obstacle for emerging products like smart clothing and textile electronics. Further to the above, the ease with which they may be connected to a power source, data transmission through Bluetooth or Wi-Fi, privacy, and security are some of key factors to take into consideration.

7.3.5.1 Technical details of hardware system for MCI assessment

Hardware system is produced for entertaining or monitoring the physiological behaviour of the aged or people with declining cognition level. Specified music as well as games have been used for prototype physical computing. Microelectronics, sensors, fabrics, battery, and data logging system have been used for basic interactions between patients and textile [78]. The feedback is incorporated by light and sound which is achieved by using speakers and switches [79,80]. Fabric has been designed based on the user's persona which is obtained from the relatives of the user [81]. Owing to greater packaging and moisture protection, normal tactile switches are more difficult to operate. Toggle switches, on the other hand, can be manipulated which should conform to respective standards. It can be operated when the switch is attached firmly with the body. Additionally, the switches are physically larger and require more force to work. Textile layer contains the details of persona which is freely attached with the bottom technological layer through capacitive sensing. This kind of attachment provides the flexibility in terms of alternate textile layer attachment which may be designed by the experts in the textile field according to the user or patient. The data for designing the upper layer may be retrieved from the aspects like self-esteem, familial troubles, psychological suffering, and daily concerns, etc. [26,82,83]. The bottom technological layer houses all components associated with sensing, data transmission, and output signal etc. It is produced with soft, malleable layer of thin felt sheeting that protects the patient from the integrated electronics, reducing their visibility. The technology layer has been waterproofed before being coupled with the textile layer. This layer is physically attached with various components such as capacitive sliding sensor, touch sensors, a detector for the sensors,

an eight-channel multiplexer, and a game-switching LED array. Sensors are connected to eight-channel multiplexer through specified detectors. Specified Arduino component is connected to multiplexer, LED, and music player [84,85]. Arduino has been used to change the switches and LEDs with the program used. The designs used in the upper layer will imitate the behaviour of the corresponding things in real life. In this prototype, top layer is designed with cat, butterfly, flower with different colours. Based on the patient's behaviour, the output will be generated in the form of light and sound through LED and speaker, respectively. So, it is necessary to consider the comfort level of user while constructing the electronic components in the bottom layer. Specified lithium-based power source is used which can be designed to charge through wireless type [86].

In this prototype, music is used to reveal the cognition level and sensing ability of the patient. As it is constructed by the microprocessor, it can be used for engaging the aged people or assessing the people with dementia disease. However, the fabrics do not possess any solid structural integrity by their very nature. Hence, there is a limitation with regard to reliability. Further to the above, the electronic components must fulfil the quality requirements for the respective country. Additionally, the other assessment like movement and assessment can be added to the prototype as it is working based on capacitance. The details such as total engagement time, length of each stroke, lighting order of LEDs and duration of lighting, etc. can be collected during the patient's engagement. The data collected during the application is stored in the memory card which can be encrypted further for security reasons [87,88]. As the top layer is made of textile, it is required to be washed periodically. It has benefited by designing free attachment with the bottom layer. On the other hand, the technological components including battery and other electronic components in the bottom layer can be protected by using the polymer layer. Thus, the components have been shielded from any external influences.

7.3.5.2 Study on sliding sensor assessment

The sliding sensor assessment is carried out by varying stroking duration of sliding sensor on the specified range of fabric thickness materials [26]. It has been analysed between the successful detection in percentage and effective thickness of the material for different stroking time duration. It has been revealed from the findings that successful detection decreases with the increase in thickness irrespective of stroking time. The findings also reveal that successful detection is reduced with stroking time reduction. This could be due to the limitation in detecting the predetermined correct sequence by the sensor. It is important to mention that the circuit is designed to activate for predetermined correct sequence only. Software-level adjustments can be made to the response frequency in accordance with user preference.

7.3.5.3 Study on touch sensor assessment

The touch sensor assessment is carried out using two different blocks with specific dimension. Cardboard has been used to protect the measuring element from any influences in the backside [26]. In order to evaluate the effectiveness of the touch sensing capabilities, different specified thickness of the covering material is used. A specific detector chip has been utilized for measuring the sensor signal. During the assessment, switch is positioned in stable position. As part of the performance evaluation, a predetermined number of touches are carried out in a given amount of time. Touch sensor assessment is carried out by finding out the successful detection in percentage against effective thickness of the material for different block size. It has been found from the experiments that the detector plates with a larger surface area offer much superior performance in comparison to those with a lower surface area. As far as thickness is concerned, the percentage of proper detection is quite good up to a specific thickness. Additionally, it has been drastically reduced in thickness above the stipulated threshold.

7.3.6 Study on skin moisture assessment

The presence of moisture level in the skin is used to provide the skin's electrical resistance characteristics which is a straightforward and non-intrusive method due to the fact that variations in skin electrical properties are caused by changes in skin hydration level [89]. Electrodermal function is employed to find the presence of hydration level of skin by using sympathetic and physiological condition which has been assessed by three methods [90]. Monitoring skin conductance or resistance, also referred to as galvanic skin response, is the simplest method. By applying alternating current (AC) or direct current (DC) at a constant frequency, the electrical conductance across two electrodes can be determined. It is well-established that the skin conductivity sensor measures hydration levels in the top layer with remarkable precision. Top layer is referred as stratum corneum (SC). Yet, in comparison to alternative measurement techniques, the dependability of these assessments in identifying pathological skin conditions is comparatively low and good for intact skin [91]. In the other method, the degree of hydration of the skin can be assessed through the capacitance of the skin, as the skin's relative permittivity varies in response to its hydration status. Corneometry refers to the measurement of capacitance and derives its name from the initial commercial instrument, the Corneometer [92]. The conductance and capacitance values in healthful skin are influenced by the hydration on the skin. However, the values are not highly reliable for the skin having less hydration level, like skin issue of lesions and palmoplantar [91]. Comparatively, the assessment of skin hydration level is more comprehensively informed by the evaluation of total impedance in comparison with individual evaluation of capacitance and capacitance.

The conductance and the capacitance of individual skin layers can be determined by using impedance analysis [93–95]. Due to these benefits, numerous studies have utilized wearable sensors like film type to measure skin impedance [96,97]. The impedance value is reduced when the skin moisture level is increased [96].

In order to measure the reliable electrical characteristics of a skin, it is essential for the skin and instrument to be in consistent contact. A substantial amount of research has been carried out related to patch sensor for moisture assessment where less amount of pressure is given to the skin during measurements. Moreover, it is used to observe the physiological data continuously and able to cover a substantial area of skin while simultaneously ensuring proper conformation with curved body parts. These sensors are constructed from flexible materials, such as polymer thin films like polydimethylsiloxane (PDMS) elastomer, which contrasts with discrete bar-type skin hydration sensors that are presently available in the commercial market [91].

Composites composed of polyurethane and conductive reduced graphene oxides used in the skin sensor detect the resistance variations based on the moisture level. In some flexible sensor for skin moisture assessment studies, spectroscopies are used to measure the impedance. It has been revealed from the findings of the study that ultrathin skin hydration sensor composed of polyimide is used for the development of epidermal electronics where the resulting ultrathin sensor adheres to the skin successfully through weak molecular force like van der Waals, enable to retrieve spectra associated with impedance from the epidermis [98].

Fabric has been utilized as a substrate for a skin sensor, thereby increasing its flexibility and wearability [89]. A stable signal could be obtained by the highly flexible textile-based sensor by virtue of its uniform attachment with the epidermis of uneven body parts like face, heel, etc. The substrate material selected for the skin hydration sensor has been a woven cotton textile due to its hypoallergenic properties, high air permeability, and extensive applicability in the medical and cosmetic sectors [99,100]. In this research study, skin moisture level is examined by using the wearable sensor where textile substrate is used. Despite the fact that polymer films are long lasting by using lithographic processes, a cloth-based sensor for measuring skin hydration has been manufactured by using inexpensive equipment and process. Screen printing has been utilized to imprint silver material onto the textile substrate for creating electrode to measure impedance value.

The stability and dependability of this prototype are improved through the application of conductive adhesive and additional encapsulation material [89]. In this research work, porcine skin samples have been used to assess the skin's impedance value where the samples are either treated with saline or dried for varying the degrees of hydration and AC field with distinct frequencies. In this study, various parameters such as impedance,

capacitance, resistance, and phase shift, etc. have been examined as the skin comprises different layers. Further to the above, the values are collected for varied bending cycles of the samples and compared. Lastly, the hydration status of human skin is estimated based on the impedance readings obtained through specific cotton fabric-based sensor and compared with commercially available skin moisture meter.

7.3.7 Technical details

Cotton fabric with specific dimensions, weave, and yarn characteristics has been selected for use in the skin hydration sensor. A predetermined thickness of thermoplastic polyurethane (TPU) film has been hot-pressed onto the cotton fabric at a specific temperature followed with silver paste and encapsulant being imprinted [89]. Subsequently the materials are dried out at a particular temperature for a specific time duration. Silver-based adhesive is used to coat on the silver paste electrodes' extremities and dried at a particular temperature and time. It was then stored for a minimum of 1 week at room temperature in order to achieve optimal adhesion and sensing performance.

The porcine skin with specific thickness has been purchased and cut into rectangular pieces for the research work. Later, it was dehydrated or immersed in the saline solution for the specific duration and conditions for controlling the hydration level of the skin. Thermogravimetric analysis has been used to assess the moisture content quantitatively. The measurement has been repeated three times with specific temperature levels. Afterwards, the aforementioned skin materials with varied moisture content have been treated with paraffin wax in order to examine each layer for the changes with regard to moisture level. Haematoxylin and eosin have been used to stain the aforesaid sections and slide scanner has been used for scanning.

Initially, uniform adhesion between the sensor and skin was ensured. The impedance characteristics were measured by using cotton-based sensor at a certain voltage and frequency. The said prototype sensor's physical deformation is examined against repetitive stretching and bending by using specific tools and a standard process. Impedance of the skin is measured before and after the stretching cum bending assessment. A cotton-based skin sensor was utilized to measure the impedance of human skin on different parts of the body. Later, the data from cotton-based sensor is compared with data from the available skin moisture assessment sensor.

7.3.7.1 Study on cotton-based skin sensor

The electric characteristics of the skin are assessed using the electrodes in the sensor for assessing the skin moisture level. The skin's thickness is usually said to fall within a certain range including all layers such as SC, the epidermis, and the dermis [101–103]. The length, width, and space between

two straight lines of electrodes have all been carefully planned. The electrode gets wider when depth of entry goes up [89,104–106]. If the width of electrode is smaller, it would be difficult to reach all the layers of skin. Additionally, the process of manufacturing would be more difficult. When the electrode width is too big, the electric field assessment will be more than the skin thickness that requires to study. Hence, specific formula is used to calculate the width of the electrode by using the parameters like gap between the two electrodes, width of the electrode, and penetration depth. Electrodes have been selected based on their width in relation to the thickness of the skin for assessing entire thickness of the skin [107]. Moreover, electric field frequency also affects the depth of entry, i.e. electric field is less with more electric frequency.

The cotton cloth-based sensors have been chosen for developing the prototype. It is used a lot in medical goods and cosmetics because it is hypoallergenic, comfortable to wear, and air permeable. In addition, woven cotton has a naturally hairy, porous, and rough structure. TPU is been laminated on cotton fabric material for creating a smooth, flat surface that makes the electrodes more stable and gives them more consistency and flexibility.

To make electrodes, the Ag paste is imprinted on the cotton substrate in two horizontal lines. In order to sense, the electrodes must come into close contact with the skin at their ends. An extra conductive glue is used to cover the areas so that they can make a good bond with the skin. An outside impedance tester is linked to the other end of electrode. An insulating encapsulant made of urethane resin covers the electrodes' surface, but not the parts used for sensing or connecting. With the encapsulant, the sensing region is separated from the connection points for getting accurate and stable electric signal readings. The encapsulant also makes the sensor last longer while keeping its flexibility.

7.3.7.2 Study on the effect of storage conditions of porcine skin' moisture level

Porcine skin has been used as a sample as it has similar morphological and physiological characteristics of human skin [89,108]. For varying the moisture level of porcine skin, it is dried or soaked in saline water under certain conditions. It has been observed from the results of the experiments that the skin becomes more moist and puffy as the amount of time spent soaking increases [109]. For example, the thickness of the skin top layer, which is the outermost yellow layer of the porcine skin, increases due to swelling with increased soaking time duration.

7.3.7.3 Study on the impedance analysis of porcine skin

Generally, mammal skin has three layers, namely, SC, epidermis, and dermis which includes human beings and porcine. The top layer is made up of

dead cells that do not contain a nucleus owing to the keratinocytes' differentiation from the epidermis [89,110]. This layer has less moisture content and thickness is around several tens of micrometres. Moreover, the impedance properties are different from inner layer, viz. epidermis [106]. The epidermis, which lies underneath the SC, is a hydrophilic layer. In this layer, skin impedance is influenced by the keratinization of viable keratinocytes. The innermost layer, namely dermis, has nerves, glands associated with sweat, blood vessels, and hair follicles. A cotton fabric-based sensor is used to measure the skin impedance. The parameters such as resistance and capacitance are measured at the interfaces of the electrodes, the top layer and the middle layer, i.e. R_{se} , C_{se} [111]. At low frequencies, the diffused reactive species and ions in the skin are recognized which aligns with Warburg impedance (Z_w) [112]. The deepest layer as well as the tissues that lie beneath it have been considered as a resistor R_d . The complete structure is expressed as $C_{se} - Z_w$ and R_{se} are in parallel, $w R_d$ is connected in series [111]. In order to study the impact that the amount of hydration of the skin has on the impedance characteristics, an in-depth investigation of Electrochemical Impedance Spectroscopy (EIS) has been carried out. Initially, the impedance is examined by using frequency and impedance in Bode magnitude plot. It has been found that skin impedance magnitude is decreasing with the increase in moisture content. Hence, impedance is considered as a measurement gauge for assessing skin moisture level.

For obtaining more specific information regarding impedance components, a Nyquist plot is constructed for the different moisture levels. It has been revealed that resistance of the dermis (R_d) does not change irrespective of moisture content. Hence, it has been concluded that dermis is not significantly influenced by the skin's moisture level. In contrast, R_{se} decreases with increased moisture content. Hence, the skin bulk resistance is calculated by the sum of two resistances at low frequency where resistance of the dermis is only used at high frequency. Moreover, the impedance value is decreased with increased moisture level owing to the decrease in R_{se} . In order to verify that the sensor is reliable, the impedance of the skin has been measured three times for each level of moisture and assessed using Nyquist plot.

The capacitance (C_{se}) is decreased with increase in frequency which could be due to reduction in dielectric permittivity of tissue at higher AC frequency [93,113,114]. Further to the frequency, skin hydration is also influenced by the capacitance value, i.e. the capacitance is increased with the increase in skin moisture level. This is due to the increasing dielectric constant value of the top two layers. It has been further explained that phase becomes closer to 0° for more AC frequency which is due to the parallel connection between capacitor (C_{se}) and resistor (R_{se}) and resulted in more current flow. It has been summarized that dermis resistance is not affected by the skin moisture level. Moreover, the impedance of the skin is

influenced by the respective component in first two layers, namely SC and epidermis. The moisture level of the skin is measured by using phase shift, resistance and capacitance, impedance at the interfaces of the electrodes, the top layer, and the middle layer.

7.3.7.4 Study on performance of cotton-based skin sensor

The performance of the sensor is assessed by its long-lasting and bending behaviour during the usage as it influences physical deformation of the material [89]. The aforementioned parameters are affected by the level of conformity with the parts of body. Moreover, it has been influencing the assessment behaviour and reliability. Hence, the electrical signals have been examined under repeated specified number of bending cycles for examining the physical deformation. The resistance value is increasing with the increase of specific bending cycles, afterwards, the value becomes constant. However, there is no discernible difference in the impedance values as a result of the bending cycles. It is likely that the increased resistance of the electrodes is the cause of the minor rise in impedance values that is caused by the bending cycles. The sensor is able to generate a consistent electrical signal even when subjected to repetitive bending cycles because it is both flexible and sturdy.

Tensile strain is also experienced by the electrodes due to the fact that the sensor must be mounted in a conformal manner to the curved surfaces of the skin. It has been revealed from the experimental analysis that resistance is increasing with the strain till the specific strain value. Afterwards, the resistance has increased drastically. The functioning of the sensor is not anticipated to be negatively impacted by the skin's mobility, which is considered to be light and moderate.

7.3.7.5 Study on cotton fabric-based skin sensor on human skin

Two distinct sets of experiments have been carried out for demonstrating the usage of cotton-based skin sensor. In the first experiment, impedance values for various body parts are measured. In the second experiment, impedance of hand skin is measured based on time. In this research work, impedance of specific four body parts has been measured using the prototype developed. The degree of callus formation and the manner in which one takes care of their skin both have an impact on the moisture level of each individual body part [89,115]. For instance, elbows and heels are noticed with higher degree of callus formation due to more frequent frictions and resulted in less moisture level in comparison to cheeks. Accordingly, the impedance of the cheeks is the lowest, while the impedance of the heels is the highest. In addition, it has been observed that a body part with lower

skin moisture content exhibit a higher standard deviation of impedance value. The moisture level in the top layer has affected the sensor adherence. The inverse impedance values depend on moisture content. It has been confirmed by comparing the reciprocal value of moisture content measured by the instrument available in the market and the impedance value assessed by the cotton fabric-based skin sensor.

In another experiment, hydration level of hand is measured by impedance value over the specific period of time and after washing. It has been observed from the results that the impedance value is increased progressively with time as the skin's moisture level is decreased after hand washing. A similar pattern is noticed in the commercial instrument available in the market.

It is important to note that the cotton fabric-based skin sensor has produced less standard deviations than the commercial sensor while carrying out repeated measurements.

The reason for improved measurement repeatability of the cotton-based skin hydration sensor is that it maintains a steady conformal contact with the skin while having only a little amount of pressure applied to it. Because of this, the cotton fabric-based skin sensor has the potential to successfully detect the varying degrees of hydration that human skin possesses and for different time periods.

7.4 CONCLUSION

In wearable textile, components associated with sensing or monitoring, processor and transmission devices are integrated with the textile materials in the manufacturing process. This kind of prototype can be produced in large scale only when the industries are having ability to adopt weaving or knitting techniques. The knitting technique has been considered as a flexible method for producing this wearable textiles as the materials and technology can be easily incorporated. Similarly, another architecture for smart textile product development is the layering technique. Here the layers have been coupled in loose structure with the great flexibility for manipulating various functionality-based electronic devices as well as maintenance of textile materials. Moreover, this method has the potential to protect the various electronic components, and LEDs, etc. in the technological layers. Textile layer can be customized based on the patient's characteristics and monitoring requirements such as cognitive assessment, entertainment, etc. A cotton-based wearable sensor has been developed for monitoring the skin hydration level through impedance evaluation. Porcine skin has been used in the experiment as it resembles the characteristics of human skin. The cotton-based skin sensor has been used to monitor the moisture level of the skin in different areas of the human skin and different time periods. Hence, it has been concluded that the blend of electronics with conventional

textile materials is the need of the hour for meeting the consumer needs in various sectors like health care, biomedical, sports, environment, etc. Several studies are underway to develop smart textiles in a sustainable manner with less cost of production and user friendliness. Further to the above, research is focused towards the creation of improved life quality and better environment.

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Recent advances in MXenes and their composites for flexible electronics

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8.1 INTRODUCTION

MXenes to the electronics and materials science sectors, a paradigm shift has started that is creating previously unthinkable potential for the creation of flexible electronics [1]. The excellent mechanical strength, amazing flexibility, and high electrical conductivity of MXenes, a family of 2D transition metal carbides, nitrides, and carbonitrides, have aroused a great deal of attention [2]. This work aims to present a thorough study of the latest developments in MXenes and their composites for application in flexible electronics. The purpose of employing MXenes in composite materials, the importance of flexible electronics, and the inherent qualities of MXenes will all be covered in this chapter [3]. A high-level overview of MXenes, their synthesis processes, and their applications is shown in Figure 8.1.

Materials scientists and nanotechnologists have studied MXene two-dimensional materials [4]. The transition metal carbides, nitrides, and carbonitrides family may explain some of these compounds' structural differences [5]. The precursor MAX phases form the aluminum 'A' layer for MXene [6]. The layered structure is $M(n+1)X_nT_x$, where M is a transition metal, X is nitrogen or carbon, and T is a hydroxyl or oxygen group surface termination [7]. MXenes' unique properties benefit many applications. MXenes' metallic properties explain their high electrical conductivity [8]. Due to their large surface area, MXenes are excellent for energy storage devices such as batteries and supercapacitors [9]. MXenes' strength, flexibility, and other mechanical qualities make them ideal for flexible electronics and structural materials.

The exceptional chemical reactivity and compatibility of MXenes with various functional groups are further enhanced by the wide range of surface alterations that may be made for particular purposes due to their surface terminations [10]. MXenes' superior thermal stability, which enables their usage in a range of high-temperature applications, is another benefit [11]. As researchers continue to improve MXenes' manufacturing processes and maximize their features, several industries, including energy storage, electronics, catalysis, and sensing applications, stand to gain significantly

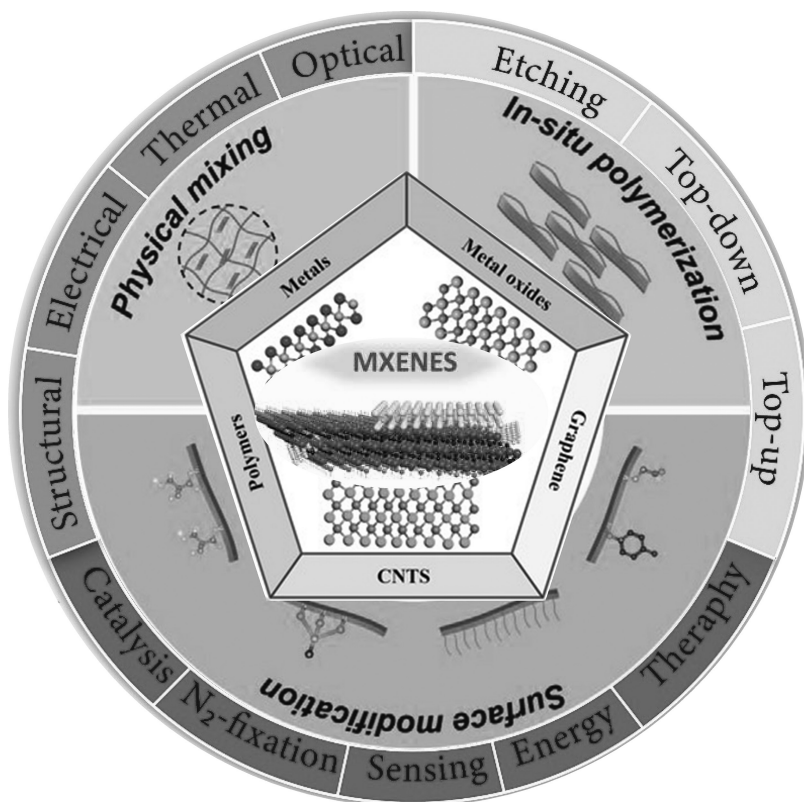


Figure 8.1 An overview of MXenes, their synthesis techniques, and uses.

from them [12]. Studying MXenes is an exciting field of materials science that requires constant work to realize its full potential and remove obstacles to its implementation in real-world applications.

MXenes possess a unique planar structure resulting from the selective removal of precursor MAX phases, enabling their seamless integration into flexible electrical devices [13]. MXenes possess intrinsic metallic conductivity, which enables efficient charge transmission. This characteristic makes them very suitable for use in flexible electrodes, interconnects, and other crucial components of flexible electronics [14]. The inherent pliability and resilient mechanical characteristics of MXenes facilitate the advancement of malleable and extensible electronic devices [15]. The capacity to adapt to the human body is crucial in applications such as wearable electronics, making this flexibility highly useful. The capacity of MXenes to endure mechanical strain while maintaining their electrical performance positions

them as crucial contributors in the quest for robust and versatile electronic solutions [16]. In addition, the compatibility of MXenes with different functional groups on their surfaces enables customized alterations, hence improving their incorporation into flexible electronic systems [17]. The simplicity of surface functionalization provides opportunities for enhancing interactions with other materials, enhancing adhesion, and broadening the scope of applications. MXenes are crucial in propelling the progress of wearable gadgets, flexible screens, and stretchy sensors in the continuously changing field of flexible electronics [18]. MXenes play a crucial role in enhancing the overall performance and endurance of electronic devices, going beyond their mere mechanical flexibility [19]. Continued research in this sector suggests that MXenes have the potential to drive significant advancements in flexible electronics, enabling the development of technology that can smoothly adapt to the dynamic and deformable aspects of our everyday lives [20].

The flexible electronics community has lately shown a great deal of interest in composites based on MXene because of its special mix of characteristics, which enable them to overcome significant issues in this field [21]. MXene-based composites are a good option due to their remarkable mechanical robustness, electrical conductivity, and pliability [22]. MXenes are good conductors due to their metallic properties, which let electrical charges flow easily throughout the composite. This feature is very helpful in flexible electronic applications since it is essential to preserve conductivity even when mechanically distorted [23]. By adding MXenes into composites, the mechanical qualities, overall strength, and longevity of flexible electronic devices are all enhanced. Since MXene-based composites can tolerate bending and stretching without compromising their structural integrity, they are perfect for application in flexible displays and wearable electronics [24]. MXene-based composites provide an adaptable foundation for customizing material characteristics to meet particular requirements. Their surface may be readily modified to increase adhesion, improve the overall performance of the flexible electronic device, and improve compatibility with other composite components [25]. The composite's qualities may be adjusted to match the unique needs of each application because of its malleability.

This chapter explores the most recent advancements in MXenes and their composites for application in flexible electronics. It clarifies the benefits of employing MXenes in composite design, the characteristics of MXenes themselves, and the expanding significance of flexible electronics. These materials are pushing the frontiers of innovation and offering a future where electronic gadgets effortlessly blend into our daily lives with unsurpassed adaptability and flexibility, thanks to MXenes' exceptional qualities and the demands of flexible electronics.

8.2 OVERVIEW OF MXenes

8.2.1 Definition and characteristics of MXenes

MXenes are a novel family of 2D materials with a unique structure that is described by the formula $M_{n+1}X_nT_x$ [26]. The letter M in the formula stands for a transition metal (titanium, tantalum, or niobium), whereas the letter X stands for carbon or nitrogen. The subscript n indicates the number of layers, emphasizing MXenes' fundamental two-dimensional characteristic [27]. Figure 8.2 illustrates the significant compositions of the MXene structure, which include M_2CT_x , $M_3C_2T_x$, $M_4C_3T_x$, and $M_5C_4T_x$. These compositions represent distinct arrangements of metal carbide core layers.

Crucially, the presence of metal carbide core layers distinguishes MXenes. One of the main factors contributing to MXenes' exceptional mechanical qualities is their increased structural stability, which is a result of these layers [28]. The core structure of transition metal carbides is strong and durable; it frequently has a sandwich-like appearance when combined with layers of carbon or nitrogen. This particular structure improves both the mechanical toughness and the capacity to insert other functional groups [29]. These functional groups have a major impact on the surface characteristics and chemical reactivity of MXenes.

The functionalized surface of MXenes sets them apart from other materials. The surface terminal, represented by the letter T in the formula, may

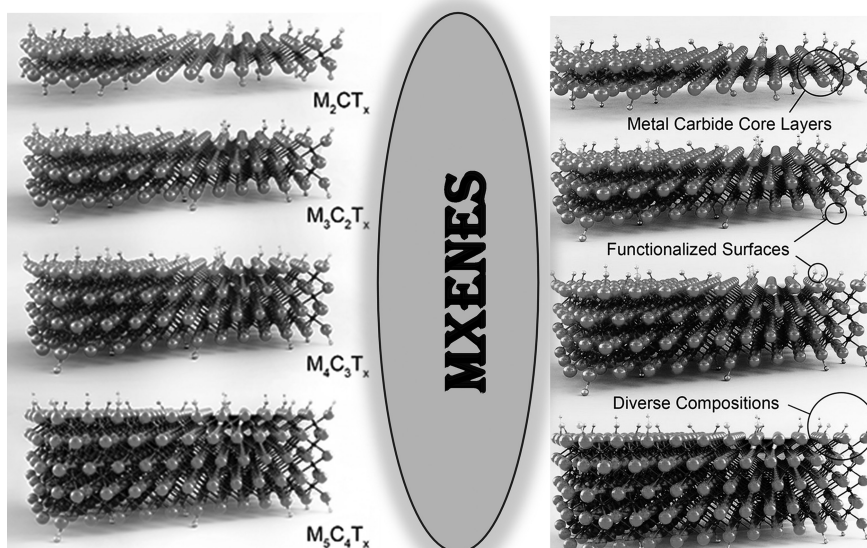


Figure 8.2 Structure of MXenes.

include fluorine, oxygen, or hydroxyl groups [30]. The terminations have an impact on several characteristics of MXene, including electrical conductivity, chemical reactivity, and wettability. Hydroxyl-terminated MXenes are perfect for water-related applications due to their water-interacting nature [31]. On the other hand, fluorine-terminated MXenes are hydrophobic, which means they don't like water. Functionalized surfaces not only improve MXenes' compatibility with other materials but also increase their versatility in electrical devices and composites [32].

When additional MXene chemicals are added to them, they become considerably more desirable. Scientists can modify the ratio of metal to carbon or nitrogen and replace it with alternative transition metals to customize MXene's characteristics for certain uses. Because of their versatility, MXenes have been the subject of substantial study in a wide range of domains, such as sensing, energy storage, and catalysis [33,34]. MXenes (M_n+1X_nTx) are composed of metal carbide core layers with functionalized surfaces and different compositions. These compounds are very sought-after for a variety of high-tech applications due to their many appealing qualities.

8.2.2 Synthesis methods and structural properties

To create MXenes, a certain procedure is utilized to extract the 'A' layer from the MAX phases. Aluminum or silicon is frequently found in the 'A' layer. The intended MXene layers may be retrieved using this technique [35]. During the etching process, hydrofluoric acid or a mixture of hydrochloric acid and lithium fluoride are frequently employed as acidic treatments [36]. Numerous synthesis techniques, such as chemical etching and electrochemical processes, have been devised to generate MXenes with precise control over thickness, composition, and surface termination.

A metal carbide core is surrounded by layers of carbon or nitrogen, which defines the layered structure of MXenes. The layer thickness of MXene may be precisely controlled throughout the production process, ranging from a few nanometers to tens of nanometers. MXenes have special electrical and mechanical characteristics that allow them to be regulated in thickness, which makes them valuable in a variety of applications [37]. The surface terminations produced during the etching process have a significant role in defining the structural characteristics of MXenes. MXenes with an oxygen terminal are perfect for applications involving water because they tend to draw water [38]. MXenes with fluorine ending display hydrophobic properties and water resistance. Because of its adaptability, MXene's properties may be tailored to match the unique needs of various applications by adjusting its surface chemistry.

By carefully adjusting the synthesis conditions, which in turn impacts the phase composition and crystallinity of the resultant compounds, a high degree of crystallinity in MXenes may be attained. The outcome is an improvement in the mechanical and electrical characteristics [39]. Furthermore, the

etching procedure and the precursor MAX phase material used are crucial in determining the particular metal carbide core, which affects the overall structural stability of the MXene. MXenes' synthesis techniques and structural characteristics are closely related to one another. Because MXene is malleable and easy to manage for surface terminations and etching procedures, it has a wide range of possible applications, including energy storage and electrical devices [40]. Table 8.1 shows the MXenes as well as their synthesis methods, structural traits, advantages, and disadvantages.

Table 8.1 MXenes with synthesis methods, structural properties, advantages, and disadvantages

<i>Synthesis methods</i>	<i>Structural properties</i>	<i>Advantages</i>	<i>Disadvantages</i>	<i>Ref.</i>
Liquid exfoliation	Layered MXene structure with -OH or -F termination	Scalable and low-cost production	Limited control over layer thickness	[41]
Etching of MAX phases	Transition metal carbide or nitride layers	Large surface area for applications	Requires strong etchants for MAX phases	[42]
Chemical vapor deposition (CVD)	Uniform coating of MXene on substrates	Controlled film deposition	Limited to specific substrates	[43]
Hydrothermal synthesis	MXene sheets with various terminations	Mild reaction conditions	Longer reaction times	[44]
Mechanical delamination	Delaminated MXene layers	Minimal chemical usage	Energy-intensive process	[45]
Electrochemical etching	Controlled removal of A-layer from MAX phases	Tunable electronic properties	Limited scalability for bulk production	[46]
Oxidative etching	Introduction of oxygen-containing groups in MXene layers	Enhanced hydrophilicity	Requires careful control of oxidation	[47]
Aluminum-based etching	Aluminum intercalation in MAX phases	Altered electronic and mechanical properties	Limited to specific MAX phases	[48]
Molten salt synthesis	Molten salt intercalation in MAX phases	Enhanced structural stability	High-temperature process	[49]
Selective etching	Removal of specific layers in MXene	Tailored properties for specific applications	Requires precise control over etching	[50]

8.2.3 Unique electrical and mechanical features

MXenes have exceptional electrical and mechanical properties, distinguishing them prominently in the realm of 2D materials. The high electrical conductivity of MXenes is a direct outcome of their transition metal carbide core, which permits efficient electron transport [51]. MXenes have favorable properties that make them well-suited for many electronic applications, particularly as electrodes in energy storage devices such as supercapacitors and batteries. The modifiable electrical properties of MXenes result from their ability to modify their surface terminations [52]. Oxygen-terminated MXenes exhibit high efficiency as n-type semiconductors, while fluorine-terminated MXenes have insulating properties. MXenes possess a diverse array of electrical properties, enabling their use in various electronic devices such as field-effect transistors and sensors.

MXenes demonstrate remarkable mechanical robustness and pliability. The inclusion of metal carbide core layers guarantees the material’s structural integrity, hence augmenting its exceptional mechanical stability [53]. MXenes have remarkable mechanical robustness, maintaining their electrical properties even when subjected to significant deformation. These properties make them very suitable for applications that require materials that are both strong and flexible, such as wearable electronics and flexible energy storage devices. MXenes have remarkable electrical and mechanical properties, distinguishing them from conventional two-dimensional materials [54]. These materials are flexible and may be employed in many applications such as energy storage and electronics due to their high conductivity, changeable electrical properties, and excellent mechanical strength. The continuous advancement in MXenes’ research is anticipated to expedite the advancement of innovative technologies and materials in the fields of materials science and engineering, due to their distinctive attributes. Figure 8.3 shows the synthesis methods, and structural, mechanical, and electrical properties [55].

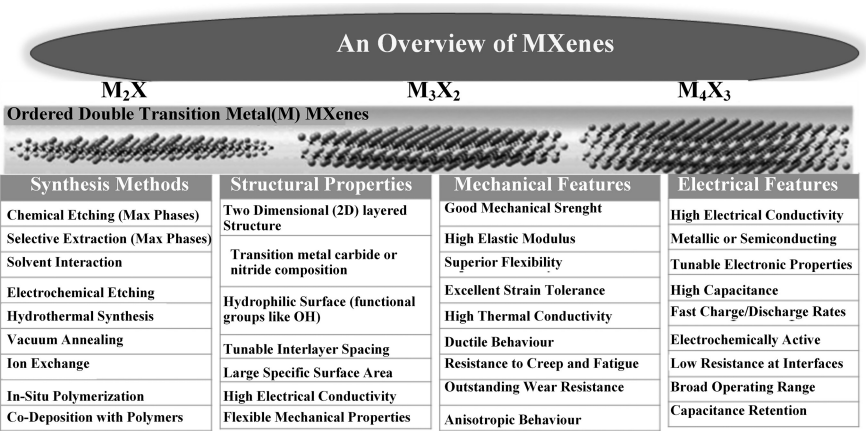


Figure 8.3 Synthesis methods, structural, mechanical, and electrical properties.

8.3 MXenes IN FLEXIBLE ELECTRONICS: BENEFITS, USES, DIFFICULTIES, AND OPPORTUNITIES

Researchers have recently investigated the incorporation of MXenes into flexible electronic systems, including flexible sensors, wearable electronics, and energy storage devices. The distinctive amalgamation of electrical conductivity and pliability in MXenes enables the creation of sensors capable of adapting to uneven surfaces, hence opening up new possibilities for innovative applications in healthcare, environmental monitoring, and human-machine interactions [56]. An important use of MXenes in flexible electronics is in the realm of energy storage. MXenes have been utilized as electrodes in flexible supercapacitors and batteries, capitalizing on their substantial surface area and effective charge storage capacities [57]. MXene-based energy storage devices have the requisite adaptability to be seamlessly incorporated into wearable electronics and other pliable systems.

Recent work has emphasized the techniques used to synthesize MXenes with customized properties, enabling researchers to precisely adjust their attributes for particular uses in flexible electronics [58]. Furthermore, endeavors have been undertaken to enhance the scalability and cost-efficiency of MXene manufacturing methods, aiming to overcome obstacles that might impede their general use. Recent research has focused on the functionalization of MXenes to improve their performance in flexible electronic systems. By investigating surface modifications and compositional alterations, researchers have broadened the range of MXene-based materials' use in flexible electronics, thereby boosting their performance for specific applications [59]. Despite encouraging developments, MXenes are still far from realizing their full promise in flexible electronics because of issues with biocompatibility, long-term stability, and large-scale manufacture. Research into these problems is at an all-time high, with the ultimate goal of closing the knowledge gap between academia and the actual world. In recent years, several studies have investigated the use of MXenes in flexible electronics. For instance, MXenes were investigated in healthcare sensors and in large-scale flexible electronics [60,61]. Findings from these investigations provide fresh light on ongoing initiatives to improve flexible electronics through the application of MXenes' distinctive characteristics.

MXenes have several applications in bendable electronics due to their high electrical conductivity and mechanical flexibility. Environmental sensors and wearable health monitoring systems might benefit greatly from MXenes due to their extraordinary flexibility on non-uniform surfaces. Their use of flexible sensors is another exciting prospect. As an electrode in flexible supercapacitors and batteries, MXenes have shown promise due to their huge surface area and strong charge storage capacities [62]. This might lead to its usage in energy storage applications.

Several benefits are associated with MXenes in the context of flexible electronics. They have excellent electrical conductivity, which allows for efficient charge transfer, and they can be manually twisted and stretched into electronic components. In addition to being innately lightweight, MXenes have excellent thermal stability, making them perfect for applications that value weight, such as wearable electronics, and extending the lifespan of flexible electronics.

Nevertheless, integrating MXenes into bendable electronics is not without its hurdles. Researchers have started looking at the long-term degradation and durability of MXene-based products since people are worried about these things. Biocompatibility is a crucial factor to consider whenever there is direct interaction with living tissues. To make commercial applications affordable and scalable, advancements in technologies for mass manufacturing are required. Among these problems, there is enough space for more research and innovation. Scientists are now exploring new ways to create and modify MXenes to modify their characteristics for specific uses. There is a great opportunity to address issues with large-scale manufacturing by enhancing techniques of scalable production. By integrating MXenes with other state-of-the-art materials, it is also feasible to construct hybrid systems that are more efficient and practical.

8.4 MXene COMPOSITES IN FLEXIBLE ELECTRONICS

Recent research on MXene composites in flexible electronics has significantly advanced our understanding of these materials and their potential uses. Scientists have extensively studied the production of MXene composites, aiming to customize their characteristics to suit certain flexible electronic uses. An investigation conducted by Zhang et al. (2023) examined the production of MXene-polymer composites that had adjustable electrical conductivity [63]. The study showcased the composites' capability in flexible sensors, highlighting their improved sensitivity. This study emphasizes the significance of accurate manipulation of the composite structure to get certain performance metrics.

Composites based on MXene for flexible supercapacitors were demonstrated to be superior to their predecessors in research conducted by Luo et al. (2022) [64]. The combination of MXenes with conductive polymers resulted in enhanced mechanical flexibility and electrochemical performance, according to the findings. These discoveries are critical to the integration of flexible energy storage devices into wearable electronics and other portable applications.

Research on improving MXene dispersion inside composites has recently been conducted. Maintaining the mechanical and electrical conductivity characteristics of the matrix material requires an even dispersion of MXene flakes throughout the material. Researchers like Wang et al. (2022) have

looked at surface functionalization and enhanced processing procedures as two possible answers to these issues [65]. Their study's findings provide light on how to mass-produce high-performance MXene composites. Current research also addresses the usage of MXene composites in new technologies such as flexible optoelectronics. MXene-polymer composites have the potential to be used in the creation of transparent conductive films that are flexible and impermeable [66]. Flexible displays and electronic skin are two potential uses for these materials. The versatility of MXene composites is demonstrated by these discoveries in numerous domains of flexible electronics.

Recent studies on the use of MXene composites in flexible electronics have significantly increased our knowledge of these materials and their possible uses. Researchers are tackling a wide range of issues and exploring novel areas, two examples of which include enhancing energy storage performance and increasing sensing capabilities. The advancement of MXene composites, which will enable the creation of more complex devices with superior features and functionality, is crucial for the future of flexible electronics and is the result of all of these studies.

8.4.1 Role of MXenes in enhancing flexibility

New studies have shown that MXenes are essential for making a wide variety of materials more flexible, especially in the field of flexible electronics. Chen et al. (2022) [67] investigated the incorporation of MXenes into polymer matrices and demonstrated that the resultant composites exhibited much greater flexibility. This study demonstrated that polymers may be enhanced with electrical conductivity and maintain their intrinsic flexibility by including two-dimensional MXenes. Because of this discovery, MXenes may find application in stretchy electrical devices and flexible sensors.

Additional information on how MXenes might enhance flexibility is provided by the work conducted by Liu et al. (2022) [68]. The mechanical characteristics and flexibility of MXene-based composites were the primary areas of study. The researchers found the sweet spot between conductivity and flexibility by manipulating the amount and distribution of MXene in the composite. This proves that MXenes can be used for a wide variety of flexible electronics.

As a possible energy storage method, Zhang and colleagues (2023) examined the inclusion of MXenes into flexible batteries [63]. These results shed light on the role that electrodes based on MXene play in the enhanced mechanical durability and energy storage capacity of the system as a whole. Because of its improved electrical and mechanical characteristics, MXenes are crucial to the creation of durable and flexible energy storage systems. The importance of MXenes in enhancing flexibility extends beyond the conventional electrical world. Integrating MXene into flexible

optoelectronic structures was the subject of a recent research by Wang et al. (2023) [65]. Researchers showed that transparent conductive sheets containing MXenes improved electrical performance for flexible displays and sensors. This exemplifies how versatile MXenes are when it comes to technological advancement.

Recent studies have reiterated the importance of MXenes in significantly enhancing the flexibility of many materials. The future of flexible electronics is being shaped by the unique features of MXenes, which have several applications such as energy storage, flexible sensors, and innovative optoelectronic devices. Research like this sheds light on the fundamentals of MXene-based material design and its potential uses, which might lead to more versatile electrical devices.

8.4.2 Flexible substrate integration

Researchers have investigated the idea of depositing MXenes onto flexible materials such as paper or polymers to create electrical devices that are both lightweight and flexible. The study suggests that MXene-based flexible devices might be advantageous for wearable electronics, flexible sensors, and malleable energy storage systems. Even when mechanically distorted, these gadgets can continue to operate electrically. MXenes' malleability allows for the modification of their characteristics to meet certain market demands. The performance and longevity of future generations of flexible electronic devices might be considerably enhanced by the introduction of MXenes onto flexible substrates. Ongoing research aims to increase the effectiveness of these flexible electronics for practical uses by investigating novel MXene compositions and creative integration techniques.

8.5 SYNTHESIS TECHNIQUES FOR MXene COMPOSITES

Numerous methods are employed to optimize the special qualities of MXenes on flexible substrates to create MXene composites for bendable electronics. These synthesis methods have lately been the focus of research into the effectiveness of materials based on MXene in flexible electronic devices.

- a. **In situ growth:** Certain research claims that MXenes can be directly synthesized or deposited onto flexible substrates during the manufacturing process to accomplish in situ growth. By guaranteeing a robust connection between the MXene and substrate, this method enhances adhesion and mechanical qualities [69]. It also enables accurate control of the MXene distribution over the bendable material, as Figure 8.4a demonstrates.

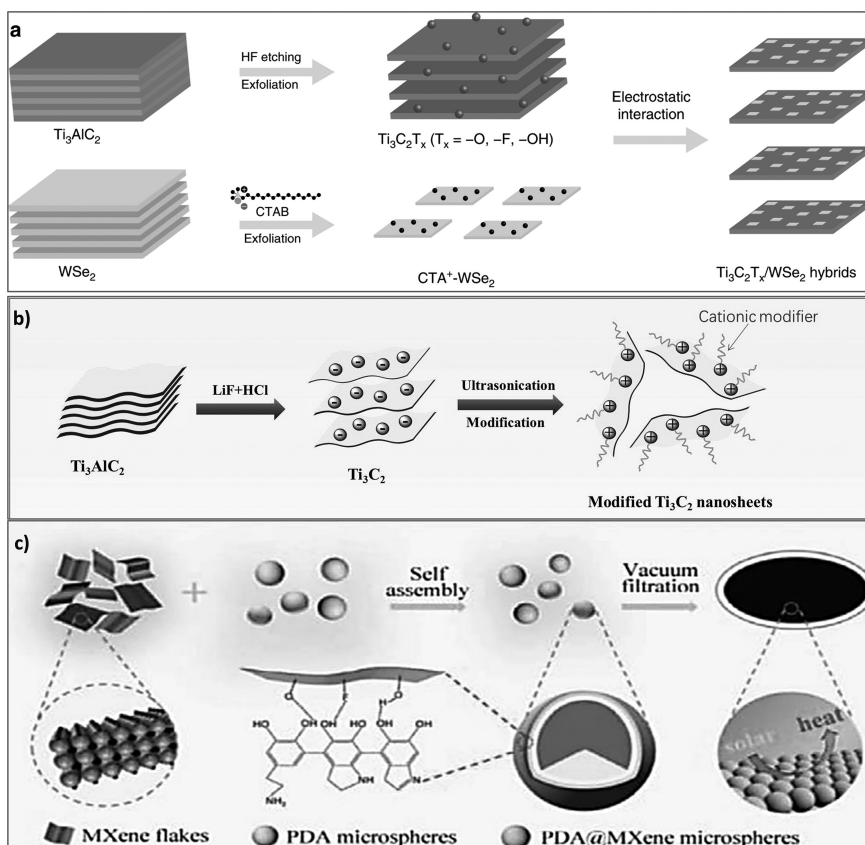


Figure 8.4 (a) In situ polymerization technique of MXene nanosheets for polystyrene. (Reproduced with permission from Ref. [69]). (b) Chemical functionalization of nanohybrids of MXene and transition metal dichalcogenide. (Reproduced with permission from Ref. [70]). (c) Composite formation and dispersion optimization of MXene-polymer composites. (Reproduced with permission from Ref. [71].)

- b. Chemical functionalization:** To transform the surface chemistry of MXenes and make them more suitable for flexible substrates, researchers have investigated chemical functionalization approaches. Changes to the surface functional groups can enhance dispersion and adhesion inside the composite material [70]. Figure 8.4b shows that the objective of this technique is to enhance mechanical and electrical performance by enhancing the interface interactions between MXenes and the flexible substrate.
- c. Composite formation:** Current studies have mostly concentrated on integrating MXenes into composite materials by mixing them with

polymers, carbon-based materials, or other nanomaterials. The objective of this integrated methodology is to merge the distinctive characteristics of MXenes with other substances to produce hybrid structures that possess enhanced mechanical durability, electrical conductivity, and flexibility [71]. The ultimate attributes of the flexible electronic device are illustrated in Figure 8.4c; these attributes are significantly impacted by the choice of the second composite phase.

- d. **Dispersion optimization:** Attaining a homogeneous dispersion of MXenes inside the composite matrix is essential for guaranteeing uniform characteristics across the material. Scientists have concentrated their efforts on devising techniques to enhance the dispersion of MXene, including sonication, surfactant-assisted dispersion, and several other ways. Evenly distributed MXenes enhance both the conductivity and mechanical strength in flexible electronics, as shown in Figure 8.4c [71].

Recent investigations have demonstrated the efficacy of these synthesis processes in customizing MXene composites for precise applications in flexible electronics. The refinement of these techniques has resulted in the creation of lightweight, flexible electronic devices with improved functionality, opening up possibilities for the advancement of future flexible and adaptable electronic technologies. Current research in this area is actively investigating innovative methods of creating MXene composites with different materials to enhance the performance of flexible electronics.

8.5.1 Methods for incorporating MXenes into composites

When integrating MXenes into composites for flexible electronics, it is crucial to carefully assess the processing techniques to achieve consistent distribution and robust adhesion with the matrix material. Below are many techniques for integrating MXenes into composites to develop flexible electronics:

- a. **Solution mixing:** Because of MXenes' superior solvent dispersibility, a stable solution can form. The solution can then be incorporated into the polymer matrix using methods like magnetic agitation, ultrasonic treatment, or agitation. A composite material is produced when the solvent evaporates following the mixing procedure [72].
- b. **In situ synthesis:** This method eliminates the need to move or transfer materials or substances by synthesizing them right there in their natural surroundings. While building a composite, MXenes can be created on-site within the polymer matrix. The first step is to add the MXene synthesis precursor chemicals to the polymer, and then to start the

- synthesis reaction. According to Ref. [73], this method ensures that MXenes and the matrix will interact robustly.
- c. **Melt mixing:** Blending or combining materials when they are in a molten condition is called melt mixing. For polymers that melt at low temperatures, MXenes can be mixed into the molten mixture right away. The next step in making a solid composite is to cool the mixture. Thermoplastic polymers are good candidates for this method.
 - d. **Electrospinning:** This process creates polymer nanofibers that include MXenes. Electrospinning a polymer and MXene solution results in nanofibers. The produced nanofibrous mat has potential as a malleable electrical material [72].
 - e. **Layer-by-layer assembly:** When building in this manner, MXene and polymers are deposited in alternate levels. By using this method, the thickness of individual layers may be precisely controlled, leading to composite structures with clear boundaries.
 - f. **Spray coating:** This method involves utilizing a spray cannon or a comparable instrument to put a thin layer of substance onto a surface. Spraying MXene dispersions onto a substrate allows for the formation of thin, uniform coatings. An application requiring large-scale flexible electronics is a good fit for this method.
 - g. **3D printing:** For 3D printing flexible electrical devices, MXenes can be included in polymer matrices. Complex, custom-made buildings are now within reach, all thanks to this technological advancement.
 - h. **CVD, or chemical vapor deposition:** It builds a thin coating on a substrate by the interaction of chemicals in the vapor phase with the substrate. Using chemical vapor deposition (CVD), MXene films may be deposited over various surfaces. When making flexible electronics, this method is ideal for getting the layer thickness just right.
 - i. **Roll-to-roll processing:** This continuous production approach, known as roll-to-roll processing, has the potential to mass-produce flexible electronic devices.

Figure 8.5 represents the schematic representation of solution mixing, electrospinning, and melt mixing techniques. MXenes can be used in the roll-to-roll production process to augment the characteristics of flexible materials. Optimizing the processing is of utmost importance.

8.5.2 Challenges in synthesis and solutions

Researchers have been endeavoring to overcome several problems in the production of MXene composites to improve the performance and adaptability of MXene-based materials. Table 8.2 represents a series of obstacles and possible resolutions:

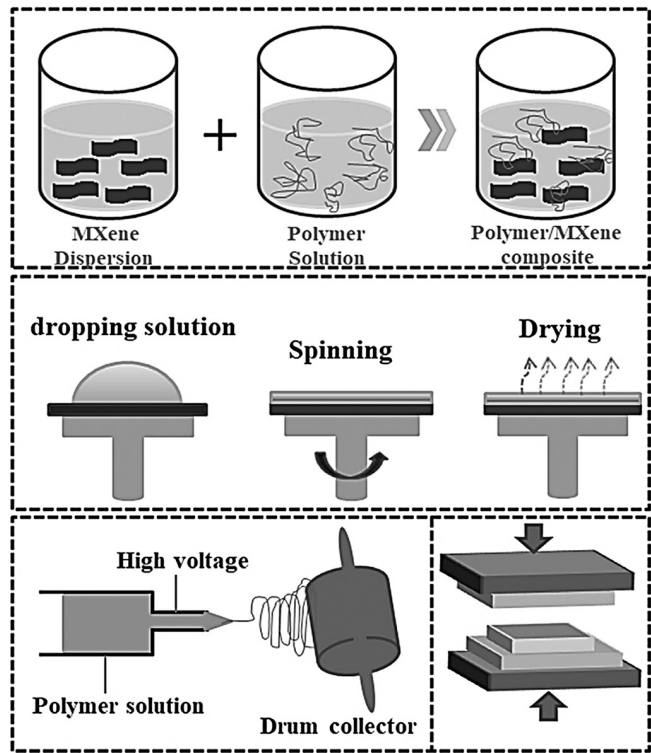


Figure 8.5 Schematic of the methods for mixing solutions, electrospinning, and melt mixing.

Table 8.2 Synthesis methods, challenges, and possible resolutions

Synthesis techniques	Challenges in synthesis	Solutions
In situ growth	Limited control over MXene distribution on the substrate	Optimization of growth parameters
	Potential substrate compatibility issues	Surface modification of substrates
Chemical functionalization	Achieving uniform and stable functionalization	Tailoring surface functional groups
	Balancing functionalization without compromising MXene properties	Systematic study of functionalization effects
Composite formation	Ensuring homogeneous dispersion within the composite	Improved mixing techniques
	Compatibility with diverse secondary phases	Rational selection of compatible materials
Dispersion optimization	Agglomeration and poor dispersion in the matrix	Sonication, surfactant-assisted dispersion
	Minimizing damage to MXene during the dispersion process	Controlled energy input during dispersion

8.6 ELECTRICAL AND MECHANICAL PROPERTIES

The emergence of new materials, such as MXene composites, has greatly advanced the area of flexible electronics in recent years. The utilization of these materials has significantly enhanced the capabilities of conventional electrical equipment. Scientists are fascinated with MXenes, which are a group of two-dimensional transition metal carbides and nitrides, because of their extraordinary electrical and mechanical characteristics. MXene composites have distinctive characteristics that make them highly versatile, with a particular advantage in the field of flexible electronics.

The defining characteristic of MXene composites is their remarkably high electrical conductivity. MXenes exhibit metallic conductivity due to the presence of transition metal carbides or nitrides in their layered structure. Their appeal for utilization in flexible electronics arises from their inherent ability to facilitate effective charge transfer. The utilization of flexible electronic devices is increasing. Scientists have identified several possibilities for MXene composites, including wearable electronics, electronic skin, flexible displays, conductive sheets, and electrodes.

MXene-based composites have exceptional electrical properties and possess superior mechanical flexibility. MXenes, due to their two-dimensional structure, may be easily integrated with flexible substrates without experiencing any deterioration. To construct gadgets with versatile shapes or wearable designs, electrical equipment must possess resilience and flexibility. Potential applications abound for flexible sensors and elastic circuitry fabricated with MXene. In the future, wearable technology may likewise get advantages from comparable applications.

The primary objective of the present research is to enhance the performance of flexible electronics by incorporating MXene composites into nanocomposite materials. The integration of MXenes with other nanomaterials enables these composites to enhance their electrical and mechanical properties. Nanocomposites of MXene and graphene exhibit enhanced mechanical robustness and electrical conductance, rendering them a very attractive alternative for challenging applications in flexible electronics.

Subsequent studies have verified this finding, and investigations into the possible uses of MXene composites in flexible electronics are currently in their preliminary phases. MXene was studied to achieve a significant improvement in energy density [69]. Their primary focus was on developing flexible supercapacitors using MXene materials in the realm of energy storage. Enhancing wearable strain sensors based on MXene indicates that MXene composites have the potential to be utilized in a diverse range of sensing applications [70].

MXene composites have mechanical and electrical properties that make them very suitable for the constantly growing domain of flexible electronics. MXene composites provide exceptional mechanical flexibility and

conductivity, rendering them very suitable for a diverse array of applications. These applications encompass the utilization of wearable sensors and flexible displays. Continuously studying MXene composites, to enhance performance and explore novel applications, has the potential to greatly advance the progress of flexible electronic devices in the future.

8.6.1 Performance metrics in flexible electronics

Table 8.3 summarizes performance metrics of MXene composites in flexible electronics. Please note that the specific values can vary depending on the MXene type, composite composition, and fabrication methods. Table 8.3 is just an illustrative example:

Table 8.3 Performance metrics in flexible electronics

<i>Performance metric</i>	<i>Description</i>	<i>Typical values</i>
Electrical conductivity	Measure how well the composite conducts electricity.	1000 S/cm or higher
Mechanical flexibility	The ability of the composite to bend and flex without breaking.	Tensile strain >5%
Tensile strength	Resistance to a force pulling the material apart.	50 MPa or higher
Young's modulus	Measure of stiffness or elasticity of the composite.	10–50 GPa
Thickness	The thickness of the composite material.	Nanometers to micrometers
Transparency	The degree to which the material allows light to pass through.	Highly transparent
Cyclic stability	The ability of the composite to maintain performance over repeated bending cycles.	Low-resistance change over cycles
Temperature stability	Stability of electrical and mechanical properties over a range of temperatures.	Stable up to 100°C or higher
Surface resistance	Resistance of the material's surface to the flow of electric current.	Low surface resistance
Dielectric constant	Measure the ability of the material to store electrical energy in an electric field.	Low dielectric constant
Adhesion strength	Strength of the bond between MXene and the matrix material.	Strong adhesion required
Flexural fatigue life	Number of flexural cycles before failure.	Thousands of cycles

8.7 APPLICATIONS OF MXene COMPOSITES IN FLEXIBLE ELECTRONICS

MXene composites have garnered considerable interest in the realm of flexible electronics owing to their distinctive attributes, including exceptional electrical conductivity, mechanical pliability, and elevated surface area. Figure 8.6 shows the applications of MXene composites in flexible electronics. Below are many examples of how MXene composites are utilized in the field of flexible electronics:

- a. **Flexible sensors and actuators:** MXene-based composites have demonstrated significant promise for enhancing flexible actuators and sensors. Because of MXene's exceptional mechanical flexibility and electrical conductivity, recent research has focused on developing sensors that can detect a wide range of inputs. The invention of very sensitive and adaptable strain sensors that can track even the slightest form changes in real time was shown by the researchers. These sensors have the potential to be very helpful in three areas: wearable technology, HMI, and structural health monitoring. Research has also been done on MXene composites' potential to enhance gas sensors.

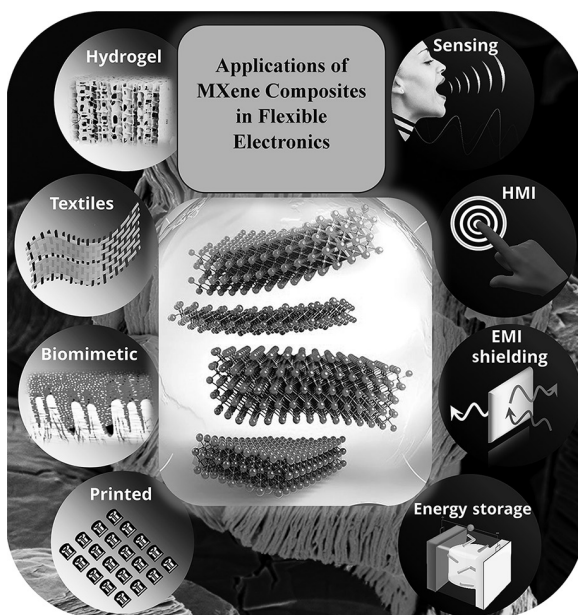


Figure 8.6 Applications of MXene composites in flexible electronics.

The application of MXene in flexible gas sensors is ecologically beneficial. The study demonstrated the material's exceptional and selective ability to detect a small number of gases [74].

- b. **Wearable electronics:** MXene composites are becoming crucial components in the realm of wearable electronics. Scientists' main attention has been on integrating MXene materials into wearable energy storage systems. Supercapacitors exhibited exceptional electrochemical performance and mechanical flexibility. These supercapacitors provide a lightweight, portable power source for wearable electronics. MXene composite materials have also been used in wearable health monitoring systems. The wearable devices might use MXene-based sensors to monitor physiological data. The study proved that real-time health monitoring is feasible and might have uses in fitness and healthcare [75].
- c. **Flexible energy storage devices:** Recent research suggests that MXene composites might play a significant role in flexible energy storage devices, such as supercapacitors and batteries. A research article details the remarkable mechanical durability and electrochemical efficiency of flexible supercapacitors based on MXene materials. These versatile supercapacitors offer advantages for electrical devices that are flexible and foldable [76]. Furthermore, researchers have explored the application of MXene materials in flexible batteries. A thorough investigation of the progress of MXene-based flexible batteries possess greater energy density and extended lifespan. Furthermore, these findings enhance the efficiency of adaptable energy storage systems and facilitate the advancement of flexible power sources for emerging technologies and portable devices.

Recent research has emphasized the versatility and potential of MXene composites in the field of flexible electronics. The unique attributes of MXene, including its electrical conductivity, mechanical flexibility, and biocompatibility, are revealed through its application in flexible sensors, energy storage devices, and wearable electronics. Considering such factors, MXene is a very suitable option for implementation in state-of-the-art breakthroughs in this field.

8.8 CHALLENGES AND FUTURE DIRECTIONS

The use of MXene composites in flexible electronics has displayed significant potential. However, as with any nascent technology, it encounters obstacles that need careful consideration [77,78]. Furthermore, the current research indicates promising prospects that might further optimize the

efficiency and broaden the range of applications of MXene composites in flexible electronics. The following are a few obstacles and areas for future exploration:

Challenges:

- a. **Costs and scalability of production:** Significant improvements are needed to make manufacturing methods for MXene composites more scalable so that they can meet the demands of commercial applications requiring large-scale production. Equally important to attaining general acceptability is minimizing production expenditures.
- b. **Environmental stability:** MXenes are unstable in the presence of moisture and oxidation, two environmental stresses. The long-term stability of MXene composites depends on how well they hold up in a variety of climates.
- c. **Substances or materials** are considered to be interfacially compatible if they can exist and interact with one another without producing undesirable side effects.
- d. **Interfacial compatibility:** It's not easy to get MXene composites and flexible substrates to work together in the best way possible. Maintaining mechanical and electrical performance requires ensuring a strong connection and lowering resistance at the interface.
- e. **Characterization methods standardization:** It is difficult to compare results from different research projects due to the lack of defined testing methods for MXene composites. To make meaningful comparisons and drive advancement, it is essential to establish standardized methods for precisely measuring and characterizing the electrical, mechanical, and other properties of materials.
- f. **Biocompatibility:** For MXene composites to be used in implantable and wearable devices, it is crucial to ensure that they are compatible with live beings. To determine if these materials are toxic to cells or whether they may interact positively with living things, more research is needed.

Future scopes

- a. **Versatility:** We can discover new possibilities for state-of-the-art flexible electronic devices by harnessing the multifunctional properties of MXene composites, which include electrical conductivity combined with sensing, actuation, and energy storage, among other capabilities.
- b. **State-of-the-art manufacturing technologies:** More flexible and intricately structured MXene-based flexible electronics may be developed and created through the exploration and use of state-of-the-art

manufacturing technologies, such as additive manufacturing and 3D printing.

- c. **Self-healing materials:** Developing a system for continuous maintenance and restoration is essential for enhancing the durability and reliability of modern materials and devices. Flexible electronics may last longer using MXene composites because they can self-heal from mechanical strain and environmental stresses.
- d. **Integration with other nanomaterials:** Composite materials with enhanced capabilities can be created by studying the probable interactions between other nanomaterials, such as polymers, nanotubes, or nanoparticles. To do this, we make use of each component's unique qualities and combine them. There are several biomedical uses for smart textiles.
- e. **Biomedical devices and smart textiles:** Since biomedical devices require biocompatibility and high degrees of flexibility, there is promising potential in the exploration of smart textiles and their usage in these fields. Implanted medical gadgets and wearable health monitors are two potential uses for MXene composites.
- f. **Energy harvesting:** This technique involves collecting and transforming different types of energy from the environment into electrical power that may be used. One way to get toward fully autonomous flexible electronics is to include MXene composites in energy-harvesting devices that are already on the market, such as piezoelectric or flexible solar cells.
- g. **AI-enhanced design:** By integrating AI into materials design and optimization, novel MXene composites with tailored properties for certain flexible electronic applications might be discovered more quickly.

Addressing these challenges and moving further along these lines will likely increase the variety of flexible electronic applications using MXene composites, which in turn would inspire innovation and improve the performance of future electronic devices.

8.9 CONCLUSION

In conclusion, the recent advances in MXenes and their composites represent a transformative leap forward in the field of flexible electronics. The unique properties of MXenes, such as excellent conductivity, mechanical flexibility, and high surface area, have paved the way for the development of highly efficient and flexible electronic devices. The synergistic effects achieved through MXene composites further enhance the performance and versatility of these materials. As we witness the continual refinement of

MXene-based technologies, it is evident that they hold immense potential for applications in flexible and wearable electronics, ushering in a new era of lightweight, bendable, and high-performance electronic devices. The ongoing research in this area is poised to unlock even more innovative possibilities, driving the evolution of flexible electronics and contributing to the advancement of next-generation electronic systems.

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A comprehensive review of sustainable graphene-based electronics for next-generation applications

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9.1 INTRODUCTION

Graphene is a two-dimensional arrangement of carbon atoms in a hexagonal lattice, and has garnered significant attention for its potential in diverse electronic applications. Serving as a fundamental role in other carbon structures such as graphite, carbon nanotubes (CNTs), and fullerenes, graphene possesses exceptional properties that make it a compelling material for a wide range of use [1–7]. This comprehensive study explores the latest developments in sustainable graphene-based electronics and their potential for next-generation applications [4–12]. In recent times, the incorporation of graphene into electronic systems has captured the interest of both scientific and technological communities, thanks to its extraordinary electronic characteristics. As scientists delve into unlocking the complete potential of graphene, there is a growing emphasis on ensuring the sustainability of its applications for the next generation of electronic devices. This comprehensive review aims to provide an in-depth exploration of sustainable practices in graphene-based electronics, encompassing synthesis techniques, environmental impact assessment, and applications in renewable energy.

The application of graphene in flexible and wearable electronics is another focal point, considering both the sustainability of materials used and the recyclability of end products. Furthermore, the review delves into the role of graphene in renewable energy solutions, examining its integration into solar cells, batteries, and super capacitors. Regulatory and ethical considerations play a crucial role in developing and deploying new technologies. The review evaluates existing regulatory frameworks related to graphene production and use and ethical considerations surrounding its application in electronics.

The review offers insights into prospects and challenges in the sustainable graphene-based electronics landscape. By identifying potential breakthroughs and addressing current research gaps, the evaluation aims to contribute to advancing environmentally conscious and socially responsible electronic technologies for the next generation. Graphene, renowned as a

super material, boasts exceptional mechanical, electrical, and thermal properties [1–12]. It typically exhibits sp^2 hybridization, leading to its impressive electrical conductivity attributed to the abundance of free electrons within its carbon atoms. As a 2D nanomaterial, graphene possesses a thickness in the nanometer scale, typically in the range of 10^{-9} . Due to its one dimension in the nano range, it has more flexibility. It has high strength due to $C=C$. We can replace graphene with other materials to improve its mechanical strength. It has Young's modulus of 130 GPa. Graphene has a more substantial structure than other carbon composites. Graphene has three structures: graphene sheets, CNTs, and quantum dots. It was discovered in 2003 as an allotrope of carbon single-layer graphite. It has a honeycomb-like structure, making it more electrically conductive. Graphene, a carbon material structured in two dimensions, measures approximately 0.345 nm in thickness and is characterized by sp^2 hybridization. It stands out as one of the strongest and thinnest materials known, excelling in heat conduction and offering optical transparency. Moreover, graphene exhibits impermeability to gases. Its remarkable properties and versatility render it applicable across a spectrum of uses, including electronics, optics, sensors, and bio-devices. It has a high degree of sensitivity to electron speed.

The synthesis of graphene is evaluated with a focus on environmentally friendly and scalable production methods. This includes examining green synthesis techniques that minimize the ecological footprint associated with graphene manufacturing. Following this, the study addresses the use of graphene-based electronics in renewal energy development, considering life cycle assessments and strategies to mitigate any adverse effects. Energy efficiency is a critical consideration in the development of cutting-edge electronics devices. This review looks over the design of graphene-based transistors, sensors, and other devices emphasizing high energy efficiency.

9.2 OVERVIEW OF GRAPHENE

Graphene, comprised of a hexagonal arrangement of carbon atoms in a two-dimensional lattice, has emerged as a groundbreaking substance renowned for its unmatched electronic, mechanical, and thermal attributes. Its single-layer structure imparts exceptional strength, high thermal conductivity, and remarkable electrical conductivity, making it a compelling candidate for various electronic applications. In this comprehensive review, we explore the integration of graphene in the pursuit of sustainable electronic technologies for the next generation. The material's extraordinary properties enable high-performance electronic devices and open avenues for environmentally conscious and socially responsible applications in the next generation of electronics [13]. The identification of graphene and its extraordinary characteristics resulted in the Nobel Prize in Physics in 2010, honoring Andre Geim and Konstantin Novoselov, who first isolated graphene

in 2004 [14]. Since then, researchers and industries have been exploring various applications for graphene. Graphene-based materials have found applications across numerous fields. The “graphene roadmap” has envisaged the use of graphene in many different fields, ranging from electronics, photonics, and sensing to composites, energy storage devices, medical devices, photonics, bio applications, materials science, etc. Graphene transistors, flexible displays, and wearable devices have been developed in electronics. Graphene has been explored for high-performance batteries and supercapacitors in energy storage. Additionally, it has been investigated for applications in sensors, water purification, composite materials, biomedical devices, anti-corrosion materials, etc. Graphene-based coatings provide corrosion protection for various materials. Graphene tremendously shows exceptional strength, anti-corrosion properties, high electron mobility, high electronic and optical properties, high heat conduction, etc., which have captured the attention of researchers worldwide. The typical properties of graphene [1–14] are presented below.

Exceptional strength: Graphene is incredibly strong, even surpassing steel. Its strength is attributed to its hexagonal lattice’s strong covalent carbon-carbon bonds. It is the most powerful substance known to humanity, with a tensile strength over 100 times greater than steel. Its lattice structure allows it to distribute stress evenly, making it incredibly robust.

High conductivity: Graphene possesses remarkable electrical conductivity, enabling electrons to flow through it with minimal hindrance. This characteristic holds immense promise for various applications in electronics and nanotechnology. Due to its unique atomic structure, graphene demonstrates superior electrical conductivity compared to traditional materials like copper. The arrangement of carbon atoms within its lattice structure facilitates the unrestricted movement of electrons, rendering it an ideal material for electronic applications.

Exceptional thermal conductivity: Graphene demonstrates remarkable thermal conductivity, positioning it as a promising material for applications involving heat management and thermal devices. Graphene possesses superior thermal conductivity, even surpassing that of diamond. Its ability to efficiently transfer heat makes it highly desirable for applications in thermal management and electronics.

Optical properties: Despite being a single layer of atoms, graphene is transparent. This transparency and its conductivity make it worthwhile for applications in transparent conductive films, such as electronic displays and touchscreens. Graphene absorbs only 2.3% of light across the visible spectrum, rendering it nearly transparent. This property, combined with its exceptional electrical conductivity, makes it an excellent candidate for optoelectronic devices.

Flexibility: Graphene is flexible and can be bent without breaking. This flexibility is advantageous for applications in flexible electronics, wearable devices, and other flexible materials.

Impermeability: Graphene is impermeable to gases, even helium, due to its tightly packed carbon atoms. This property is beneficial for applications requiring gas barriers.

Biocompatibility: Graphene is biocompatible, making it suitable for potential applications in medical devices, drug delivery, and other biomedical applications.

Based on their association and layer count, graphene materials are categorized into various types.

Layer classification

- Single-layer graphene
- **Very few layers graphene (VFLG):** Consisting of 1–3 graphite layers
- **Few layer graphene (FLG):** Containing 2–5 graphite layers
- **Multilayer graphene (MLG):** Comprising 5–10 graphite layers
- **Graphene nano-platelets:** Containing 11 or more graphite layers

With time, scientists have devised alternative approaches for the mass production of graphene. These preparation techniques for graphene-based materials are typically classified into two categories: top-down and bottom-up strategies. Currently, common top-down approaches for producing graphene-related materials (GRMs) comprise the Hummers method, liquid phase exfoliation, and electrochemical exfoliation (ECE). In contrast, bottom-up methods involve techniques such as chemical vapor deposition (CVD) and epitaxial growth etc.

9.3 SYNTHESIS OF SUSTAINABLE GRAPHENE-BASED MATERIAL FOR ELECTRONIC APPLICATIONS

The rapid evolution of electronic applications demands innovative materials that push the boundaries of performance and adhere to sustainability principles. With its exceptional electronic attributes, its remarkable electronic characteristics have established graphene as a promising prospect for the next generation of electronic devices. This comprehensive review focuses on synthesizing sustainable graphene-based materials and their utilization in electronic technologies. It addresses critical considerations such as green synthesis methods, environmental impact, and scalable production for large-scale applications.

Broadly, two approaches are followed for graphene production: the top-down approach and the bottom-up approach. Figure 9.1 depicts different commonly practiced top-down and bottom-up approaches to graphene production. Below are discussions on some typical methods of graphene production.

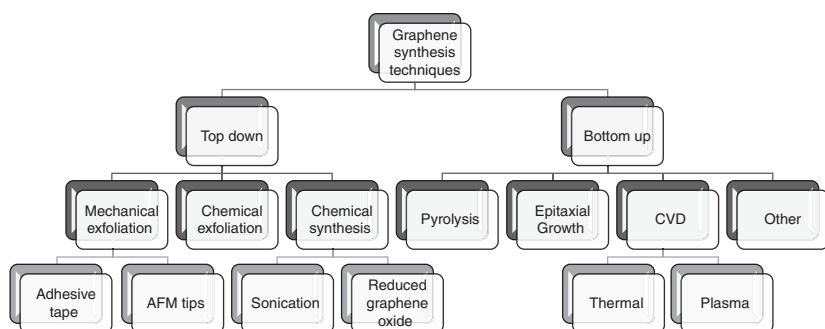


Figure 9.1 Diagram illustrating various techniques of graphene synthesis [17, Creative Commons CC BY license, Copyright © 2024, Springer Nature].

9.3.1 Graphene synthesis from the top-down perspective

Exfoliation: It is a widely used method to extract graphene from graphite. Exfoliation includes mechanical exfoliation and chemical exfoliation/ECE.

9.3.1.1 Exfoliation by mechanical means

Exfoliation by mechanical means or mechanical exfoliation, often called the “Scotch tape method,” is a simple technique used to produce graphene by peeling off thin layers of graphite until graphene is reduced to a single layer [15,16]. This approach was crucial in the initial discovery of graphene and is often used in research laboratories to generate graphene samples of superior quality for characterization and study. Nevertheless, it is not suitable for mass production, as it is labor-intensive as well as with low-throughput nature.

Mechanical exfoliation is carried out as follows:

Starting material: The process begins with a piece of natural graphite (a crystalline form of carbon), a three-dimensional structure composed of layers of graphene stacked together.

Adhesive tape: A piece of sticky tape, often Scotch tape, is pressed onto the surface of the graphite. The tape adheres to the top layer of graphene.

Peeling: Upon peeling the tape away from the graphite, it lifts off a thin graphene layer. The adhesive force of the tape is strong enough to isolate the graphene layer from the bulk graphite.

Repetition: The process is repeated multiple times, with each iteration resulting in a thinner layer of graphene being obtained.

Identification: The obtained graphene layers are identified and verified using characterization methods, such as optical microscopy or Raman spectroscopy, to validate the existence of single-layer graphene.

The graphene layers can sometimes be transferred onto a substrate for further analysis or application. This is typically done by pressing the tape onto the target substrate, allowing the graphene layer to adhere. While the mechanical exfoliation method is straightforward and provides high-quality graphene samples, it has several limitations:

Low scalability: The method could be more practical for large-scale production due to the manual and time-consuming nature of the process.

Variability: The quality and size of the obtained graphene layers can vary from sample to sample.

Despite these limitations, the Scotch tape method remains valuable in graphene research, especially for producing small quantities of pristine graphene for fundamental studies and device prototyping.

9.3.1.2 Chemical exfoliation

Chemical exfoliation is a method used to produce graphene by chemically treating graphite to separate and isolate individual graphene layers. One common form of chemical exfoliation involves oxidizing graphite to produce graphene oxide (GO), then reducing it to obtain reduced graphene oxide (rGO) or even graphene. Prevalent method of chemical exfoliation entails the following.

9.3.1.2.1 Hummers and Offeman method for GO preparation

Hummers and Offeman [18] have prepared GO from graphite by using chemical solution consisting of concentrated sulfuric acid, sodium nitrate, and potassium permanganate at the temperature of 45°C and 2 hours residence time of reaction. Later on, this process was modified by Kovtyukhova [19] in 1999 where GO with a specific degree of oxidation was produced by employing a mixture of H_2SO_4 , $\text{K}_2\text{S}_2\text{O}_8$, and P_2O_5 to oxidize the graphite at 80°C over a span of hours. Subsequently, the solution was diluted, filtered, rinsed, and dried to produce good-quality GO. The process is tedious and time-consuming, but it helps synthesize high-quality GO. However, the process is scalable and has been widely explored for research and potential industrial applications.

Another process is the ECE process, which involves applying an electric potential to a bulk graphite electrode in a liquid medium to induce the exfoliation of graphene layers. This method provides a scalable and relatively simple way to produce graphene.

9.3.1.2.2 Electrochemical exfoliation process

ECE process used for developing GO with following steps [20].

Set up: A bulk graphite electrode is immersed in a liquid medium serving as the electrolyte. The electrolyte typically contains an electrolyte salt (such as lithium perchlorate) to enhance conductivity.

Electrode configuration: The graphite electrode is often used as the working electrode, and a counter electrode (usually made of a conductive material like platinum) is also immersed in the electrolyte. A reference electrode may be used to monitor the electrochemical potential.

Interfacial reactions: An electric potential is applied between the working electrode (graphite) and the counter electrode. This potential induces electrochemical reactions at the interface between the graphite electrode and the electrolyte.

Intercalation of ions: The applied potential leads to the intercalation of ions, typically cations, into the interlayer spaces of the graphite structure. Inserting ions between the graphene layers weakens the Van der Waals forces holding the layers together.

Exfoliation of graphene layers: Because of intercalation, the graphene layers are gradually exfoliated from the bulk graphite. The weakened interlayer forces cause the individual graphene layers to separate and disperse into the electrolyte solution.

Colloidal suspension: The exfoliated graphene forms stable colloidal suspensions in the liquid medium. The electrostatic repulsion between the charged graphene layers helps to prevent their re-aggregation.

Collection and separation: The graphene suspension is collected and can be further processed to remove any remaining impurities or unexfoliated graphite. Techniques such as filtration or centrifugation may be employed for the separation and collection of exfoliated graphene.

Considerations in electrochemical exfoliation: Optimization of Parameters: The electrochemical potential, electrolyte composition, and other parameters must be carefully optimized to control the exfoliation process and achieve the desired properties of the resulting graphene. ECE offers advantages in terms of scalability, control over the process, and potential for large-scale graphene production, making it a promising method for various applications.

9.3.1.3 Chemical synthesis

9.3.1.3.1 Chemical reduction of graphene oxide (reduced GO)

The chemical reduction of GO yields rGO, a common step in the synthesis of graphene. Alternatively, sonication, which employs sound waves to agitate particles in a liquid medium, can be utilized for dispersing and exfoliating graphene sheets [21]. In synthesizing graphene, sonication is often

employed to exfoliate graphite or GO, breaking down larger structures into individual graphene layers or only a few-layer graphene sheets. This process is also known as liquid-phase exfoliation.

Graphite oxidation: In this process graphite is oxidized to create GO, often accomplished through the treatment of graphite with potent oxidizing agents like sulfuric acid (H_2SO_4) and nitric acid (HNO_3). This oxidation introduces oxygen-based functional groups, such as hydroxyl and epoxide groups, which interfere with the sp^2 carbon-carbon bonding within graphene.

Isolation of graphene oxide: The resulting GO is typically in sheets or flakes. These GO sheets are hydrophilic, allowing them to disperse in water. The GO sheets are separated from the reaction mixture using techniques like filtration or centrifugation.

Chemical reduction: The critical step in the chemical synthesis of graphene is the reduction of GO to restore the sp^2 carbon-carbon bonding. Reduction agents are used to remove the oxygen-containing functional groups. Typical reducing agents include hydrazine, which is effective but can be hazardous, or milder alternatives like ascorbic acid (vitamin C), which is more environmentally friendly.

Depending on the specific conditions and requirements, the reduction process may involve solution-phase or thermal methods.

Washing and filtration: The rGO is washed thoroughly to remove residual chemicals and reaction by-products. Filtration or other separation techniques are employed to collect the rGO.

Drying and annealing: The obtained rGO is often dried and may undergo additional thermal annealing. Annealing at elevated temperatures helps to further reduce functional groups and improve the electrical conductivity of the materials. The synthesized graphene or rGO is characterized using various techniques to confirm the restoration of sp^2 carbon-carbon bonding and assess the graphene quality produced.

9.3.1.3.2 Sonication-assisted graphene synthesis

Sonication-assisted synthesis is used for preparation of graphene with the following steps [22–24].

Graphite oxide is often used as a precursor in synthesizing graphene. It is obtained by oxidizing natural graphite using potent oxidizing agents.

Dispersing in a liquid medium: The graphite oxide or other graphene precursor is dispersed in a liquid medium, typically water or organic solvents, to form a suspension or slurry.

Introduction of sonication: Ultrasonic waves are introduced into the suspension using a sonication device. The high-frequency sound waves cause cavitation in the liquid, creating bubbles that collapse rapidly. The collapse

of these bubbles generates intense local forces, breaking graphite oxide or GO sheets into smaller fragments.

Exfoliation and formation of graphene sheets: The sonication process leads to the exfoliation of graphene sheets from the more significant graphite or GO structures. The shear forces generated by cavitation help break the intermolecular forces holding the layers together, resulting in the dispersion of individual graphene sheets or small stacks.

Post-treatment (if necessary): Depending on the specific application and desired properties, the synthesized graphene dispersion may undergo post-treatment steps, such as reduction for GO or functionalization for tailored properties.

Sonication is advantageous in graphene synthesis for several reasons

Efficient exfoliation: Sonication effectively breaks down the larger structures into more miniature, individual graphene sheets or few-layer graphene structures.

Scalability: The sonication process is scalable, making it suitable for large-scale production of graphene dispersions.

Reduced use of harsh chemicals: Sonication may require fewer harsh chemicals than other methods, contributing to a more environmentally friendly synthesis process.

Versatility: Sonication can be used with various precursor materials, including GO, to produce graphene dispersions suitable for different applications. It's worth noting that while sonication is a valuable technique, the choice of precursor materials, liquid medium, and other process parameters also plays a crucial role in determining the quality and properties of the synthesized graphene. Researchers continue to refine and optimize sonication-based methods for graphene synthesis.

9.3.2 Typical top-up method of graphene synthesis

9.3.2.1 Epitaxial growth for graphene synthesis

Epitaxial growth is a method used for synthesizing graphene by depositing carbon atoms onto a crystal substrate in a highly controlled manner [25]. This process allows the formation of a single-layer or few-layer graphene film with a specific crystal orientation. The term “epitaxial” refers to the ordered growth of one crystal (the graphene) on another crystal (the substrate) in a way that the atomic arrangement of the graphene follows the arrangement of the substrate.

Substrate preparation: A single-crystal substrate is chosen depending on the required properties of the resulting graphene film. Typical substrates include silicon carbide (SiC) and certain metal surfaces like copper (Cu) or nickel (Ni). The selection of substrate impacts the electronic and structural characteristics of the developed graphene.

Surface cleaning: The substrate surface is carefully cleaned to remove contaminants or oxides that could interfere with the epitaxial growth process. This step is crucial for ensuring a high-quality graphene film.

Heating: The cleaned substrate is heated to a high temperature in a controlled environment, often in the presence of a carbon-containing precursor gas, such as methane (CH_4) or ethylene (C_2H_4). The high temperature activates the decomposition of the precursor gas, releasing carbon atoms.

Carbon deposition: Carbon atoms released from the precursor gas adsorb onto the substrate surface. The epitaxial growth occurs as the carbon atoms arrange themselves on the substrate in a crystallographically aligned manner. The choice of substrate crystal orientation determines the orientation of the growing graphene lattice.

Cooling: Following the deposition of carbon, the sample undergoes cooling to stabilize the epitaxially grown graphene film. Precise control over the cooling rate is crucial as it influences the properties of the graphene, ensuring the attainment of desired characteristics.

Epitaxial growth offers several advantages for synthesizing graphene

High-quality films: The ordered growth on a single-crystal substrate allows for forming high-quality, large-area graphene films with consistent electronic and structural properties.

Control over orientation: The choice of substrate crystal orientation provides control over the orientation of the graphene lattice, which is crucial for specific electronic applications.

Potential for integration with semiconductor technology: Silicon carbide substrates, in particular, are compatible with existing semiconductor technology, making epitaxial graphene synthesis suitable for integration into electronic devices.

Despite these advantages, epitaxial growth methods can be technically challenging and may require specialized equipment. Researchers continue to explore and refine epitaxial growth techniques to make them more scalable and cost-effective for various applications.

9.3.2.2 Pyrolysis process for graphene synthesis

Pyrolysis is a method commonly used for synthesizing graphene from carbon-rich precursors by subjecting them to high temperatures in an inert atmosphere [20,26]. During pyrolysis, the precursor undergoes thermal decomposition, and the released carbon atoms reassemble to form graphene structures. The choice of precursor and specific pyrolysis conditions can influence the synthesized graphene's quality, structure, and properties.

Selection of precursor: Various carbon-rich precursors can be used, such as organic compounds, polymers, or even waste materials. Common precursors include hydrocarbons like methane (CH_4), ethylene (C_2H_4), or acetylene (C_2H_2), as well as organic molecules and polymers.

Preparation of precursor material: The chosen precursor material is typically a liquid, gas, or solid. For example, if using a liquid precursor, it may be dissolved or dispersed in a solvent.

Deposition or coating: The precursor material is deposited or coated onto a substrate. The substrate can be a metal, quartz, or another suitable material. The precursor layer thickness can be controlled to influence the resulting graphene film thickness.

Heating in an inert atmosphere: The substrate with the precursor is subjected to high temperatures in the range of 800°C–1000°C or even higher. This process is carried out in an inert atmosphere (such as argon or nitrogen) to prevent oxidation of the carbon during the high-temperature treatment.

Thermal decomposition: The precursor undergoes thermal decomposition, releasing carbon-rich species. These carbon species then reassemble and arrange into graphene structures on the substrate.

Cooling: Following the pyrolysis process, the sample undergoes cooling to achieve room temperature. The rate at which this cooling occurs may impact the properties of the synthesized graphene. Subsequently, the graphene film produced is subjected to characterization using a variety of techniques.

The pyrolysis method offers several advantages

Relatively simple process: Pyrolysis is a straightforward process that can be carried out with relatively simple equipment.

Versatility: It can be applied to various precursors, including waste materials, making it a versatile method for graphene synthesis.

Scalability: The pyrolysis technique is capable of being expanded to facilitate the mass production of graphene on a significant scale.

However, it's important to note that the quality and properties of the synthesized graphene can be influenced by factors such as the choice of precursor, pyrolysis temperature, and the duration of the heat treatment. Researchers continue to explore and optimize pyrolysis methods for efficient and controlled graphene synthesis.

9.3.2.3 CVD process for synthesizing graphene

CVD is a widely used method for synthesizing graphene [20,27,28]. In CVD, a gaseous precursor is decomposed on a heated substrate, leading to the deposition of carbon atoms and the growth of graphene layers. CVD offers control over the graphene film's thickness, quality, and coverage, making it suitable for various applications.

Choice of substrate: The process typically begins with selecting a substrate. Common choices include copper (Cu), nickel (Ni), or silicon carbide (SiC). The substrate material can influence the resulting graphene's growth mechanism and quality.

Cleaning the substrate: The substrate is cleaned thoroughly to remove contaminants that could affect the graphene growth. Standard cleaning methods include acid treatment and annealing.

Precursor gas introduction: A carbon-containing precursor gas is introduced into the reaction chamber. Common precursor gases include methane (CH_4), ethylene (C_2H_4), or a mixture of gases.

Heating the substrate: The substrate is heated to a high temperature, typically 800°C – 1000°C . This temperature is critical for the decomposition of the precursor gas and the subsequent growth of graphene.

Precursor decomposition: The precursor gas decomposes on the heated substrate, releasing carbon atoms. The carbon atoms are then reassembled on the substrate to form graphene layers. The growth can occur through surface adsorption, nucleation, and coalescence.

Cooling: The sample is cooled to room temperature after the graphene growth. The cooling rate can affect the properties of the synthesized graphene.

The graphene is often transferred from the metal substrate to another substrate or device for further applications. This transfer process usually involves chemical etching to remove the metal substrate.

CVD offers several advantages for synthesizing graphene

Control over growth parameters: CVD allows precise control over temperature, pressure, and gas composition, producing high-quality graphene with desired properties.

Scalability: CVD is scalable for large-scale production, making it suitable for industrial applications.

Uniformity: The method can provide uniform graphene layers over large areas, making it suitable for electronic and optoelectronic devices.

CVD has become a widely adopted technique for graphene synthesis, and ongoing research aims to optimize the process for improved efficiency and scalability. Overall, CVD and chemical exfoliation/synthesis processes are scalable for large-scale production methods for next-generation electronics applications. For sustainability, the process should involve environmentally friendly methods that minimize resource consumption, reduce waste, and employ eco-friendly materials. Several approaches contribute to sustainable graphene synthesis, such as green reduction agents, liquid-phase exfoliation, bacterial reduction recyclable catalysts, energy-efficient techniques, biodegradable precursors, and other possible eco-friendly processes.

9.4 PROPERTIES AND APPLICATIONS OF GRAPHENE-BASED SUSTAINABLE ELECTRONIC MATERIAL FOR NEXT GENERATION

Following the discovery of graphene, researchers worldwide began exploring its potential applications. In the subsequent years, they witnessed extensive research into graphene-based materials, leading to several significant

areas of applications. Its remarkable properties, including exceptional strength, anti-corrosion properties, high electron mobility, and high heat conduction, have captured the attention of researchers worldwide. Graphene's special properties are due to its unique structure, which has a hexagonally organized mono layer of carbon atoms. The ongoing development of graphene-based technologies especially holds significant promise for revolutionizing the electronics industry due to its exceptional and versatile properties.

9.4.1 Graphene for semiconductor

Graphene can be used as a semiconductor in new areas of electronics. Graphene replaces silicon; semiconductor devices of graphene are more efficient, smaller in size, and faster working devices. Foundational components of electronics in the semiconductor reaching their limit faster, computing researchers based on Si devices nowadays replace it with graphene [29]. Graphene semiconductors have ten times greater mobility than silicon, which translates to faster computers. Semiconductors are now the backbone of the electrical and electronics industry. It is the powerhouse we use on every device, from smartphones to laptops. Semiconductor is the heart of the digital revolution. Some of the semiconductor devices are OPAMP, resistors, ICs, capacitors, diodes, transistors, and logic gates [30].

Nowadays, we are demanding more from tiny particles. We want them faster, smaller, and more energy efficient, but there is a limit to how much we use. Graphene as a semiconductor can shape future technology properties, making it flexible in electronic to high computing. Graphene needs a bandgap and is an essential property of a semiconductor; graphene cannot be switched off without a bandgap, making it suitable [31]. The bandgap of graphene can be made applicable for semiconductor devices by doping graphene with appropriate other materials. One of the critical techniques used was the advanced lithography process, which allows the presided patterning of graphene on the microscopic scale [32]. This is coupled with the revolutionary doping process to control graphene's electronic properties, setting the stage for use as a semiconductor.

9.4.1.1 Advantages over silicon

Silicone has been the star of the semiconductor world for a decade by powering smartphones and computers. Technology has gone faster with the introduction of graphene. Graphene is 100 times more conducting than Si; electrons move faster in graphene than silicon. This could translate to faster processing and more efficient power uses. Graphene is more robust than Si, so it has long durability. Thus, graphene-based semiconductors are longer lasting. Graphene is flexible and transparent. This combination is not found in silicon. This property of graphene creates a new world of possibility for graphene for the next generation. Bendable electronics and transparent circuits have more applications and are new ways for future generations.

Future implications and revaluation of the digital era with recent breakthrough demand functional graphene semiconductors.

9.4.2 Graphene for bio-sensors

Graphene is biocompatible, flexible, and transparent that paves the way for its use in wearable sensors in the human body that could play a part in critical digital health monitoring technology [33]. The high electrical conductivity of graphene enables it for rapid ultra-sensitive detection in biosensors. The thin and lightweight nature of graphene can be used in extremely small and light sensing elements without adding much weight. Graphene-based biosensors also provide a noninvasive, secure path toward the simultaneous detection of multiple parameters. Graphene-based biosensors also facilitate rapid, accurate testing of large clusters, which is extremely useful as the world starts to open and large gatherings start to become common. Graphene for various biosensing applications offers significant benefits over traditional technology at low cost.

Enabling biosensing on the nanoscale is the scope and revolutionary change for the next generation. Graphene is an excellent material for application sensors because every graphene atom is exposed to its environment and can detect changes in its surroundings [34]. It can be used to detect chemicals, toxic gases, and biological agents like drugs in our bodies. Graphene is so sensitive that it is capable of detecting one molecule of gas that lands on it. It can also be used for sensing stresses and string and structural components. It can also detect light like a camera [35].

It is also used to detect neurological and heart rates. We can use it as electron spin resonance and neuron sensors. Some research has been done in the field of GO flexible biosensors.

Owing to its extremely advantageous conductive qualities, graphene is currently the most well-known worldwide in the electronics sector. Graphene's remarkable strength, high thermal conductivity, and rapid electron mobility could completely transform electronics and their manufacturing processes in the present and future [36]. Since graphene's qualities often outperform silicon, it may eventually replace silicon, the mainstay of electronics, in many applications. To keep up with the rate of innovation, graphene manufacturing businesses will be increasing production, as demand is anticipated to climb as more applications are created [37]. Read on to learn about some of the electronic uses for graphene that could result in higher-performing, more durable, and speedier electronics.

9.4.3 Graphene for energy storage devices

It is difficult to store energy in and out of batteries quickly so far from your initial burst of acceleration. Graphene can be used as flexible power storage. Graphene can be used as supercapacitors that are bendable; therefore, graphene is used in advanced energy storage devices. It is so thin that in the future, we see storage devices that are so thin, like our skin.

9.4.3.1 Graphene used in battery

The battery has two electrodes: a cathode and an anode. In a battery, a particular chemical reaction takes place to generate electricity. A battery converts chemical energy into electric energy. Graphene batteries are smaller and lighter than existing lithium-ion batteries (LIBs) [38]. Higher charge capacities are also made possible by the usage of graphene. Graphene has an energy storage capacity of up to 1000 Wh/kg, whereas lithium ions have an energy storage capacity of only 180 Wh/kg. Unlike typical LIBs, a graphene battery has shorter charging periods and is lightweight, strong, and suitable for storing large amounts of energy. Graphene can also be added to the battery anode of LIBs (and other rechargeable battery types) to increase performance and optimize morphology [39]. Lithium is a material that is often used in batteries, whether they are rechargeable or not. Although there are batteries made of zinc and alkaline, their high charge density usually results in a shorter lifespan. They are limited to lower voltages than lithium-based batteries. Because there is just one electrode in a primary (non-rechargeable) battery, current can only travel through an intermediate electrolyte in one way. Lithium ions can flow in either direction depending on whether the battery is charging or discharging, although secondary (rechargeable) batteries still have two electrodes. Generally speaking, the cathode is porous carbon, and the anode is a lithium-based metal oxide complex. Lithium ions can be absorbed into the holes in the stiff structures of the cathode and anode when the current comes through them. When the electrolyte solution is not subjected to current, the ions disperse. The anode and cathode are both capable of absorbing the lithium ions. Ions migrate to the cathode of a battery during operation. Anode ion absorption occurs when the current is reversed during charging. The longevity of this process is increased by the ability to produce numerous cycles. The preferred anode is typically LiCoO_2 , LiMn_2O_4 , LiNiMnCoO_2 (NMC), LiFePO_4 , LiNiCoAlO_2 , and $\text{Li}_4\text{Ti}_5\text{O}_{12}$. The cathode of choice is typically graphite. Nowadays, research is going on to develop the efficiency of LIBs by developing a new-generation graphene-based anode for LIBs.

9.4.3.2 Graphene used in supercapacitor

A supercapacitor is a device that stores energy, and that can be rapidly charged and discharged. This makes it distinctly different from a battery, which takes a longer time to utilize energy. Graphene is ideal for incorporating its remarkable conductivity and high surface area. The mechanical robustness and even flexibility allow the creation of devices that have increased efficiency and are much cheaper. Graphene superconductors possess significant potential for a diverse array of applications, starting from portable mobile phones, where you can envisage a flexible, rapidly charging phone that takes seconds instead of hours, to electric vehicles where

supercapacitors could dramatically increase the efficiency and even electricity distribution [40]. Graphene contains much energy and works better for electronics applications. Batteries and capacitors perform the same work, but in batteries, we use chemicals like Li and lead, which are toxic. If we replace graphene instead of these chemicals, we will also decrease the health hazards. Inside a capacitor, two metal plates are present, and an installed material is present inside the two materials. Capacitors don't contain toxic metals and other hazardous chemicals; capacitors do a million times of charging and discharging cycles within an hour. Supercapacitors are different from traditional capacitors in two different ways. In supercapacitors, superconducting electrodes can be developed by reinforcing graphene with various metals and metal oxides and making hybrid composites. The different types of supercapacitors are discussed in the following representations.

In electrochemical double-layer electrode semiconductors (EDLCs), the interaction of electrolyte ions and the electrode surface results in the formation of a double layer with opposing charges. Due to its large-scale availability in nature and large specific surface area for ion adsorption, porous carbon electrodes have historically been used as EDLC electrodes. Before 2005, increasing surface area was thought to be the only practical way to enhance EDLC's charge storage. However, after 2005, it was recognized that the carbon's pore size and nanostructure were crucial components of the electrochemical performance. Graphene can fulfill the requirements of EDLC.

Asymmetric supercapacitors are more efficient than old ones as they are capable of overcoming the problem of limited cycling stability and working potential. Due to the synergistic combination of operational potentials and electrochemical characteristics exhibited by the individual electrodes, asymmetric systems have more significant working potential and improved energy and power densities. The electrode of the asymmetric system depends upon some physical parameters like chemicals, mass, thinness, physical properties, etc.

In hybridized supercapacitors (HSCs), two distinct charge storage mechanisms from two systems, batteries and capacitors, are combined into one asymmetric supercapacitor type. In the case of two electrodes, one charges via the electrochemical double-layer mode, and the other charges using the Faradic mode. Transition metal oxides or carbides are used as the anode material in aqueous electrolytes in present high-performance hybrid supercapacitors (HSCs), whereas carbon-based materials, including graphene, function as the cathode, enabling the retention of 70%–80% capacitance even after 20,000 cycles, with a voltage window reaching up to 4V. Graphene indeed has unparalleled potential for uses in energy conversion and storage. However, to fully realize graphene's potential as supercapacitor electrodes, the quality of graphene must be considered during the design process. Up to now, many academics have published intriguing findings

from lab-scale research, but supercapacitors must be tweaked and closely watched to provide dependable performance in real-world applications.

9.4.3.3 Graphene in solar cells

In pursuing sustainable and high-performance electronic materials for the next generation, graphene has emerged as a transformative contender. Consisting of a single layer of carbon atoms arranged in a hexagonal lattice, graphene exhibits extraordinary properties that make it a key player in the evolution of electronic technologies [41]. Focusing on the distinctive attributes of sustainable graphene-based solar cells and their wide-ranging applications, this exploration addresses the crucial convergence of performance, environmental impact, and scalability.

The active layer of the solar cells was created by combining metal halide perovskite with pristine graphene. An analysis of the resulting graphene/perovskite material revealed that when the ideal quantity of graphene was utilized, an average efficiency value of 15% under high-stress conditions was attained [42]. According to the University of Cambridge mechanical engineer Michael De Volder, who oversaw the project, the goal is to streamline obtaining and storing solar energy. The hybrid device's cost will be less than that of combining solar cells and batteries if the researchers can increase its lifespan and efficiency. He claims that you can have both functions for the cost of a battery [43]. Researchers from Sejong University in Korea, Northwestern University, and Clemson University in the United States have investigated the factors leading to the degradation in high energy density LIB cathode materials and have created graphene-based mitigation strategies to enhance LIB performance. This research holds promise for various emerging applications, particularly in grid-level energy storage for renewable sources such as solar and wind power, as well as electric vehicles.

9.4.3.3.1 Features of extraordinary electronic properties of graphene

Graphene's exceptional electronic properties, including high electron mobility and electrical conductivity, laid the foundation for its application in next-generation electronic devices. This section focuses on the intrinsic characteristics of graphene that contribute to its role in advancing the performance of electronic materials.

Sustainable synthesis techniques: Sustainable synthesis techniques employed in producing graphene-based electronic materials are required, and the recycling process may be considered. Green synthesis methods, eco-friendly precursors, and energy-efficient processes are explored, emphasizing the importance of minimizing environmental impact throughout the material's life cycle.

Mechanical strength and flexibility: Despite being only one atom thick, graphene's remarkable mechanical strength opens up possibilities for flexible and durable electronic devices. These properties enable the development of robust and bendable electronic components for various applications.

Transparent conductivity: The transparency of graphene makes it an ideal material for transparent conductive films, which is crucial in applications such as touchscreens and displays. Graphene's transparency contributes to creating visually appealing and functional electronic interfaces.

Sustainable energy applications: Graphene's application in sustainable energy solutions is explored, including its involvement in energy storage tools such as batteries and supercapacitors, as well as energy conversion devices like solar cells. The unique properties of graphene contribute to advancements in efficient and eco-friendly energy technologies.

Flexible and wearable electronics: The flexibility of graphene makes it ideal for crafting flexible and wearable electronic devices. Graphene-based materials are shaping the landscape of electronic textiles, bendable displays, and other wearable technologies.

Sensors and IoT applications: Graphene's sensitivity to various environmental factors makes it an ideal sensor material. Graphene-based sensors are revolutionizing healthcare, environmental monitoring, and the Internet of Things (IoT).

Scalability and industrial integration: For graphene-based materials to have a significant impact, they must be scalable for industrial production. The scalability and integration of sustainable graphene synthesis methods into existing manufacturing processes need to be explored.

9.5 CONCLUSIONS

Overcoming scalability barriers, addressing environmental concerns, and pushing the boundaries of performance are integral to the continued evolution of graphene-based sustainable electronic materials. Identifying these challenges serves as a roadmap for future research and development endeavors. In conclusion, this comprehensive overview paints a vivid picture of graphene's role in shaping the next generation of electronic technologies. From its remarkable properties to the sustainable synthesis methods, diverse applications, and environmental considerations, graphene stands poised at the forefront of a sustainable electronic revolution. As research continues and innovations unfold, the promise of graphene-based sustainable electronic materials remains a beacon guiding us toward a future where performance and environmental consciousness coexist harmoniously in the realm of electronics.

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IoT towards sustainability

Bapita Roy and Saikat Majumder

10.1 INTRODUCTION

In an age defined by rapid technological evolution and a growing recognition of environmental imperatives, the phrase Internet of Things (IoT) stands out as a transformative force in addressing sustainability challenges [1–5]. Green IoT (GIIoT) has recently emerged as a focal point of research, propelled by the interconnected network of devices and sensors that comprise the IoT. This interconnectedness facilitates the seamless collection, analysis, and communication of real-time data, enabling a spectrum of applications that contribute significantly to sustainability across various domains [6–10]. Within the IoT-driven smart energy sector, IoT-driven smart electrical grids have revolutionized the landscape by optimizing energy distribution and enhancing overall efficiency [11–15]. These IoT-driven smart grids facilitate cost optimization. It is also an important tool which maintains the ecological balance between the energy production and consumption. IoT-based waste management offers innovative solutions that streamline the real-time problems of the processes and reduce environmental burden. Agriculture is another sector where IoT is making revolution towards sustainability. The farmers are getting equipped with the IoT devices which is providing unprecedented accuracy in monitoring and managing crop conditions. This precision not only maximizes yields but also minimizes the utilization of critical natural resources such as water, fertilizers, and pesticides. This results towards a sustainable earth [16,17]. In urban environments the IoT emerges as a pivotal force to optimize the resource allocation. IoT-driven solutions are reshaping urban environments into increased sustainability and liveable spaces. Additionally, IoT is taking an important role in real-time tracking of air and water quality, as well as controlling deforestation and wildlife movements with the help of several smart sensors connected in network. With all the real-time data collected from the sensor network the early-stage threat detection can possible. Achieving a delicate balance between the benefits of IoT and safeguarding individual privacy is the only key way to reach the ultimate goal of this potential technology for a sustainable environment [18–20].

10.2 IoT OVERVIEW

The IoT implies all the things in the world, which are connected to the internet. It is a system of interconnected computing devices. These may be mechanical and digital machines, objects, animals, or people that are provided with unique identifiers (UIDs) [21]. This UID is a unique number that is used for device identification. By using this UID the data transfer can be successfully done over a network without human interventions. There are huge examples of the thing in IoT. A thing on the IoT can be a person with a heart monitor implant, a farm animal with a biochip transponder, an automobile with built-in sensors, or any other natural or man-made object that can be assigned an Internet Protocol (IP) address. These all are able to transfer data over a network.

10.2.1 Core concepts of IoT

At its essence, IoT revolves around the concept of connectivity. Devices and sensors, from all nooks and corners starting from mobile handset to industrial machinery and environmental sensors, are equipped with embedded technology. In a network all the IoT devices can interact with each other through the internet connection. This interconnected network forms the foundation of IoT. It enables high-speed data transfer and smooth data exchange and system automation. An IoT ecosystem consists of smart devices which are the things of IoT. These include the use of embedded systems, such as processors, sensors, and communication hardware, to collect, send the data, and also become responsive to their surrounding environments. There is also an endless application of Artificial intelligence (AI) and Machine Learning (ML) to ease the process of data collection. This use of AI and ML makes this IoT ecosystems easier and dynamic. In another way IoT can also be defined in the following way:

The IoT defines a network to connect anything with an internet connection. Some specific protocols are framed to control the platform. Based on these protocols all the activities can be done like sensing the signal, information exchange and communications in order to achieve smart recognitions, positioning, tracing, monitoring, and administration.

All the users must be aware about this technology before benefiting from its facilities. All the IoT devices rather than the smart sensors are connected through the IoT forming a network of connected devices. All these devices must have UIDs in the form of an IP address which have embedded technologies or are equipped with technologies that enable them to sense, gather data, and communicate about the environment in which they reside.

The IoT makes things smarter by adding sensors and internet connections. This helps objects to gather and share data maintaining a high privacy.

10.2.2 Characteristics of IoT

The important characteristics of IoT are as follows:

i. **Interconnectivity**

IoT allows anything to connect to the global internet network. It enables worldwide communication. It means objects can share information and interact with each other uninterruptedly.

ii. **Services Regarding the Things**

The IoT can offer several services. The major services are privacy, data security, and compatibility of physical and virtual world. To make this happen, both physical and digital technologies need to be adapted by the users.

iii. **Heterogeneity**

IoT devices come in different types which are made by different manufacturers. Depending on the specific uses all the things are built on various hardware and networks. They communicate to other devices or services using different networks.

iv. **Energy Efficiency, Quality, and Reliability**

The smart devices which are used in the IoT may be operating in severe weather. Irrespective of environments it is also hard to reach several places. For instance, devices operating in outer space or deep inside mines. Quality, reliability, and energy efficiency are vital for them. Minimizing battery changes or charging is important in these types of environments.

v. **Large-Scale Data**

Day by day with increasing demand the number of devices that need to be managed will gradually increase. Due to the large number of smart devices connected on a network, it is very critical to handle these devices properly. More skill is needed to design the flawless devices which can manage the data generation and their interpretation for application purposes. This relates to semantics of data, as well as efficient data handling.

vi. **Safety**

Though IoT has enormous advantages, we must not be indifferent about safety, security issues. Some protocols for safety and security must be formed for both sender and receiver. This includes the safety of our personal data. It is also taking care of the safety of our physical well-being.

vii. **Connectivity**

Connectivity gives the user access and helps the users to be connected to the networks easily. Signal compatibility is another major issue. It ensures whether everyone can share and use data together on network or not.

viii. Sensing

IoT wouldn't be possible without sensors. But these sensors are different from the conventional sensors, these are the smart sensors. These will sense or detect or measure any changes in the environment. The smart sensors are used to collect the measured data. These data can be transmitted and interfaced with environment or cloud. Sensing technologies provide the means to create capabilities that reflect a true awareness of the physical world and the people in it. The sensing information is the analogue input from the physical world. This information is then processed and made compatible for further action.

ix. Processing

All the devices on the IoT will need to have a certain degree of computing power. Even the devices which are used for data transmission and cloud interfacing should have minimum computing power. IoT system requires a processor like any other computing devices. The processor embedded in it will handle such tasks, so all devices connected to the IoT will have a processor as well.

x. Cost-Effectiveness

Things or devices require sensors to collect the data first. Then transmission of the useful information to all the things which are connected through internet. So they will need to be cost-effective. For widespread use the IoT devices need affordable sensors, like tracking food expiry.

There are a wide variety of technologies that are associated with IoT that facilitate its successful functioning. IoT technologies possess the above-mentioned characteristics which create value and support human activities; they further enhance the capabilities of the IoT network by mutual cooperation and becoming a part of the total system.

10.2.3 Key terminologies**10.2.3.1 6LoWPAN**

6LoWPAN stands for "IPv6 over Low-Power Wireless Personal Area Networks". It is a specialized networking protocol designed to enable the use of IPv6 (Internet Protocol version 6) over low power. It is also designed for wireless communication technologies.

6LoWPAN is tailored for devices with limited resources, such as memory, processing power, and battery life, which are commonly found in applications like wireless sensor networks, smart home devices, and industrial automation. It addresses the need for efficient and standardized communication in such scenarios. Some of the key features are:

i. **IPv6 Compatibility**

6LoWPAN allows IPv6 packets to be transmitted over low-power wireless networks. This ensures that all the devices can participate in the larger IPv6-based internet.

ii. **Header Compression**

To minimize overhead, 6LoWPAN employs header compression techniques. This technique reduces the size of IPv6 headers to use of limited bandwidth effectively.

iii. **Mesh Networking**

6LoWPAN supports mesh networking. In mesh networking the devices can relay data for each other. It is extending network coverage and improving reliability. It gives services even in challenging environments.

iv. **Interoperability**

It enables interoperability between different types of low-power, wireless devices. It also maintains it among the networks. This is creating a standardized way for these devices to communicate.

v. **Security**

6LoWPAN incorporates security mechanisms to protect data in transit. It is also including link-layer security and IPsec (Internet Protocol Security).

vi. **Application Range**

Its primary applications include smart homes, industrial automation, building automation, agriculture, and environmental monitoring. It's often used in scenarios where numerous small, low-power devices need to communicate wirelessly.

10.2.3.2 Application programming interface (API)

An Application Programming Interface, usually known as an API, is a list of rules and protocols that allow various software applications or systems to build communication with each other. It is an intermediate layer that initiates data transfer between several entities.

i. **Interoperability**

APIs enable different software components, services, and systems to work together. These work regardless of the programming languages or platforms. These promote compatibility and integration of all collected data and the transmission channel.

ii. **Data Access**

APIs provide a structured way to access and manipulate data from databases. These also work with web services, or external sources. These allow applications to retrieve, update, and share information.

iii. **Functionality Extension**

Developers can use APIs to enhance their applications by integrating third-party services, libraries, or components. For example, we can talk about the social media platforms. The social media platform provides APIs for developers to embed sharing features into their apps.

iv. **Automation**

APIs enable the automation of tasks. These process the tasks by allowing one application to programmatically control another application. This is particularly useful in workflows, scripting.

v. **Ecosystem Development**

APIs are very much important aspects of platforms and services. Popular examples include the Google Maps API. These have given rise to a multitude of location-based applications.

vi. **Web Services**

Many web-based services and cloud computing platforms expose APIs. It enables developers to create, deploy, and manage applications over the internet.

vii. **Security and Authentication**

APIs often include authentication mechanisms to control access, ensuring that only authorized users or applications can interact with them.

viii. **Developer Productivity**

APIs save developers effective time and effort. This time management can be possible by providing several inbuilt functions and data structures that can be reused in different applications.

APIs are a fundamental building block of modern software development. These have contributed to the better performance of connected applications and services in the digital world. They serve as bridges that connect various software components and hardware systems. These enable them to work together uninterruptedly and extend their capabilities.

10.2.3.3 Gateway

A gateway is a very important device or software component in networking and technology. It serves as a bridge between different networks or systems. It enables them to communicate and exchange data efficiently. Gateways play a pivotal role in ensuring connectivity between two IoT nodes or between device and cloud.

i. **Interconnection**

Gateways link comprises networks with varying communication protocols. It also depends on data formats and technologies. The efficient interconnection can make the communication between any two IoT devices or with cloud in a very effective way.

ii. Protocol Translation

They are responsible for translating data and commands from one network or system into a format. It should be converted in such a way that another network or system can understand. This is very much essential for interoperability.

iii. Security

Gateways often serve as a security checkpoint. It provides access control and protects networks from unauthorized access or cyber threats. They can act as a firewall by filtering. These are monitoring incoming and outgoing traffic of a particular network.

iv. Routing

Gateways determine the most efficient path for data packets to travel between several networks. These are optimizing data flow and reducing congestion.

v. Internet of Things

In IoT ecosystems, gateways are frequently used to aggregate data from multiple sensors and smart devices. Then they pre-process the data to make it compatible to the channel. At last they transmit it to cloud platforms for further analysis.

vi. Cloud Computing

Gateways are employed to establish secure connections between all connected networks. These provide many other services like cloud services, allowing data. These are used in different types of applications for the betterment of human life.

vii. Industrial Automation

In industrial settings, gateways connect different components. There are several protocols which are used within manufacturing and process control systems. These protocols also facilitate data exchange and control.

viii. Wireless Communication

Wireless gateways, such as Wi-Fi routers, connect wireless devices to wired networks. These enable wireless internet access.

Gateways are versatile components that enhance connectivity, security, and data flow in various technology domains. They ensure that different systems, networks, and devices can communicate effectively. These function as part of a unified ecosystem.

10.3 FOCUS ON GREEN IoT AND SUSTAINABILITY

The concept of “Green IoT” marks a departure from conventional IoT methodologies. GIoT incorporates the environmentally friendly components into the design, implementation, and functionality of IoT systems. The comprehensive approach of GIoT is more advantageous over the conventional realms of connectivity and device-to-device interaction. Instead,

it adopts a holistic approach which has the inherent potential to address global challenges such as climate change and misuse essential resources. GIoT is a deliberate and purposeful application of IoT principles towards a more sustainable and environmentally conscious future. This framing encourages readers to read the subsequent sections with the understanding that GIoT represents an initiative for the betterment of the planet [21].

10.3.1 Defining Green IoT

In today's rapid technological advancements GIoT stands as a pivotal initiative for environmental sustainability. GIoT is the integration of energy-efficient apparatus, sustainable constituents, and renewable energy reservoirs into IoT frameworks. It very much differs from conventional IoT, with a commitment to curb energy consumption and refine resource allocation. The material chosen for GIoT apparatus is always done in such a way without hampering the ecological balance and the well-being of humans.

While discussing the concept of GIoT, some major points to be discussed are given below:

- i. **Smart world:** Several objects/things can automatically and intelligently collaborate with each other.
- ii. **IoT:** All devices in the smart world are supposed to be equipped with additional sensory and communication add-ons, therefore they can sense the world and interact with each other, but require more energy.
- iii. **GIoT:** Focuses on the energy and efficiency in the IoT principles.

Additionally, GIoT recognizes the significance of integrating renewable energy sources into IoT systems to obey with principles of environmental conservation. By the use of non-conventional energy sources, GIoT aims to decrease the emission of greenhouse gas and reliance on non-conventional energy sources. This deviation from conventional towards renewable energy is a remarkable change towards global sustainability. To achieve this the GIoT is integrating energy-efficient devices, sustainable materials, and renewable energy sources into IoT systems. GIoT aims to create a more sustainable and resilient technological landscape and supports the well-being of our planet.

10.3.2 Key features of Green IoT

The key features of GIoT are those factors which focus on building environmental sustainability beyond conventional IoT. Figure 10.1 indicates the key functional parts of GIoTs. From this figure it is clearly understood that design, production, utilization, and recycling are the four functional steps for a successful GIoT project. The following breakdown elaborates on the outlined key components: GIoT's success lies in its meticulous attention to key components.

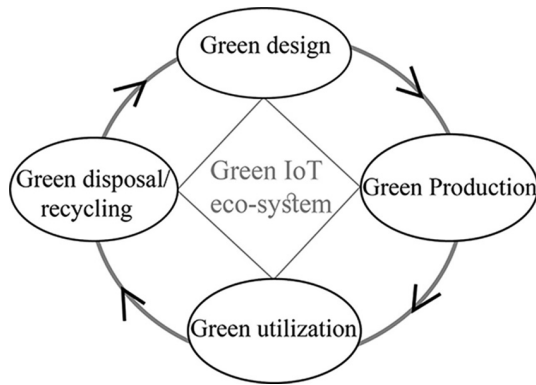


Figure 10.1 Functional diagram of GIoT.

10.3.2.1 Energy efficiency

The emphasis is on energy efficiency in GIoT [22,23]. It is implemented by the widespread deployment of IoT devices to fulfil an increased demand for energy. Achieving energy efficiency involves the strategic design and deployment of IoT devices. This design includes the integration of technologies that optimize power usage, such as low-power processors, energy-efficient sensors, and advanced power management systems. Additionally, all the smart algorithms and data analytics play a role in ensuring that devices operate at peak efficiency, consuming minimal power. In a nutshell the energy utilization must be optimized.

10.3.2.2 Eco-friendly aspects of Green IoT

The use of eco-friendly aspects is important in addressing several challenges like disposing of IoT devices. Traditional manufacturing processes generally lead to pollution and waste by extraction and processing of non-renewable resources.

Through the selection of environmentally friendly materials, GIoT can reduce these detrimental impacts. GIoT always uses the materials that are either recycled or have a minimal environmental footprint. This includes the use of biodegradable plastics, responsibly sourced metals, and materials that can be easily reused or recycled.

10.3.2.3 Use of renewable energy sources

The term “renewable energy” is a subset of green energy. Conventional energy like coal, fossil fuel, etc. adds significant amount of carbon at the time of generating energy. But instead of coal-based energy if we move

towards non-conventional energy like solar, wind, tide etc. the global environmental sustainability will be maintained.

The key components of GIoT collectively represent a holistic approach to developing and operating IoT systems. GIoT seeks to redefine technological innovation by prioritizing energy efficiency, incorporating eco-friendly materials, and integrating renewable energy sources. There are six major elements in GIoT: Identification, Sensing, Communication technologies, Computation, Services, and semantic.

10.3.3 Applications of Green IoT

There are some major applications of GIoT in the various sectors. It showcases its versatility and impact on fostering sustainability in these areas. Below are detailed explanations of how GIoT is deployed in different domains:

10.3.3.1 Smart cities

i. Optimization of Energy Consumption

GIoT technologies play an important role in the implementation of smart cities [24–26]. The main goal is to the optimization of energy consumption by the users. IoT sensors are deployed across urban infrastructures to capture the data from the sensors. Then after analysing the data, the best possible technology of energy usage can be determined. These physical data are mainly temperature, light intensity, moisture, and environmental conditions. There must be a control part where we can get the feedback regarding the optimum use of energy.

ii. Waste Management

By using the smart IoT devices a remarkable development has already been implemented in the recent waste management systems (Figure 10.2). These sensors detect the fill levels of bins, allowing for optimized waste collection routes. These features are included in smart dustbin. The generalized block diagram is shown in Figure 10.3. This not only reduces fuel consumption associated with garbage collection vehicles but also enhances the overall efficiency of waste management system.

iii. Transportation Systems

GIoT enhances the sustainability of transportation systems in smart cities. It provides real-time data on traffic patterns which is optimizing public transportation routes. It results in an eco-friendly mode of transport. This also results in reduced congestion, lower emissions, and a rather pollution-free ecosystem.

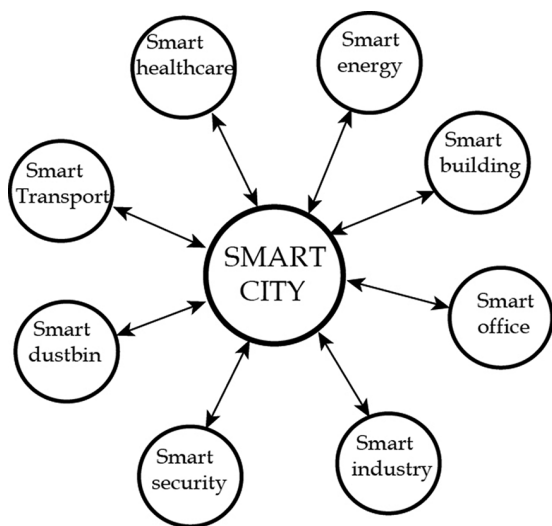


Figure 10.2 Functional diagram of Smart City.

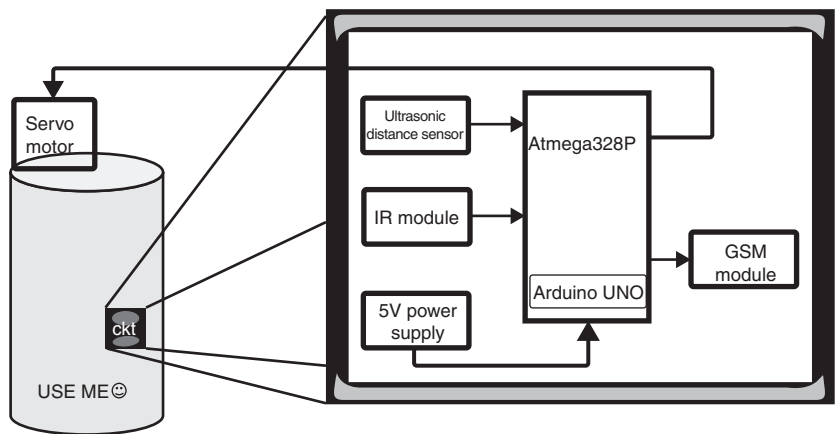


Figure 10.3 Generalized block diagram of smart dustbin.

10.3.3.2 Agriculture – precision farming

i. IoT Sensors Revolutionizing Agriculture

GIoT has a major contribution in precision farming by deploying IoT sensors. These sensors are used to monitor soil conditions and crop health. These state-of-the-art sensors collect data on soil

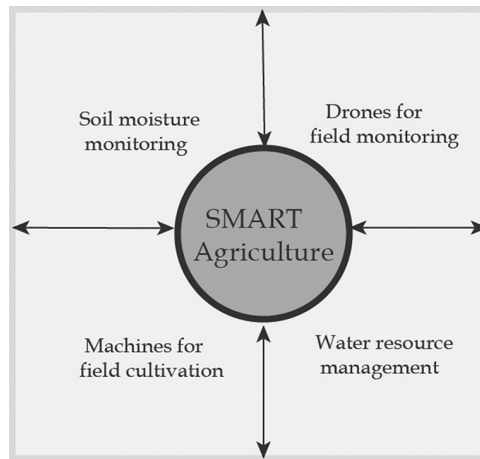


Figure 10.4 Functional diagram of Smart Agriculture.

moisture, nutrient concentrations, and environmental variables like temperature, humidity etc. The information that is being captured by the smart sensors empowers the farmers to take correct decision for farming. Rural farmers will be able to optimize the use of fertilizer, pest management, irrigation planning in their agricultural field (Figure 10.4).

ii. Resource-Efficient Practices

Precision farming techniques promoted by GIoT contribute to resource-efficient agriculture [27–30]. By precisely tailoring inputs like water and fertilizers to the specific needs of crops, farmers can achieve higher yields with lower resource usage.

10.3.3.2.1 Smart economical irrigation by Green IoT

With the new age of technology, industrialization and its rapid growth are spreading widely from the urban areas to the rural places. The fastest growth of factories and industrial firms often causes air, water, and soil pollutions in the rural areas. This system brings out the workable and low cost for the enhanced water resources for agriculture production. The action of cultivating land with lack of water increases sustainability. The proposed module is designed mainly for taking a stand beside farmers and help the farmers to trigger development in the agricultural sector of our country.

To save the quality and cultivation yield of the crops and make farming more advanced and hustle-free this project is planned. The main component used here as a controlling component is Node MCU. This module

uses Wi-Fi for real-time monitoring and saves the data to a database server, which makes the process simpler and low cost than a Bluetooth or a ZigBee modem. The system is designed to be more utilized and compacted with the multiple sensor components, well programmed with the microcontroller. Wastage of water can be prevented by this system with the help of measuring Volumetric Water Content (VWC) of the soil. For measuring VWC, soil moisture sensor kit is used.

Based on the sensor reading the microcontroller sends the command to the motor pump to switch ON or OFF. The water supply is equipped with a timer-controlled sprinkler to reduce the wastage of water. The timer is provided because it may be required to overflow the cultivation area for some time but according to the present scheme of work, the controller will not allow it. In such a case, the water is to be supplied by applying human override option with a switch. Besides maintaining the soil moisture, a pH sensor is also used to monitor the pH level of the soil so that the alkalinity-acidity level of the soil for a particular cultivation can be maintained easily. This also helps the farmers to adjust and apply the fertilizer and pesticides to a correct level. To maintain proper atmospheric temperature and humidity suitable for plants to grow in a healthy environment, temperature and humidity are also measured. The whole monitoring actions can be easily controlled by a remote location and in case of any unpredictable situation necessary actions can be taken very easily.

In the proposed system the number and quantity of unwanted pollutants present in the air can be lessened. For making the system simpler only one sensor is used here for detecting the Air quality index (AQI). Using this AQI, the different components present in the air can be calculated easily. If the toxic and pollutant particles reach the threshold point or cross the limit, then necessary actions can be taken from the remote monitoring locations. A system buzzer can also be introduced to make the local person in-charge aware. To avoid the micropollutants and dust particles, coverage of polyhouse including a heap filter and an air suctioning ventilator has been included. Using this system, we can easily prevent the respiration of harmful pollutants in plants.

This irrigation system proves that the use of water can be weakened for a given amount of fresh biomass. These smart irrigation techniques with controlled pollutants present in the air enhance the overall quality and quantity of specific crops by minimum maintenance. Additionally, the proposed module can be implemented for larger greenhouses or open fields. This module can be used in artificial farming, bio-technological applications, and many other types of modern agriculture system. The continuous monitoring of the soil parameters and storing the data over a long time can prevent drought and erosion of soil by taking useful precautions or actions by the government. Due to time independency, continued water supply when required, controlled AQI, less consumption of power, and natural power

source, the system leads to prevention of soil erosion, thus improving the quality of the crop with conserving power and water. Besides the monetary savings in water use, the importance of the preservation of this natural resource justifies the use of this kind of irrigation system. Pollution caused by the power plants and industrial factories in the rural area can be taken under control with the help of the proposed module.

Example of a real-time case study on smart economical irrigation and air pollution control and monitoring system for rural and industrial area is given below [31]:

Agriculture and industrialization are some of the most important keys in the doorway to globalization. But nowadays it is often noticed that pollution caused by many industries leads to deterioration in agricultural yield as well as the quality of crops. The system proposed here can be used to maintain the quality of the crops in a pollution-free environment. The main objective of the proposed module is to detect the moisture level of the soil and maintain a specified moisture level and temperature of the soil. Along with maintaining the proper soil moisture the proposed system also monitors and controls the air quality of the atmosphere by detecting the pollutants present in the atmosphere and filters the pollutants of air. It also gives a message to the user if the pollutant level goes beyond the level.

Hence, there is improvement in the quality of crops. Automated water supply will reduce the power consumption of the pump and wastage of water is reduced. The power mainly consumed by the pump is mainly supplied with a solar inverter. The rain sensors help in rainwater harvesting by which the use of ground-level water can be reduced. This technique also helps the farmers in a hassle-free farming method. The selector switch is also introduced in the system for manual operation in the cases of some crops which need over-flooded cultivation. Even a pH sensor can be used along with this circuit. The pH sensor shall provide critical information regarding soil nutrient deficiencies or the presence of unwanted chemicals in soil. Then the user can act accordingly from the data obtained about the soil from the pH sensor. The overall technique also helps in the prevention of soil erosion.

10.3.3.3 Energy management – smart grids

i. Green IoT Revolutionizing Energy Management

Through the implementation of smart grids, GIoT redefines energy management systems [32]. These smart grids leverage IoT sensors to facilitate instantaneous monitoring of energy consumption. By aggregating and scrutinizing data on electricity usage, the distribution and allocation of energy resources are optimized.

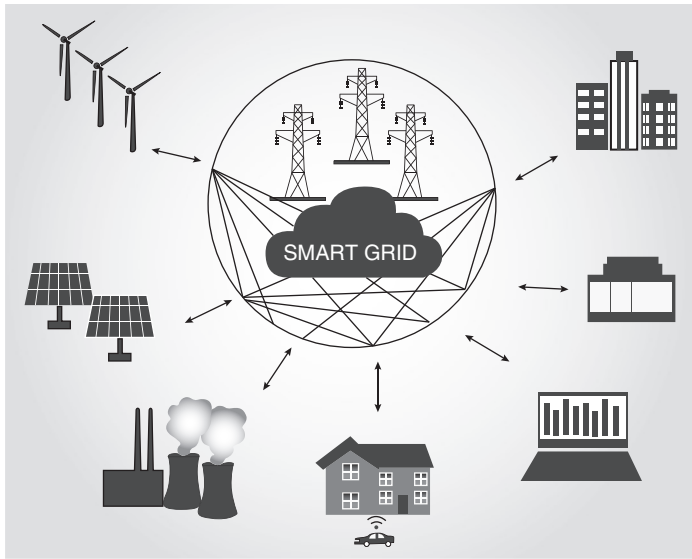


Figure 10.5 Functional diagram of Smart Grids.

ii. Optimization of Energy Usage

Smart grids are a key component of GIoT in energy management. It allows for the optimization of energy usage. This involves dynamically adjusting energy distribution based on user demand (Figure 10.5).

10.4 ADDRESSING CHALLENGES IN GREEN IoT IMPLEMENTATION

As GIoT emerges as a promising paradigm for sustainability, it is mandatory to understand and fight against various challenges on the way of its implementation. The two key challenges highlighted in this section are energy consumption concerns and data security/privacy issues.

10.4.1 Energy consumption concerns

i. Scalability of IoT Devices

The energy consumption may be a crucial matter of concern for the extensive use of IoT devices. The upsurge in energy demand creates a potential challenge to GIoT.

ii. Balancing Technological Advancements

The challenge lies in developing and deploying energy-efficient IoT devices. To develop these sometimes the manufacturers are compromising their functionality and effectiveness, but that may create a problem. GIoT aims to minimize energy consumption through optimized designs, low-power components, and innovative power management strategies.

10.4.2 Data security and privacy issues

i. Massive Data Generation

Eco-friendly IoT promotes sustainability initiatives. However, security and privacy are key concerns with IoT. Security protocols help address these issues. It's essential to safeguard data and privacy. Adopting security measures is crucial for IoT usage.

ii. User Trust

Safeguarding the Ubiquity of IoT Devices: Data security and privacy are critical for GIoT success. These are the challenges and should be overcome at any cost to maintain the acceptability of the GIoT among all users. Users want assurance about their personal data protection. Building trust requires advanced encryption and transparent data policies. Prioritizing these aspects helps users feel confident in adopting GIoT.

If all the challenges can be overcome, then the successful implementation of GIoT towards sustainability will be established. There should be a delicate balance between technological advancements and sustainable energy practices. The robust solutions for data security and privacy are crucial components for GIoT. It achieves its goals while upholding environmental responsibility and user trust.

10.5 CORPORATE RESPONSIBILITY AND REGULATORY SUPPORT

The integration of GIoT is significantly influenced by both corporate responsibility initiatives and regulatory support. This section explores how multinational companies and governments play pivotal roles in promoting GIoT.

10.5.1 Corporate responsibility initiatives

i. Enhancing Corporate Social Responsibility Profiles

GIoT has become so popular for its modern technologies. Embracing GIoT should be aligned with their Corporate Social Responsibility

(CSR) objectives. It also serves as a catalyst for maintaining their reputations in an eco-friendly manner. Through active engagement in sustainable initiatives, these enterprises play a major role.

ii. **Meeting Consumer Expectations**

A remarkable shift in market dynamics has been catalysed by eco-friendly consumers. In the contemporary landscape, consumers are actively demanding the products and services offered by companies that exhibit a sustainable approach. By GIoT technologies, companies are always taking care of these matters. By implementing this the consumers can live in a sustainable environment.

10.5.2 Regulatory support

i. **Enacting Regulations to Encourage Adoption**

Governments are recognizing the role of technology in addressing environmental challenges. As a result, they are starting the regulations to encourage and sometimes mandate the adoption of GIoT. By establishing a regulatory blueprint, governments assume a future of eco-innovative IoT throughout every sector worldwide.

10.6 CASE STUDIES

Examining successful case studies provides concrete examples of how GIoT is applied in real-world scenarios. Two prominent examples are explained as follows:

10.6.1 Smart buildings: optimizing energy consumption with IoT sensors

The goal of this case study is to demonstrate how GIoT technologies, particularly IoT sensors, are employed to optimize energy consumption in smart buildings [33,34]. In smart buildings, IoT sensors are strategically placed to sense the real-time environmental conditions. These sensors collect the output on the number of people in a room, natural light levels, and temperature. This data is then processed using sophisticated algorithms to adjust lighting, heating, and cooling systems accordingly. For instance, when a room is unoccupied, lights are dimmed, and the temperature is adjusted to conserve energy. Similarly, if natural light is abundant, artificial lighting is reduced.

This dynamic adjustment ensures that energy is used efficiently, reducing overall consumption. The implementation of GIoT in smart buildings results in significant energy savings. Occupants experience enhanced comfort, and building operators benefit from reduced utility costs. The environmental

impact is noteworthy, with a decrease in carbon emissions associated with energy production. The success of this case study underscores how GIoT can be a game-changer in optimizing energy usage in commercial and residential structures.

10.6.2 Waste management: revolutionizing practices with IoT-enabled solutions

This in-depth exploration delves into the transformative realm of GIoT, specifically focusing on the revolutionary role of IoT-enabled solutions in reshaping conventional waste management practices. In this context, the integration of IoT sensors into waste bins stands as a pivotal innovation, dynamically monitoring fill levels. Upon reaching a predefined capacity, the sensor initiates a signal transmission to a centralized waste management system [32–34], orchestrating a seamless and timely waste collection process. The deployment of IoT-enabled solutions further allows for the optimization of waste collection routes, strategically minimizing unnecessary pickups and curtailing fuel consumption in real time.

Beyond immediate operational enhancements, the incorporation of data analytics unveils a deeper layer of insight into waste generation patterns over time. This analytical prowess facilitates nuanced planning and resource allocation, cementing the implementation of GIoT in waste management as a catalyst for heightened efficiency and sustainability. The resultant benefits extend to municipal cost savings, stemming from optimized collection routes, reduced fuel usage, and entire improvement in waste material management efficacy. From an environmental standpoint, the reduction in superfluous waste collection trips emerges as a tangible contribution to lowering greenhouse gas emissions, positioning GIoT as an ecological ally in waste management.

In summation, these case studies encapsulate concrete evidence showcasing the transformative potential of GIoT in not only optimizing energy consumption within smart buildings but also spearheading a revolution in waste management practices. Through the strategic integration of IoT technologies, these applications not only elevate operational efficiency but also emerge as formidable contributors to environmental sustainability. The conclusive narrative underscores the profound impact of GIoT in steering positive change across diverse sectors, underscoring its potential as a driving force for a cleaner and more sustainable future.

10.7 FUTURISTIC INNOVATIONS

GIoT is a dynamic field that continues to evolve, and several emerging trends and innovations are shaping its future trajectory. Two prominent trends – integration of edge computing and the promotion of circular economy principles – highlight the ongoing advancements in GIoT:

10.7.1 Integration of edge computing

i. Reduced Energy Consumption

The integration of edge computing in GIoT represents a trend towards decentralized data processing. Edge computing helps to minimize the load of the server. This reduces the need for extensive data transfers and decreasing energy consumption.

ii. Improved Response Times

Edge computing offers improved response times for critical applications. By processing the system lag is reduced, enabling faster decision-making. This is particularly crucial for applications where real-time responses are essential, such as in smart grids or precision agriculture. The integration of edge computing in GIoT enhances the overall efficiency of systems while contributing to energy savings.

10.7.2 Promotion of circular economy principles

i. Better Product Lifecycle Management

GIoT is increasingly aligning with circular economy principles, emphasizing better product lifecycle management. This involves tracking products from their production phase through their use and eventual disposal. IoT sensors play a crucial role in collecting data at each stage, providing insights into the entire lifecycle of a product. This data-driven approach facilitates more informed decisions regarding product design, usage patterns, and end-of-life considerations.

ii. Encouraging Recycling and Reuse Practices

GIoT is promoting recycling and reuse practices by providing valuable data on the recyclability and reusability of products. By incorporating sensors that can identify materials and components, manufacturers can design products with easier disassembly and recycling in mind. This approach encourages the sustainable way to consumption and conserving resources. The future scopes and innovations in GIoT are to shift the paradigm towards even greater sustainability. The integration of edge computing offers not only reduced energy consumption but also improved responsiveness for critical applications. Concurrently, the promotion of circular economy principles through better product lifecycle management and a focus on recycling and reuse practices reflect a commitment to creating a more sustainable and environmentally friendly technological landscape. As GIoT continues to advance, these trends underscore its potential to be at the forefront of responsible and forward-thinking technological innovation.

In conclusion, the emphasis on GIoT signifies a paradigm shift towards sustainable technological practices, heralding a new era where innovation and

environmental responsibility converge. As the global community grapples with pressing environmental challenges, GIoT emerges as a beacon of hope, showcasing the transformative potential of technology to drive positive change.

This concluding section encapsulates the essence of GIoT and its key role in shaping a uniquely sustainable and environmental-friendly future. GIoT represents a departure from conventional technological paradigms, emphasizing the need between innovation and environmental responsibility. GIoT serves as a pillar to the potential of this new technology to be a catalyst for positive change. By integrating environmental sustainability into the core of IoT principles, GIoT demonstrates that technological advancements can go hand-in-hand with efforts to address climate change, resource depletion, and other environmental concerns.

The emergence of GIoT heralds a paradigm shift, positioning technology as a linchpin in the quest for a sustainable and eco-friendly future. It transcends mere principles, embodying a steadfast dedication to aligning technological advancements with environmental stewardship. This commitment permeates every facet of the IoT lifecycle, from conception and deployment to operation and eventual disposal. As stakeholders across industries, governments, and communities increasingly embrace the significance of GIoT, the momentum behind its adoption surges.

This growing recognition underscores the pivotal role of GIoT in addressing broader environmental challenges and laying the groundwork for a resilient and sustainable world. Positioned at the vanguard of a transformative movement, GIoT signifies a harmonious fusion of technology and environmental stewardship, poised to drive forward a future where technological innovation coexists seamlessly with ecological balance.

10.8 BENEFITS

The benefits of IoT towards sustainability are wide-ranging and impactful, encompassing various aspects of environmental, social, and economic sustainability. Here are some key benefits:

i. Resource Efficiency

IoT technology enables the optimization of resource usage in various sectors such as agriculture, energy, water management, and transportation. By collecting real-time data on resource consumption, IoT sensors and devices can identify inefficiencies and enable more precise allocation and utilization of resources, leading to reduced waste and increased efficiency.

ii. Energy Conservation

IoT assumes a pivotal mantle in advancing energy preservation endeavours and curbing greenhouse gas emissions. Propelled by

IoT sensors and data analytics prowess, intelligent energy management systems meticulously fine-tune energy utilization across edifices, industrial complexes, and transit grids. By scrutinizing energy consumption trends and enacting astute control methodologies, IoT fosters a culture of frugality and buttresses the transition towards renewable energy reservoirs.

iii. **Environmental Monitoring**

IoT sensors enable real-time monitoring of environmental parameters such as air and water quality, soil health, and biodiversity. By collecting and analysing environmental data, IoT facilitates early detection of pollution, habitat degradation, and ecosystem changes, supporting informed decision-making and conservation efforts.

iv. **Sustainable Agriculture**

IoT technology enhances sustainability in agriculture by enabling precision farming techniques. IoT sensors monitor soil moisture levels, weather conditions, and crop health in real time, allowing farmers to optimize irrigation, fertilization, and pest control practices. By minimizing inputs and maximizing yields, IoT-driven precision agriculture promotes sustainable farming practices and reduces environmental impact.

v. **Smart Transportation**

The fusion of IoT with transportation networks heralds a new era of urban mobility. It is marked by heightened efficiency, safety, and eco-sensitivity. Intelligent traffic can be managed by IoT sensors and data analytics to fine-tune traffic patterns. It can be able to mitigate gridlock and curtail emissions. Furthermore, IoT-infused public transit infrastructures provide instantaneous updates on routes, timetables, and vehicle availability. It also promotes the adoption of public conveyance and diminishing dependence on individual automobiles.

vi. **Waste Revolution**

IoT sensors and ingenious waste management systems revolutionize waste collection. It also improvises the recycling and disposal operations. It can only be possible by scrutinizing bin capacities, optimizing collection paths, and integrating cutting-edge sorting technologies. IoT fosters a culture of waste reduction.

vii. **Water Conservation**

IoT sensors undertake real-time surveillance of water quality, consumption, and distribution. It catalyses the adoption of more efficient water governance methodologies. Smart irrigation frameworks need fine-tuned watering regimes in response to meteorological projections and soil moisture metrics, curbing water extravagance.

viii. **Disaster Management**

IoT technology enhances disaster preparedness. It can respond by providing real-time data on weather patterns, natural disasters, and emergency situations. IoT sensors monitor environmental conditions.

In this way it can detect early warning signs of disasters such as floods, wildfires, and earthquakes, enabling timely evacuation and emergency response efforts.

In situation where environmental crises become large and urgent, the demand for sustainable remedies reaches a peak. IoT emerges as a novel technology for tackling these emergency situations. Due to the merits of GIoT there is a transformative shift. IoT has enough feature to build a more sustainable tomorrow.

10.9 CHALLENGES

IoT has a tremendous capacity to reshape our world. It ranges from smart homes to industrial optimization and healthcare units. Despite these scopes IoT has many challenges. Among all the challenges the security issues are main. The security issues can be optimized by following steps:

- Step 1: Trust:** Allow only designated people/services device or data access
- Step 2: Identity:** Validate the identity of people, services, and “things”
- Step 3: Privacy:** Ensure device, personal and sensitive data is kept private
- Step 4: Protection:** Protect devices and users from harm
- Step 5: Safety:** Provide safety for devices, infrastructure, and people
- Step 6: Security:** Maintain security of data, devices, people, etc.

The other challenges are technical complexities, ethical issues etc.

i. Interoperability and Compatibility

A primary challenge of IoT exists in establishing interoperability and compatibility among huge number of nodes and different platforms. With a diverse array of IoT devices and sensors operating on different protocols and standards, ensuring seamless communication is a very tough task. The lack of interoperability not only hampers the scalability and deployment but also escalates complexity. It is also the main reason behind the increased expenditure for businesses and organizations.

ii. Scalability and Management

Issues with scalability emerge in areas such as device provisioning, configuration, firmware updates, and data management. Without robust management tools and platforms, organizations may face operational inefficiencies and security challenges.

iii. Security and/or Privacy

Security or privacy is very importance in the IoT domain. This issue must be taken care of for the sake of sensitive data captured and

communicated by connected devices. Sensitivity in IoT devices exposes users to risks like unauthorized and illegal access of data. The main reasons for the security issues are feeble authentication mechanisms, data encryption deficiencies, and insecure communication protocols.

iv. Data Management and Analytics

IoT handles the sensor networks which comprise of huge numbers of sensors. So, the data collected from the sensors also in a large volume must be handled by IoT very delicately. The data management, storage, and analysis are the very important and crucial tasks of IoT. Organizations must look into the advance tools and mechanism to utilize the IoT data. This can be further used to develop a robust decision-making system for sustainable growth of the society.

v. Reliability and Quality of Service

Ensuring the reliability and quality of service (QoS) of IoT deployments is another significant challenge. Factors such as network connectivity, device reliability, and latency are very important for performance and reliability. Implementing redundancy, failover mechanisms, and quality assurance processes is required for uninterrupted operation.

vi. Regulation and Ethics

IoT presents complex regulatory and ethical considerations related to data privacy, security, and consent. Protection of data and regulation requires robust privacy policies. Ethical considerations like data ownership and data transparency must also be acknowledged. Then the data is used ethically with sheer responsibility for IoT technology.

vii. Complexity of Ecosystems and Integration

The IoT ecosystem comprises diverse stakeholders, including manufacturers, developers, service providers, and end-users. Coordinating and integrating various components can be challenging due to differences in standards and protocols.

Organizations must adopt a holistic approach to tackle technical, security, privacy, regulatory, and ethical challenges. By investing in robust measures organizations can remove the complexities of IoT. Then they can leverage its capabilities to drive innovation and create value in a connected world.

10.10 CONCLUSIONS

In this era of rapid technological advancement, the IoT emerges as one of the driving technologies to maintain the environment sustainability. From the aspect of industrial automation, IoT applications are fundamentally reshaping our interactions with the environment. This technology

has various applications across diverse sectors. The assimilation of IoT technology into our daily routines makes revolutionary changes which are achieving sustainability milestones. In IoT, several sensors are used to gather the real-time data for further analysis and decision-making. In the above section it has been discussed that in the agricultural domain, IoT-driven smart farming methodologies empower farmers to remotely monitor soil moisture levels, crop vitality, and meteorological conditions. By using this IoT devices the farmers can irrigate in a very efficient way. They can yield crops with minimum water consumption and chemical inputs.

Furthermore, IoT has the potential to revolutionize energy management and conservation by the integration of renewable energy. IoT-based smart grid infrastructures has the capability to monitor electricity consumption instantaneously. It results in an optimized power distribution and reducing energy consumption. The smart agriculture can be able to minimize greenhouse gas emissions. Moreover, IoT-assisted transportation systems became very popular to ease the daily human life. Intelligent traffic management system with IoT nodes and data analytics can optimize traffic flow. It is also useful for unnecessary congestion. Additionally, IoT-enabled public transport infrastructures, such as electric buses and trains, reduce the use of fossil fuels. This is the remedial measure to reduce the air pollution in metropolitan cities. Smart waste management system can be controlled remotely by using the IoT through the server. It optimizes the collection routes using efficient waste management methodologies. Beyond these specific applications, the IoT has made a remarkable change in water management, biodiversity conservation, and disaster crisis management.

Though IoT ecosystems comprise of devices and platforms from diverse manufacturers, it still ensures seamless communication and compatibility among these devices. It is generally used to increase the system efficacy and scalability. Furthermore, the environmental footprint of IoT devices depends on their production, operation, and disposal. Today's IoT is approaching towards sustainability through efficient designs, such as energy-efficient components, recyclable materials, and end-of-life recycling initiatives. IoT technology with immense potential has a diversified field like agriculture, energy, transit, waste management, and beyond. By facilitating real-time data gathering, analysis, and decision-making, IoT ensures more efficient resource utilization and reduced energy consumption. However, realizing the full potential of IoT some well-defined policies must be framed to overcome the challenges such as privacy of data and security. By knowing the power of IoT responsibly and innovatively, we chart a course towards a more cognizant and resilient future for generations to come.

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Integration of Artificial Intelligence and Machine Learning for wearable electronics

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II.1 INTRODUCTION

The field of wearable electronics consists of wearable sensors/medical implant devices which are tiny sensors equipped with an embedded processor, sensing unit, and wireless transceiver [1]. A group of such sensors with the ability to correlate and transfer data among themselves and to a central server forms a body area network (BAN). The wearable sensors may also be equipped with tiny cameras that can be used for capturing images/videos of the subject or its surroundings for surveillance-based tasks. The captured image/video first needs to be compressed, followed by coding and wireless transmission to neighboring devices or a central hub for further processing. One of the prominent features of BAN is that the monitoring can be done without any hindrance to the daily routine of the subjects, as per the upcoming anywhere-anytime surveillance paradigm. These devices have the benefit that they provide continuous monitoring of subjects wherever they may go. These devices are used nowadays for a plethora of applications like remote diagnosis, monitoring sleep patterns, species monitoring, patient/elderly monitoring, artificial retina, visual aided monitoring for surgery, etc. Moreover, the current situation of the world caused due to the Covid-19 pandemic necessitates the continuous monitoring of people from all sections of society which would require more efficient techniques of data collection, coding, and transmission through wearable electronic devices connected to the BAN/wireless multimedia sensor networks/Internet of Things (IoT) [2]. A representation of the communication between on-body wearable devices (wearable sensors) and in-body wearable devices (implanted sensors), cloud and server along with some applications is shown in Figure 11.1.

Wearable technology is currently being used by workers in public and professional services to reduce/prevent injury, remote management/assistance, and enhanced security. The wearable sensors/implants have their potential in almost every aspect of life including the textile industry, fashion industry, cosmetics, medical, military, etc. One of the prominent features of wearable/

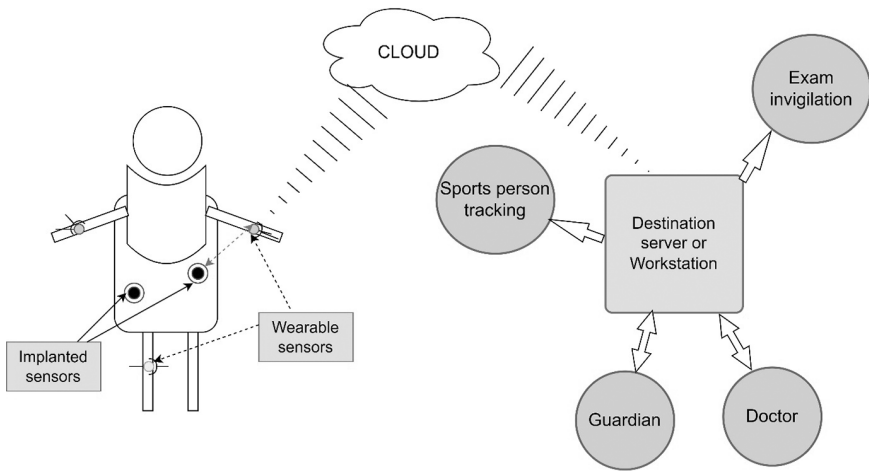


Figure 11.1 An illustrative setup showing the wearable/implanted devices, their communication, along with some applications.

implants is that it would aid in maintaining the dignity of patients while providing more privacy. The Medtronic Public Limited Company which is a US-Irish-based medical device company whose headquarters are in Dublin, Ireland, has a total revenue of USD 31 billion (<https://www.emergenresearch.com/blog/top-10-leading-companies-offering-next-generation-implants>).

A total of 1068 medical implant manufacturing organizations are in the UK and their total funding amounts to approximately USD 5.6 billion (<https://www.crunchbase.com/hub/united-kingdom-medical-device-companies>). The international medical devices market which is currently valued at USD 495.46 billion is expected to grow to USD 718.92 billion by 2029 (<https://www.fortunebusinessinsights.com/industry-reports/medical-devices-market-100085>). The implants could help to switch the load of care from the Health Service Executive (HSE) to the person. It would facilitate more freedom for the individual while decreasing the hospital expenses. The necessity of remote healthcare and reducing the burden on hospitals has become obvious since the Covid-19 pandemic. The implant technology can achieve both the above-mentioned requirements. A list of companies mentioning their website address and type of wearable electronic device they deal with is shown in Table 11.1.

The wearable sensors/medical implants are small in size and are constrained in computational resources, and cannot support high data rates within nominal transmission power [3]. Most of these devices are used for healthcare/surveillance/tracking applications, which means that the signals need to be transmitted fast, and error-free while maintaining secrecy. Because a delay in transmission may be fatal to a human who may be a

Table 11.1 List of companies producing wearable devices along with their types (accessed as of 31.12.2023)

<i>S. no.</i>	<i>Company</i>	<i>Wearable device type</i>	<i>Link</i>
1	Garmin	Fitness and health tracking devices	https://www.garmin.com/en-IN/health/
2	Apple	Watch	https://www.apple.com/in/healthcare/apple-watch/
3	Withings	Watch, sleep analyzer	https://www.withings.com/in/en/
4	Owlet Baby Care	Baby monitoring system, sleep analyzer	https://www.owletcare.com/
5	Alive Cor	Heart monitoring	https://www.alivecor.com/
6	Fitbit	Activity trackers	https://www.fitbit.com/global/in/home
7	Whoop	Fitness	https://www.whoop.com/us/en/
8	MASON	Wearable medical device component	https://bymason.com/
9	Petkit	Pet wearables	https://petkit.com/
10	Vitalsinc	Patient monitoring wearables	https://www.vitalsinc.com/
11	Silvertree	Stylish wearables for fall detection of adults	https://www.red-dot.org/project/silvertree-reach-70038
12	Apollo Neuro	Wearables for sleep therapy	https://apolloneuro.com/
13	Grapheal	Remote monitoring	https://grapheal.com/
14	Atlas Wearables	Health tracking	https://wearables.com/collections/atlas-wearables-1
15	Neurable	Brain chips, etc.	https://www.neurable.io/
16	Fujitsu Limited	Driver drowsiness detector, etc.	https://www.fujitsu.com/global/microsite/wearables/ubiquitousware/
17	Vuzix	Smart glasses, e.g. Vuzix smart swim	https://www.vuzix.com/products
18	Catapult	Wearable electronics devices for athletes	https://www.catapult.com/
19	Matrix	Healthcare	https://www.matrixindustries.com/

child, a patient, or an elderly person. Errors in the transmission would result in the wrong interpretation or diagnosis of a scenario at the receiver end. Furthermore, the wearable devices are small in size and are resource-constrained, so energy-efficient scheme for wireless transmission is a must. Secrecy is also a major concern, as the information in the signal is specific to a person and is intended to be received by a particular observer/receiver only. For example, the patient data needs to be sent only to a particular

doctor, the surveillance information of a child needs to be shared only with guardians/caretakers, etc. Another issue with medical implants is the presence of neural noise which would vary from person to person due to variation in the neurons of each individual. So, optical methods to eliminate or minimize the neural noise need to be developed. The characteristics of neural noise need to be investigated and they should be modeled (using Machine Learning (ML)) close to that of popular noise like Gaussian noise, white noise, etc. If the characteristics of neural noise can be approximated as those of popular noises, then state-of-the-art remedies for reducing popular noises should be tested with neural noise.

Moreover, in most of the application scenarios, the wearable devices/medical implants would be in direct contact with the skin. So, the techniques should be safe for living beings. The channel modeling and scattering phenomenon also need to be considered for designing the transmission system. The channel modeling is a challenging task for in-body implants as they are inside the skin of living beings. So, even slight changes in the posture of the subject would indicate a change in the equivalent communication channel. Finally, any kind of analysis related to the in-body implants would require the device to be implanted within the skin of a living being. The implanted devices may interact with the living cells/tissues present within the body and may lead to allergies, toxic reactions, or other health hazards. It would be difficult to convince human volunteers for participating in such types of studies by implanting those devices within their skin. So, any kind of technique/communication used for in-body implants should adhere to the safety of living beings. To this end, Artificial Intelligence (AI)/ML [4] based techniques would be needed for performing such kind of analysis while ensuring that the developed techniques are safe for humans and other living species.

AI/ML is affecting almost every aspect of human life. Wearable electronic devices are ubiquitous nowadays and attached to the human body for 24 hours. AI/ML models also exist which have been incorporated into these devices and there are many companies that provide specific AI-based applications in wearable devices. The upcoming concept of TinyML [5] which emphasizes the development of ML models for resource-constrained devices seems particularly suitable for wearable devices. The details about the AI/ML, its relevance to wearable devices, etc. are presented in detail in forthcoming sections.

The rest of the chapter is organized as follows. Section 11.2 presents a brief introduction to AI, followed by ML foundations in Section 11.3. In Section 11.4, AI/ML-based wearable electronic devices are presented. The challenges with AI-integrated wearable electronic devices are detailed in Section 11.5 and the challenges with AI-integrated wearable devices are discussed in Section 11.6. Finally, the chapter concludes in Section 11.7 with some future research directions.

11.2 ARTIFICIAL INTELLIGENCE

AI [6] is the concept of making machines capable of learning, thinking, adapting, and making autonomous decisions like human beings. With the use of AI, models/algorithms that have the ability to mimic the functioning of human sensory organs, particularly brain, have been developed. The neural structure of the human brain has motivated researchers to come up with the concept of Artificial neural network (ANN), Convolutional neural network (CNN), etc. [2] which can be considered as basic building blocks of AI. These neural networks make the machines smart enough to gather and process the data in order to extract useful information from them and make suitable decisions. AI can be broadly classified into two categories, i.e. weak/narrow AI and strong/general AI. The narrow AI is developed to perform tailored/specific tasks, like classification of images, voice recognition, etc. General AI has the ability to perform multiple tasks like human beings. The general AI is still being researched and more complex AI models are continuously evolving [7]. An example of general AI is natural language processing (NLP) which aims to make machines understand and create human languages [8]. This would make the machines more integrated into human lives. In the next section, a subset of AI which can also be called its backbone, ML, is presented.

11.3 MACHINE LEARNING FOUNDATIONS

The concept of ML [9] is motivated by the way humans learn and its main objective is to make machines learn and develop the ability to make decisions making any system completely autonomous. There is one important difference between humans and other species that mainly relates to the incredible “learning” ability of human beings. A human child when born is extremely weak and learns each and everything starting from scratch. The learning of a human child is a gradual and continuous process. First, the child learns crawling, then standing followed by walking and finally running. Likewise, in every aspect of human life, the person has to learn that theoretically and physically before it can be implemented in real life. A person may be an expert swimmer, but his child will not know swimming by birth. The child has to learn swimming after all. One may be born in a desert, thousands of miles away from a river/sea, but that person has the ability to learn and become one of the best swimmers in the world and can surf on the ocean waves or dive deep inside the marvelous natural wonders of the ocean. This is not the case with animals, as the offspring of animals inherit the qualities of the parents by birth. There is no need to teach a fish or a duckling how to swim, a calf how to run, a baby bird how to fly. Animals have inherent/tailored features specific to their species, e.g. if someone puts

grass in front of a cub, it will never eat it. Moreover, the learning ability of animals is very limited and they can learn only specific things.

The learning ability of humans is tried to be mimicked in machines in the concept of ML. In this concept, the machines are being trained to learn from experience and datasets without being programmed for specific functions. For instance, a person wants to throw a waste paper in the bin. One may not be successful in the first attempt to throw the paper in the bin. However, after it the person may realize his mistake and make suitable corrections in the approach. Eventually, after a few attempts, the person can successfully throw the paper in the bin. Once that person has thrown the paper in the bin, after that it will be quite easy for the person to throw the paper successively in the bin in the very first attempt. Likewise, the machines are made to learn through successive iterations.

There are basically three types of ML approaches, viz, supervised, unsupervised, and reinforcement learning (RL) as shown in Figure 11.2. The supervised learning technique uses labeled data (available from open-source standard datasets) for training a model to do a general task. After the training, this model can be used on anonymous data as well. Classification and regression are two basic approaches used in supervised learning. In the case of unsupervised learning, unlabeled data is used for training purposes. Clustering and association are the major techniques used in this approach. RL is another ML technique used for training the models to make decisions in order to achieve the best possible results. It imitates the trial-and-error approach of learning used by humans to attain their objectives. The details about these learning strategies can be found in [4]. The relevance/need of AI/ML in the domain of wearable electronics is presented next.

11.4 RELEVANCE TO WEARABLE ELECTRONICS

Wearable electronics, ranging from fitness trackers and smartwatches to medical implant devices, gain from AI/ML models that process the data, excerpt insights, and get accustomed to user behaviors. The existing wearable sensors are generally tailored to some particular features and are for personal use only. With the integration of AI/ML, wearable sensors can be

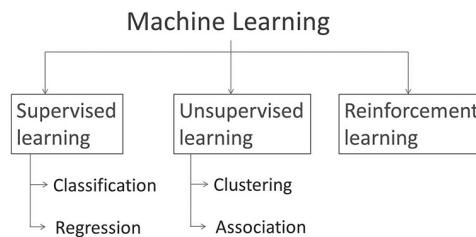


Figure 11.2 Broad classification of different types of learning strategies in ML.

easily made a part of the IoT. The family members each wearing a wearable sensor can communicate with each other or share their data related to health or other activities with each other easily. Like the virtual concept of groups in social media apps such as WhatsApp, family/friends groups of individuals wearing electronic devices can be easily formed with the usage of AI. This will help to foster stronger family bonding and will solve the issue of loneliness which is becoming a very serious issue these days [10]. AI/ML models are being developed to predict emotions as well [11,12]. The majority of the decisions of human beings are based on emotions and their day-to-day activities are linked with emotions. The wearable sensors may be very fruitful for recognizing the emotions of humans and interpreting their behavior. One very useful application of wearable devices integrated with AI would be to detect the special emotions of the person wearing it, like he/she is in depression, anxiety, etc. [13].

Disease diagnosis using ML-based algorithms in wearable devices is already available in the market [14]. By studying user habits, likes, and circumstantial information (like situation, time, etc.), these devices can provide more appropriate and prompt notifications, creating a truly personalized user experience. One of the primary goals of ML in wearable devices is individualized health and fitness tracking. Through the process of persistent learning, these devices adapt to the user's priorities, providing more authentic and tailored observations on health and well-being. The customizable nature of AI/ML ascertains that these devices mature with the user's fitness levels and health goals.

Various monitoring/surveillance techniques exist like CCTV monitoring or fixed camera/visual sensor-based monitoring. However, the monitoring through fixed visual sensors/CCTV is limited to the field of view of the camera. Wearable devices have the added advantage of monitoring the person wherever they go. The integration of AI with wearable sensors will make the monitoring of the person fully automated. Such a system can monitor the behavior of the person and provide feedback or warning messages to doctors/guardians in case the person becomes unconscious. A completely new era of ML for IoT sensors and micro-controllers with the theme of "ubiquitous intelligence" is coming up under the umbrella term of TinyML which will be very fruitful for wearable electronic devices [5,15]. TinyML is in fact being researched to incorporate the ML models on resource-constrained devices. It would enable many AI applications ensuring real-time processing of data.

11.5 AI/ML-BASED WEARABLE ELECTRONIC DEVICES

The traditional wearable sensors can count the steps. Let's say a user has set his daily walking challenge to walk 5 km. The wearable sensor, e.g. smart-watch, can count the number of steps and calculate the distance walked and raise an alarm or intimate it by a message signal on the screen of the

wearable device if the user has not walked 5 km. Sometimes, the weather may be bad, the user may be extremely tired, or driven by some emotional feeling which would make the user difficult to walk 5 km. In such cases, AI-integrated wearable sensors may understand the situation of user and give advice on whether to continue walking or not. The integration of AI in wearable devices will make these devices one of the most loyal friends of the user at the same time working as a guardian or doctor.

As mentioned in Ref. [17], the system consisting of wearable electronics consists of three main parts, namely data gathering, processing of the data, and provision of feedback. The AI and ML models need data in order to train, test, and validate them. One of the major challenges with the development of these models is the availability of datasets. The wearable devices themselves collect data as long as they are tied to the human body and they are also saved/transferred for further processing. So it will be quite easy to develop datasets with the purpose of training AI/ML models for wearable devices.

A review and meta-analysis detailing various AI models made for or which can be integrated with wearable devices for identification of cardiovascular-related diseases is presented in Ref. [18]. An interesting article covering many aspects of the usage of AI-integrated wearable sensors in the field of medical/health can be found in Ref. [19]. A list of some companies manufacturing AI-integrated wearable electronics products along with the applications is presented in Table 11.2. Some of the interesting and socially useful applications of AI/ML in the field of wearable electronics are described in the following subsections.

Table 11.2 List of some companies/products along with the applications for which they use AI/ML [16]

<i>S. no.</i>	<i>Company/product</i>	<i>Use of AI/ML</i>
1	Fitbit	Sleep pattern tracking and fitness
2	Apple watch	Detection of heart rate irregularities
3	Etho	Smart helmets for riding bikes
4	Tractive	Pet monitoring
5	IvAlpha	Defense
6	Audicus	Hearing aid
7	Arena Labs	Healthcare
8	Vue Lite 2	Smart eye glass
9	Gluuko	Diabetes management
10	Vimo labs	Indoor workout tracking

11.5.1 Indoor health and fitness monitoring

An important application scenario of AI-integrated wearable sensors would be in the field of indoor fitness tracking [20]. Existing wearable sensors are implanted at various locations on the human body while they are working in a gym or other exercise centers where the body movements/posture during the exercise is recorded by the sensors. AI models may learn and then give suggestions as per the requirement of the person regarding his/her health and fitness. Recently researchers have studied the effects of prolonged sitting on human health. It has been reported that this may lead to obesity, musculoskeletal disorders, sarcopenia, diabetes, and even premature death [21]. AI/ML models integrated into wearable devices may be used to track the sitting habits of people along with their physical activity monitoring. Based on the observations, the user may be intimated to perform physical activity as and when needed. Another important use of these devices would be to study the posture-related habits of the user while sitting, walking, eating, etc., and then suggest measures to correct them, in case they are not scientifically correct. Learning swimming or other exercises by the use of AI-integrated wearable devices can be an interesting area of application of these devices. The devices can record the movement of arms/legs, etc. and then suggest on real-time basis the errors in the movements and give signals or requirements to correct them. These devices can in fact work as a coach.

11.5.2 Persons with disability

One of the very fruitful applications of AI/ML-integrated wearable electronics would be to help persons with disabilities. The deaf and dumb people are unable to listen or talk with normal persons which makes it difficult to inter-communicate between these people. The persons who are unable to speak and listen have their own means of communication known as sign language recognition. However, it is very difficult for normal human beings to learn this language. Researchers have developed electronic gloves that can convert sign language into speech which makes it easy for deaf and dumb people to communicate with normal people. However, these gloves are bulky and currently tailored for one-to-one communication. AI-integrated wearable sensors are a promising alternative for establishing communication between groups of individuals from various sections of societies either offline or online via sign language conversion to speech signals [22,23].

Moreover, there are many people in the world who are deprived of vision. Some are blind by birth and some people become blind due to some illness. Like other human beings, visually challenged people also have feelings

and want to live like normal humans with sight. The AI-integrated wearable devices may be integrated with ultrasonic sensors which would help in obstacle avoidance for the blind. They can be also used for playing sports, specifically these devices will be very helpful in the upcoming concept of sports for blind [24]. These devices can be further advanced to help blind persons in route following, location sensing, way finding, etc. There are some existing electronic devices in the form of travel aids and navigation systems tailored for the blind. However, they are designed for specific purposes and are unable to solve all the issues related to blind people. Also, the unavailability of low-cost Braille learning kits is also a major reason for the educational backwardness of blind people. AI-enabled wearable Braille learning kit may be developed to promote the spirit of education in blind people. The AI-integrated wearable electronic may function as an all-in-one solution for blind people.

11.5.3 Emotion recognition

Humans live in societies and have social interaction everywhere: whether in schools, offices, markets, homes, etc. Due to constant mingling of humans with each other, they exchange their feelings, experiences, etc. Human decisions and performance are driven by emotions on several occasions. A person may be an expert driver and would be habitual of fast driving, but when he/she drives a car with own child seated, then the speed of the car will be automatically reduced. The behavior and even the functionality of human beings are driven by emotions. The blood pressure of a person may increase/decrease due to emotional feelings. Sometimes heart attack occurs when a person hears very shocking news about some of his/her beloved person. This is also the case when such emergency situations occur due to emotions.

The existing wearable sensors can measure various vital health parameters but are currently not able to exactly predict emotions. Wearable electronic devices integrated with AI/ML would be one of the best devices that may be used to predict emotions. Human beings recognize the emotions of a person mainly from facial expressions. Another approach would be to record the body parameters like blood pressure, temperature, and other biological changes in the human body through wearable sensors under different circumstances. These collected data can be used for training and testing of AI/ML models in the context of emotion recognition. The different approaches for emotion recognition are shown in Figure 11.3 and explained in detail here.

- A. **Surveys:** One of the simplest approaches for detecting emotion is through questionnaires/surveys. In this case, the wearable electronic device like the smartwatch can be used for asking and replying to questions either through text or audio. It may be then shared with some psychologists/doctors/counselors for predicting the emotions. ML-based

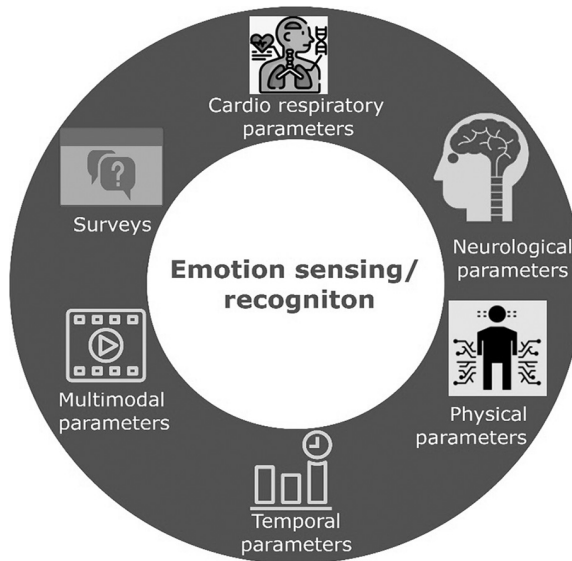


Figure 11.3 A schematic representation of different strategies of emotion sensing/ recognition.

algorithms also exist that automatically guess the emotion based on the questions and answers [25]. A text-based depression (a form of emotion) recognition dataset has been developed that is available at <https://ieee-dataport.org/documents/text-based-depression-detection-dataset-chinese> (accessed as of 14.01.2024) which has the data of 31 patients and 33 healthy persons. Another question-and-answer-based emotion dataset in Turkish language is available at <https://ieee-dataport.org/documents/turkish-question-answering-sentiment-dataset-scd> (accessed on 14.01.2024). This dataset is created with the aim of developing and teaching the students suffering from Down syndrome.

- B. **Cardiorespiratory parameters:** The parameters like heart rate, respiratory rate, blood pressure, pulse oximetry, tidal volume, etc. which can be measured by electronic devices including wearable sensors and medical implants fall under this category. These parameters are also popularly used for emotion recognition. A dataset for emotion recognition using physiological parameters is available at <https://ieee-dataport.org/documents/emotional-status-determination-using-physiological-parameters-data-set> (accessed on 14.01.2024). There are various analyses separately done on the variations on these parameters according to the human emotions. For instance, the work in Ref. [26] has presented an analysis of the effect of anger (a human emotion) expressions on blood pressure.

- C. **Neurological parameters:** The other widely used parameters which are used for emotion recognition are neurological parameters, like electroencephalogram (EEG), brain magnetic resonance imaging (MRI), electrocardiogram (ECG), etc. Large datasets of these neurological parameters already exist which can be used for the training, testing, and validation parameters for ML/AI emotion recognition models. However, the biological parameters (neurological+cardio respiratory) are mainly personal data of patients obtained in hospitals or during routine health checkups. So, it is necessary to follow proper ethical and privacy guidelines while using this data.
- D. **Physical parameters:** The external observable changes of the human body are also a significant class of parameters used for emotion recognition. The emotions of a human being can be easily guessed by his body posture, hand gestures, speech, facial expressions, etc. [27]. AI/ML-based algorithms are currently being developed for emotion recognition using the physical parameters [28]. The most common emotion recognition used by humans since time immemorial is by the observation of facial expressions. The various human emotions like happy, sad, afraid, surprised, irritated, sorrow, etc. can be easily interpreted by one's face. AI-based emotion recognition using facial expressions is an ever-increasing field of research [29]. Emotion recognition with wearable devices utilizing facial and physiology is presented in Ref. [30].

There are already low-cost tiny visual sensors available in the market with the ability to capture, compress, and send the images through the internet. The wearable devices also have cameras integrated to them to capture the images and transmit them which are used for surveillance-related applications, like fall detection, child care, remote exam proctoring, etc. These cameras can be used to capture the images of the person's face whose emotion is to be guessed. Most of the human expressions can be judged by the movement/position of the eyebrows/lips at a particular time. Some of the expressions along with the face are symbolically shown in Figure 11.4. In this figure, the eyebrows and lips are only shown for a better understanding of their

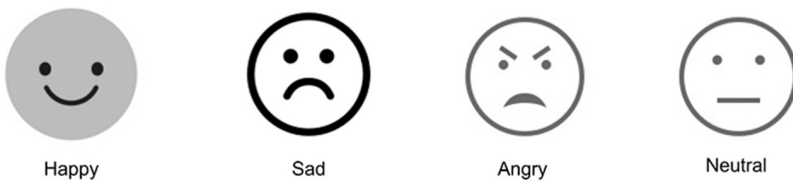


Figure 11.4 Emotion recognition using facial expression (eyebrows and lips).

relation to human emotions. The three expressions (happy, sad, and neutral) can be easily observed from the lips only. The raised corners of the mouth upward signify joy/happiness, while a downward bend of the mouth is related to sadness, and a flat mouth represents neutral expression. If a person is angry then the eyebrows get lowered which is not the case with the other three expressions discussed here. So, image processing techniques like detection of region of interest (ROI), feature extraction, segmentation, etc. approaches can be utilized to figure out the changes in eyebrows and lips which may be further given as input data to AI/ML models for training purposes.

These are only a few of the expressions mentioned here. Many more facial expressions exist which are the combination of other physical parts of the face like cheeks, eyes, etc. Generalized and comprehensive AI/ML models need to be developed that can incorporate all the parameters and then successfully predict human emotions. One another important point to consider while working with facial expressions is that the images need to be pre-processed before transmission.

The pre-processing of the images will save memory and bandwidth requirements. There are low memory and low complexity image coders available for IoT sensors [31] which need to be tested on actual hardware so that they can be utilized for this application.

In Figure 11.5, a general layout depicting the approach that can be used for emotion detection using images captured using wearable sensors along with AI is shown. In this approach, the images are first captured through the visual sensors followed by feature extraction/ROI-based pre-processing of the information required. Then the extracted features/information would be compared with the available information from the standard database images annotated with emotions (in the Figure 11.5, images from Kaggle dataset [32] under the category happy has been shown). Based on the comparison, the emotion would be predicted.

The captured images can be broadly categorized into three: (a), (b), and (c). In category (a), the visual sensor has captured the image of the complete face from the front which may be easily compared with the standard images. The category (a) images can be easily observed that they are of happy faces. In category (b), the full face is not clear or the person is wearing black spectacles covering his eyes (one of the most prominent physical parameters used in emotion detection). However, by proper observation, these images can also be categorized as happy. In category (c) images, either only one side of the cheek is visible or there was no proper illumination while capturing the image. In this case, a decision cannot be made and the emotion detection setup may not work. So, there may be an additional step of categorization of images captured by the sensors before comparing them with standard

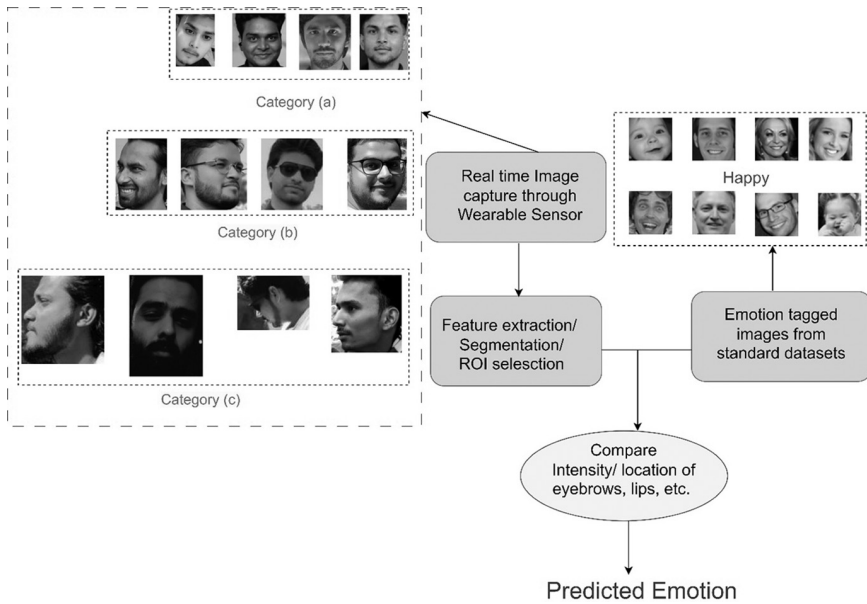


Figure 11.5 A schematic representation of facial prediction approach using images captured through wearable devices and AI.

images. An alert may be given by the sensor, if the image captured may not be used for emotion detection. This will make the user recapture the image using the wearable device/sensor. Another alternative would be to program the wearable sensor such that it would automatically recapture the image once an alarm is issued regarding the failure of the image regarding emotion detection. The wearable sensor can iteratively recapture the image until a suitable image is obtained which can be successfully used for emotion prediction. The above-mentioned facial expression approach was that the person wearing the wearable device will capture the image of another person whose emotion need to be discussed. Another approach for emotion recognition is that the wearable sensor will capture the changes in the facial activity (like facial muscle contraction, variations in cheek, eyebrow movement) of the person wearing that wearable sensor [33,34]. In this approach, there will be no need for images.

- E. **Temporal parameters:** These are the time-related features which are used for emotion recognition like speech prosody changes, speech rate, and pauses, temporal changes in bio-metric data, etc. [35,36]. The facial expressions also change with time and a video may be more informative compared to images as a means for predicting emotions as it contains both spatial and temporal information. Likewise, the

other parameters can also be obtained for a particular span of time which may be utilized for emotion recognition. However, the temporal data would require more memory and as the data increases more complex algorithms need to be developed for handling them.

- F. Multimodal parameters:** These parameters are formed with the theme that emotions are complex and can be best expressed by a combination of other parameters like facial expressions, speech, physiological responses, etc. [37–39]. The combination of different parameters would allow for a more precise emotion recognition system with the need to use more advanced processors. A multimodal database is available at <https://www.eecs.qmul.ac.uk/mmv/datasets/deap/> (accessed on 17.01.2024). For incorporating and analyzing the multimodal parameters, wearable devices need to be integrated with more advanced sensors with proper communication facilities between different modalities. So, there exists a trade-off between accurate emotion detection and complexity of the sensors. A list of datasets is presented in Table 11.3.

Table 11.3 List of some of the available datasets of images for emotion recognition (accessed as on 31.12.2023)

S. no.	Dataset	Link
1	Ascertain	http://mhug.disi.unitn.it/wp-content/ASCERTAIN/ascertain.html#/
2	Extended Cohn-Kanade Dataset (CK+)	http://www.jeffcohn.net/Resources/
3	EMOTIC	https://s3.sunai.uoc.edu/emotic/index.html
4	CelebFaces Attributes Dataset (CelebA)	https://mmlab.ie.cuhk.edu.hk/projects/CelebA.html
5	UMDFaces	https://umdfaces.io/
6	MS-Celeb-1M	https://www.microsoft.com/en-us/research/wp-content/uploads/2016/08/MSCeleb-1M-a.pdf
7	Wider Face	https://www.kaggle.com/datasets/iamprateek/wider-face-a-face-detection-dataset
8	IMDB-WIKI	https://data.vision.ee.ethz.ch/cvl/rrothe/imdb-wiki/
9	Emognition Wearable Dataset 2020	https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/R9WAF4
10	Emotion Image dataset	https://www.epfl.ch/labs/mmisp/download/emotion-image-datasets/
11	Facial Emotion Detection Dataset	https://salford.figshare.com/articles/dataset/Facial Emotion Detection Dataset/22495669
12	ElderReact	https://github.com/Mayer123/ElderReact
13	OAHEGA: Emotion Recognition Dataset	https://data.mendeley.com/datasets/5ck5zz6f2c/2

(Continued)

Table 11.3 (Continued) List of some of the available datasets of images for emotion recognition (accessed as on 31.12.2023)

S. no.	Dataset	Link
14	Aff-Wild2 database	https://ibug.doc.ic.ac.uk/resources/aff-wild2/
15	Facial Expression in-the-Wild (ExpW) Dataset	https://www.kaggle.com/datasets/shahzadabbas/expression-in-the-wild-expw-dataset
16	Real-world Affective Faces Database (RAF-DB)	http://www.whdeng.cn/RAF/model1.html#dataset
17	IIITM FACE EMOTION	https://ieee-dataport.org/documents/iiitm-face-emotion#files
18	135-Class Emotional Facial Expression Dataset	https://ieee-dataport.org/documents/135-class-emotional-facial-expression-dataset

11.6 CHALLENGES WITH AI-INTEGRATED WEARABLE ELECTRONIC DEVICES

Every technology has to face several challenges before its maturity and success. The AI-enabled electronic devices also face some challenges that need to be handled properly as described in the next subsections.

11.6.1 Ethical considerations

The wearable electronic devices either integrated with AI or not have to be worn by human beings and they collect various personal data of the user which necessitates standard ethical practices to be followed in their manufacturing and usage [40]. The ethical requirements for these devices will vary as per the application. For instance, the ethical standards for a wearable sensor used only for indoor fitness activity within a gymnasium would be different from that used for medical purposes. When these devices are used for medical-related activities, the ethical framework/regulations set up by the medical association/hospitals need to be considered. Moreover, in all the application scenarios of wearable electronics, human beings are involved. So, the regulatory measures for conducting research/experiments involving human beings will be applicable to these devices as well during their manufacturing as well as during their real-life usage. When these devices would be integrated with AI/ML, then these devices will become smarter with the capability to make decisions and give necessary feedback to the user as and when needed. So there is a need to frame proper ethical guidelines to be followed for AI-integrated wearable devices. Most of the researchers think that AI should not dictate humans but should be governed

by human decisions. Moreover, the person wearing these devices should also follow ethical guidelines. For example, one should not click photos or make videos of another person using wearable devices integrated with the camera without their consent. It would be challenging to program ethics into the devices, so the major responsibility lies with the user of these devices to abide by the law. One important issue to be considered is the upcoming concept of Do it Yourself (DIY) projects. Many companies share various DIY projects on their websites. These DIY projects can be developed by any person, even by minors. So these DIY projects must be thoroughly reviewed for ethical requirements. The authors in Ref. [41] have detailed the independent review requirement and its procedure for ethical considerations of wearable devices.

11.6.2 Data protection and privacy

One of the major concerns regarding the wearable sensors integrated with AI/ML is of data protection and privacy [42]. The personal data of a person related to health, sleeping patterns, activity, etc. is being continuously recorded by wearable devices. These data are specific to a person and are confidential. Moreover, these devices are small in size and have limited onboard data storage capability. The data of users is stored mainly over cloud networks and in various scenarios, third-party access is given to companies for enhancing their services, etc.

If there is a data breach or someone hacks the user data, then it is a serious issue of privacy violation. The hacked data may be sent to advertising companies, or others, while the person whose data is hacked may not be even aware of the scenario. These may lead to financial losses of the person as most of the online financial transactions nowadays are done through wearable devices like smartwatches. There have been several cases of data misuse and privacy breaches in the past related to the data collected through wearable sensors. As reported in Ref. [43], approximately the fitness records of 61 million Apple and Fitbit wearable device users data were breached in 2021.

One of the possible solutions for data protection is that the data to be shared with any other person needs to be authenticated by the user. Authentication is a very crucial step these days in heterogeneous wireless networks where various devices share data using the internet. To prevent privacy, encryption of data is a must which needs to be performed before the data is sent to the channel for transmission. For the exchange of data/communication between the wearable sensor and external servers, communication protocols must be used. Also, strong passwords should be used for accessing the data saved in the smart devices. The increasing adaptation of biomedical authentication in the case of personal wearable sensors is also a good practice for data protection and privacy. These devices should also be

integrated with the feature of a remote erase option by which the user can remotely erase all the contents of that device in case if it is lost/stolen. This will help in maintaining the user privacy.

11.6.3 Real-time processing

Real-time processing of data is another challenge being faced by wearable sensors [44]. These devices are small in size with limited memory, computational power, and need to be charged for proper usage. If the programs embedded in them are complex, then they will consume more power and the devices will be discharged soon. In most of the applications related to medical/surveillance real-time processing of data is needed. Real-time processing of data implies that the sensors collect the data, process them followed by their transmission, all in real/current time. This is similar to live telecasts of any scene, like broadcasting of a football match on television. In order to facilitate real-time processing, the data collected by these devices needs to be compressed before transmission. The compression of data will save memory and reduce the bandwidth requirement as well. Moreover, these devices generally gather a continuous stream of data from different sensors which need to be integrated for proper analysis. These devices are typically constrained by compact form factors and rely on small, power-efficient processors. Real-time processing requires quick decision-making, but the constraints on processing capabilities can hinder the ability to perform complex computations rapidly. The integration of AI/ML models will further enhance the complexity of the devices and a feedback mechanism will be established for smart surveillance/guidance. The feedback time should be less to make decisions within a reasonable time. Thus, the real-time processing should be made faster and accurate.

11.6.4 Human-computer interaction

The human-computer interaction (HCI) is a multidisciplinary field that deals with the interaction involving human beings and machines [45]. The wearable sensors are in fact machines capable of gathering/sensing useful data from the human body and then communicating it to doctors/guardians and even to the user itself. HCI includes the design, fabrication process of the wearable sensors, communication protocols, interfacing, privacy, etc. The traditional communication between humans and machines is non-interactive in nature. One of the promising applications of integrating generative AI [46] with wearable sensors would be that the communication between humans and wearable sensors will be made interactive. The user may feel like he/she is talking with the machine in the same way as with any other human. The HCI considers the scenarios of machines and humans and tries to form a feedback loop for effective communication. The demands of

Table 11.4 Human side (user) and machine side (wearable electronic device) for human-computer integration

<i>S. no.</i>	<i>Human side</i>	<i>Machine side</i>
1	Geographical location	Outdoor/indoor, environmental effects
2	Cost	High-/low-end processors
3	Privacy	Encryption/cybersecurity
4	Application scenario	Tailored device/general
5	User's requirement	Quality of service

humans and the capabilities of machines need to be synchronized for effective product design to meet the expectations of the end user. Some of the factors to be considered from the user side and the machine side are shown in Table 11.4.

One of the initial considerations while designing the wearable sensor is whether they will be used for indoor/outdoor activities or both. Then the environmental effects also need to be considered during the design. For example, a wearable sensor designed for people living near deserts/dry regions will be different from those living near beaches. Another important parameter from the user side is cost, i.e. how much the user can afford for the device. Based on this, the wearable device will consist of high-/low-end processors. The privacy requirement from the user side is general for all wearable devices. Corresponding to this on the machine side encryption and cyber security techniques need to be developed. The wearable devices also need to consider the application scenario of the user based on which the device would be tailored for a specific task (such as heart rate monitoring only) or a general wearable device for overall health monitoring. Finally, the most important thing is to convince and satisfy the user by providing a good quality of service.

Moreover, apart from the technical details and available resources, the limitations of the human body, psychology, etc. also need to be considered in HCI. For example, the image coders which are used for compressing an image before its transmission exploit the redundancy of the human eye. The human eye cannot differentiate between very low pixel intensity differences among successive pixels, known as psycho-visual redundancy. Also, the human eye cannot visually differentiate between the quality of two reconstructed images at the destination if both have a peak signal to noise ratio (PSNR) greater than 40 dB. Likewise, by exploiting and considering the limitations of various parts, especially the sensory organs of the human body, efficient and cost-effective techniques can be designed for HCI with good quality of experience at the user end which would eventually satisfy the demands of humans.

11.6.5 Communication

Most of the wearable sensors are worn outside the human body; however, the in-body medical implants are within the human skin. There are many applications wherein for a particular application, the setup consists of a wearable sensor worn on the body, and a medical implant inside the skin is also needed, such as a cochlear implant, gastric stimulator, retinal implants, etc. In these setups, generally, the connection between the on-body wireless sensor and the in-body medical implant is established via radiofrequency (RF) radiation. However, it provides less data rate and consumes large energy which leads to frequent replacement of batteries.

Optical wireless communication (OWC) [47] is an attractive solution in these scenarios which will provide higher data rates while consuming less energy. The use of OWC in these devices will not only solve the problem of low data rates, as OWC has high bandwidth, but also prevent interference with different devices, is safer for humans compared to RF radiation, and provides energy efficacy [48]. Before standardizing a communication technique for intercommunication among wearable devices/implants there is a need to separately analyze the features and requirements of devices worn outside the body and medical implants fixed inside the skin. Then the channel characteristics need to be modeled since in these cases, there will be interference with the internal body organs/tissues of various dimensions ranging from millimeter to nanometer range. Cell nuclei, proteins, epidermis, melanin, etc. will vary the light absorption of different wavelengths. There are chances of interference by the body sweat, while skin color may also have an effect. The OWC systems also suffer from shot noise produced from sunlight [49]. A path loss model also needs to be developed for these OWC-based devices. So, the model designed should consider all the aspects of developing a good communication system. There is a need to develop a fast energy-efficient and error-free approach for OWC in wireless wearable devices or in-body medical implants integrated with AI/ML while maintaining secrecy.

11.7 CONCLUSIONS

This chapter presented the integration of the upcoming AI/ML technology with wearable electronics making these devices much smarter, faster, and socially useful. These devices can be used for indoor activity tracking, surveillance, tracking of a specific person in sports, health monitoring, fall detection, etc. AI/ML algorithms also exist which are used for emotion recognition using facial expressions. Apart from these applications, one of the very interesting and useful applications of these devices would be for persons with disability. AI-based wearable devices for navigation, obstacle

avoidance, sports for the blind, Braille learning kits, etc. may be extremely beneficial for visually impaired people. However, it would be a challenge to incorporate the AI/ML algorithms/models on low-cost wearable electronic devices as they have limited random access memory (RAM) and low processing power. Other problems with wearable devices need to be addressed, the primary being standardization and human safety [50,51]. Moreover, the massive use of these devices necessitates the development of standard ethical rules to be formulated. The upcoming concept of TinyML also needs to be explored and tested in the context of wearable devices.

Another interesting future work in this field would be to study the OWC-based transmission system in the upcoming network function virtualization (NFV) [52]. The NFV would enable the IoT node/wearable sensors to assist several virtual sensing services in parallel. The transforms developed for resource-constrained scenarios can empower several parallel data sensing functions to be executed on a wearable sensor with minimum resources. It is expected that the sensing and computing operations in the sensor nodes will turn into a sensing layer in upcoming layered architectures that are designed to incorporate communication functions along with the computation in IoT. In the realm of wearable electronics, AI/ML appears as a life-changing force, raising the techniques and functionalities of these devices intended to seamlessly integrate into our daily lives. The integration of AI in these devices will surely make them smarter, but they should be designed such that the human beings wearing them have control over the device. The AI models should not dictate to the user and the user should also think about a particular scenario and make a decision based on his/her intention and experience rather than blindly following the suggestions of a man-made device.

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Green electronics

From fabrication to its application

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12.1 INTRODUCTION

The electronic industry is moving towards a more sustainable and ecologically friendly direction due to the rapid advancement of an area known as “green electronics”.^{1,2} In the technological advancement in the current scenario, it is almost impossible to live without using electronic-based gadgets such as mobile phones, cars, lifts etc. which include electrical circuits,³ memory components,⁴ light-emitting diodes (LEDs),^{5–7} sensors,^{8–10} lasers,^{11–13} etc. The term “green electronics”^{14–16} describes the blending of electronic components with materials derived from plants, frequently utilizing the special qualities of plants for a range of purposes, like herbal LEDs^{17,18} and optoelectronic devices.^{19,20} These plant-based products have gained a lot of attention due to their cost-effectiveness and being environmentally friendly. Exponential escalation in semiconductors and electronic technology and its ingrained applications in daily life pushed the researchers to reconsider the aftereffects on human health and the environment.²¹ The performance of modern electronic technology is prioritized on performance over environmental concerns. However, people are often unaware of the ecological damage caused by chemically produced electronics when they are disposed of. The concern of disposing the chemical-based electronics creates a necessity to stick to eco-friendly substitutes that reduce resource depletion,²² energy consumption, and the production of electronic waste created while using conventional manufacturing techniques and materials. In order to make sure that technological advancement and environmental conservation coexist peacefully, it is essential to investigate and implement greener alternatives as the demand for green electronic devices grows worldwide. Through an exploration of the fabrication methods, applications, and challenges in the field of green electronics, this chapter aims to clarify the complex issues of this rapidly evolving field. Green electronics has the potential to completely change how electronic devices are developed and to bring in a new era where creativity and sustainability work together to shape the direction of technology.

Humans are well aware of the medicinal properties of these plant-based products, as has been practiced for more than a thousand years. Lately, herbalists have mainly focused on the plants' useful medical applications through using the plant extracts and employing their unique properties therapeutically to treat a variety of ailments, wounds, and diseases.^{23–25} These herbal plants are also used to treat “Tri Doshas”, namely, Vata (Air principle), Pitta (Fire principle), and Kapha (Water principle).²⁶ India still is the largest producer of herbs; hence it is called the botanical garden of the world. These natural herbs, which have a range of medical uses due to their antioxidant property,²⁷ are now incorporated into electronic gadgets for different purposes. The history of incorporating herbs into electronic components dates back to ancient societies, where specific plants were used for their special electrical qualities. Early in the 20th century, researchers started looking into the conductive and semiconductive qualities of different plant materials. With the goal of using electrical conductivity of the herbal plants to create sustainable and interoperable electronic components, researchers have recently ventured into the field of electronics. This interdisciplinary field investigates the possibilities for novel and environmentally friendly electronic applications using herb-based materials such as henna, turmeric, and aloe vera flowers. Early in the 21st century, scientists started looking into the special qualities of some herbs, like their capacity to conduct electricity or to show piezoelectric effects, electrochromism, etc. As a result, bioelectronic devices were created that employed herbal components for sensing,²⁸ energy harvesting, and as an application in electrochromism.²⁹ Incorporating herbs into electronic components creates new opportunities for environmentally friendly and biocompatible technology development, while also providing sustainable and biodegradable substitutes for conventional materials.

Unlike conventional organic electronics, which usually use standard materials that might not give as much thought to ecological concerns during production, green electronics prioritize sustainability through the use of eco-friendly materials and manufacturing processes. The major problems with conventional organic electronic devices are (1) they are less economical as the cost of purchasing would have been extremely high, (2) they require very hazardous chemicals which are very harmful to human beings as well as the environment and sometimes lead to very serious diseases like cancer,³⁰ (3) they spread radiation and toxic fumes which can further lead to severe diseases like cough, asthma, skin diseases, etc.,^{31,32} (4) they have a very high concentration of hazardous materials like lead, arsenic, and others, which can leak into the streams of water bodies, when e-waste is dumped in landfills,³³ (5) the fertility of the soil may get affected if the e-waste is not disposed of properly.³⁴ A new era in the electronic device-producing industry called “green electronics” comes into play which emphasizes environmentally friendly manufacturing techniques and

sustainable materials. This introduction explores the unique strategies that these two fields use to illuminate the critical role that green electronics plays in promoting an environmentally conscious and sustainable future for electronic technologies.

This chapter is mainly focused on studying the optical and electrical properties of some herbal materials, such as the flowers of aloe vera and hibiscus, turmeric root, henna leaves, and yellow ginkgo tree leaves, for a variety of applications. Extract of various plants like giloy, henna etc. are good ultraviolet (UV) absorber along with luminescence property which make its application as sunscreen, biomarkers, and bioimaging. The hibiscus flower extract exhibits remarkable electrochromic properties, providing the tailored optical property under external bias for potential use as a smart window. Natural memory can be created by using aloe vera flower extract, which shows remarkable memorizing properties. Yellow light emission and white light emission can also be achieved by mixing appropriate red, green, and blue luminescence material for application in LEDs. Various characterization techniques like UV-Visible spectroscopy, photoluminescence (PL) spectroscopy, and cyclic voltammetry, etc. have been adapted to characterize these green materials for application in “green electronics”.

12.2 FEW REPORTED STUDIES USING PLANT EXTRACTS FOR GREEN ELECTRONIC DEVICES

12.2.1 Extraction of hibiscus flower in deionized water for electrochromic applications

The well-known hibiscus flower, which blooms beautifully throughout the year, was utilized to investigate redox activity.³⁵ Additionally, the hibiscus flower extract possesses an extremely special quality known as electrochromism,^{36–38} a phenomenon in which a slight external bias alters the material's colour or optical characteristics. The material must be reversible when reverse bias is introduced in order to meet the crucial requirement of being electrochromic. Since the hibiscus flower extract possesses this characteristic, an attempt to create an electrochromic device with natural materials is described here. For the same reason, first one needs to find out the method to collect the hibiscus flower extract. Chaudhary et al. reported a simple approach for the collection of hibiscus flower extract in deionized (DI) water and utilize it for the developing herbal-based electrochromic device.³⁹ In the extraction process, approximately 5 g of pink hibiscus flower petals was collected and after washing through DI water, the petals were dried in open atmosphere before preparing the extract for the experiment. The dried petals of flower were added to the clean beaker containing 10 mL of DI water. The solution of DI water containing petals was then boiled for a few minutes and left in open environment for the solution to cool down.

It was observed that the transparent solution turns pink in colour after boiling. The pink colour of the solution is due to the active component present in hibiscus flowers which fully gets extracted in DI water through the simple process of boiling. Once the solution was completely cooled, it was filtered using Whatman filter paper. The filtered solution was then divided into two equal parts and kept in separate glass vials. The first part was called as prepared extract and second one was reduced extract. To study the reduction mechanism in the hibiscus flower extract, small amount of NaBH_4 was added to the second part. The colour of extract changes from pink to yellow. This solution was called as reduced extract. Both the extract glass vials (prepared extract, reduced extract) were stored in refrigerator and used within a week.

Further, for the fabrication of electrochromic device using hibiscus flower extract, initially, an ultrasonicator was used to wash a glass substrate coated with indium-doped tin oxide (ITO). A very thin film of flower extract was prepared on cleaned ITO-coated glass substrate. For the same, 3 wt% polyethylene oxide (PEO) solution was made in acetonitrile (ACN) and mixed with prepared hibiscus flower extract in the ratio 1:1. The prepared solution was then drop casted over the cleaned ITO substrate. Next, polyvinyl alcohol (PVA) gel was prepared by mixing 10 wt% PVA in DI water followed by an addition of 1 M KCl to get the gel electrolyte in the ratio 1:2. The prepared gel electrolyte was drop casted on another ITO substrate and held together with ITO substrate containing PEO gel mixed with hibiscus flower extract using double-sided tape. The fabricated device was used to investigate the electrochromic property by applying little bias.

The extract prepared above was first used to study the redox activity in liquid form using 1 M KCl in three-electrode system (glassy carbon as working electrode, platinum wire as counter electrode, and Ag/AgCl as reference electrode). On performing cyclic voltammetry⁴⁰ (CV), a reduction in peak was observed in the negative region at around -0.7V . Since the peak was found at a negative potential, it was determined to be n-type, indicating that it is an electron acceptor. Now, while seeing under room light the prepared extract appeared to be magenta in colour and the reduced extract appeared yellow in colour. Further, to study the optical properties of the prepared extract (original extract and reduced extract), absorbance spectra are shown in Figure 12.1. From Figure 12.1, one can clearly observe that the initially prepared extract produces a broad peak in the green area and transmitting the magenta colour (represented by dark grey) which is the complementary colour of green according to RGB scheme, giving magenta colour to the initially prepared extract. Afterwards, the absorbance spectra of chemically reduced extract were recorded and found to be yellow in colour (represented by light grey) as it is transmitting the yellow colour by absorbing the blue band.

The PL spectra for both initially prepared extract and chemically reduced extract by exciting them with 200 nm wavelength are represented in Figure 12.2.⁴¹ Initially the prepared extract showed notable peaks in blue

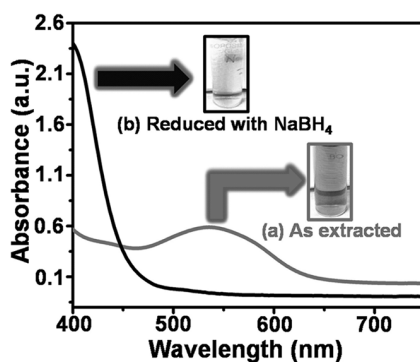


Figure 12.1 The absorbance spectra of (a) the prepared hibiscus extract with the original photograph, (b) the chemically reduced hibiscus extract using NaBH_4 with original photographs.

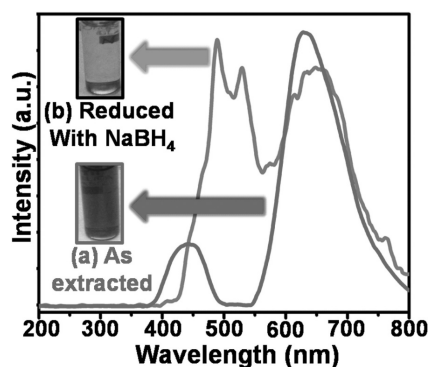


Figure 12.2 The emission spectra of (a) the prepared hibiscus extract with the original photograph, (b) the chemically reduced hibiscus extract using NaBH_4 with original photographs.

and red region, making the blue illumination from the extract. By exposing the prepared extract to UV light, the same was verified since the prepared extract was also observed to be blue in colour. The chemically reduced extract was then excited with 200 nm wavelength, it showed notable peaks in green and red region, giving the green illumination from the reduced extract. The same was then confirmed by seeing the reduced extract under UV light, as the reduced extract appeared green in colour under UV light. The reduced green extract is shown as light grey in figure 12.1b whereas blue illumination from extract is represented by dark grey color.

As the hibiscus flower extract has redox property and is changing colour by the application of bias, which is reversible, an electrochromic device

was made by Chaudhary et al., as discussed above.³⁹ Initially the fabricated device (Figure 12.3a) appeared to be magenta in colour due to the natural colour of hibiscus flower extract. When -2 V of bias was applied to the device, it switched its colour from magenta to transparent state. The same was then studied using UV-Vis absorbance. As seen from the absorbance spectra, initially fabricated device was showing significant peak in the green colour band and transmitting to the magenta colour in unbiased condition. When a bias of -2 V is applied to the device, the colour changes from magenta to transparent, by transmitting almost all the light through the device, which can be clearly observed in Figure 12.3b. To study the switching mechanism, the pulse of -2 and 0 V was applied to the device for few seconds (Figure 12.3c). It was observed that the device takes 3 seconds to switch colour, which was comparable with the already existing metal oxides. This was the first ever natural electrochromic device made using the naturally occurring hibiscus flower extract for practical application in smart window,³⁶ rear view mirror in automobile, electronic displays, aircraft windows, etc.

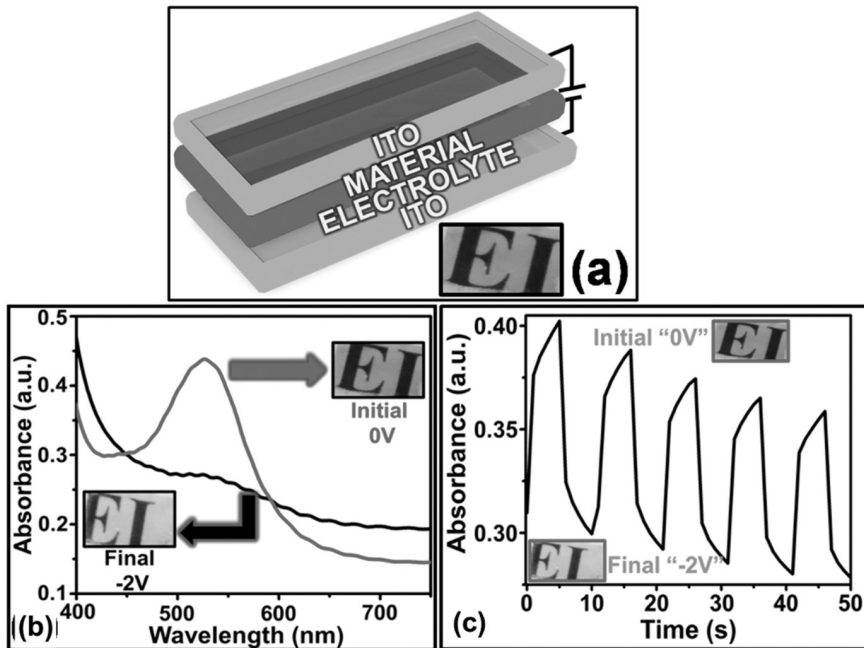


Figure 12.3 (a) Schematic of the fabricated herbal electrochromic device, (b) absorbance spectra of the device under 0 and -2 V is applied, (c) switching of the fabricated device from magenta to transparent state for five cycles.

12.2.2 Extraction of aloe vera flower as natural resistive memory

A traditional herb named aloe vera has antioxidant properties and has been practiced for various application in the medical field. But it has remained unexplored scientifically due to varied climate restrictions. The very uncommonly known aloe vera flower extract may have UV-absorbing qualities like those of conventional herbal preparations, making it a potential herbal sunscreen but here it has been explored scientifically for its application as natural resistive memory. A successful attempt to utilize the aloe vera flower extraction for resistive memory application was demonstrated by Ghosh et al.⁴² In the study, the extraction was done in methanol, as it is a generic solvent for extracting herbal material's active components. A simple non-heating technique was adopted for getting the extract. The rarely blooming 5 g aloe vera flower was collected and washed completely using DI water and left in room for the flower to dry. The washed and dried aloe vera flower was then transferred into a clean beaker containing 10 mL methanol and was covered using aluminium foil. The methanol containing aloe vera flower was left overnight. Next day, the colour of the solution was observed to be light orange as all the active components present in the aloe vera flower got extracted in methanol. Utilizing Whatman filter paper, the methanol containing the aloe vera flower was filtered. The extract was then divided in to two equal parts and poured in two separate glass vials. The first part was called as-prepared extract as it was stored in refrigerator without any interference. In the second part, the extract was reduced by adding a reducing agent NaBH_4 , immediately the colour of extract changed to transparent state. The chemically reduced extract was then kept in a glass vial and stored in fridge. Both the extracts were used within 1 week to perform all the experiments.

Some amount of extract was reduced chemically to study the redox activity in the extract. The initially prepared extract was orange in colour and when it is reduced chemically using NaBH_4 , the colour of the extract solution changes from orange to transparent, demonstrating redox activity as shown in Figure 12.4a. The optical study of the originally prepared extract and reduced extract was carried out using UV-Vis spectroscopy.⁴³ The absorbance spectra in Figure 12.4b for both original extract and reduced extract solution depicts the high absorption in UV regime, providing the application as a natural sunscreen and UV filter. Since menthol was used for the extraction, it becomes important to record the absorbance spectra of methanol as well for the control experiment. The absorbance spectra of original extract solution possessed small hump in blue region, thus transmitting the complementary colour, which is the main reason for the yellow to light orange colour of original extract. However, the absorbance spectra of reduced extract show increase in absorbance value by 33% but remained

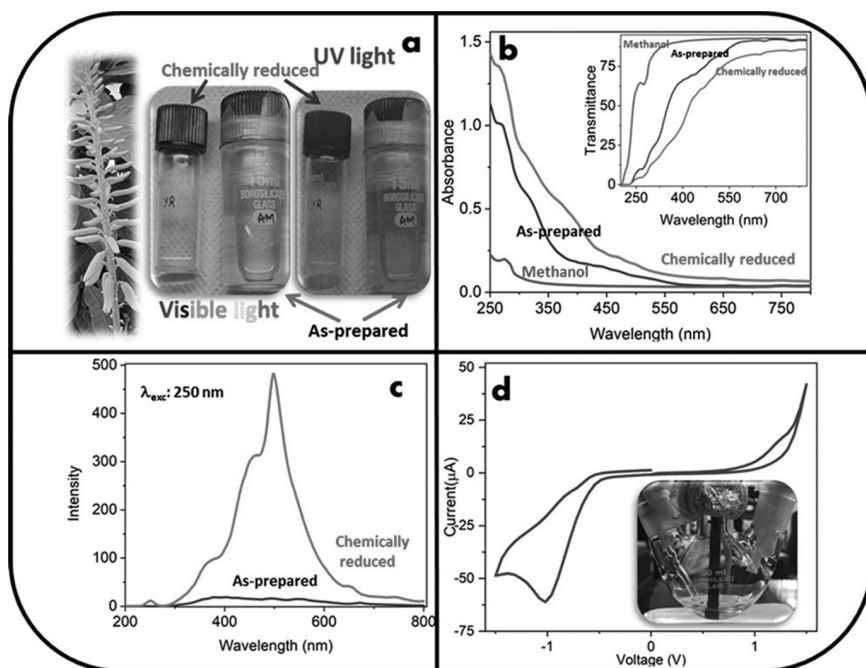


Figure 12.4 (a) Original photos of extracts and reduced extract photo when seen in room light and under UV light, (b) absorbance spectra of originally prepared extract and reduced extract with methanol as baseline, (c) emission spectra of originally prepared extract and reduced extract when excited by 250 nm wavelength, (d) CV of originally prepared extract.

flat in visible region, consequently, it was observed to be colourless. When both the extract were seen under UV light, they appeared green in colour, which can also be understood from the emission spectra. The PL spectroscopy was done to study the emission spectra. Upon examining the emission spectra of both extracts, one can observe that the green region of spectra exhibits the highest emission (Figure 12.4c).

Additionally, to investigate the extract's redox activity in liquid form, a CV in three-electrode configuration (Ag/AgCl served as the reference electrode, the role of Pt wire was the counter electrode while glassy carbon was used as the working electrode) was employed with sodium acetate as electrolyte. The CV curve of original extract (Figure 12.4d) and chemically reduced extract was compared in terms of current flowing through the circuit in the potential window of 1.5 to -1.5 V.

When comparing the current value, it was noted that the chemically reduced extract possessed ten times higher conductivity than the original extract in the positive region (Figure 12.5a), suggesting a chemical doping-like phenomenon. These two clearly distinct conductivity stages could be employed as two memory states, when the indicated resistance

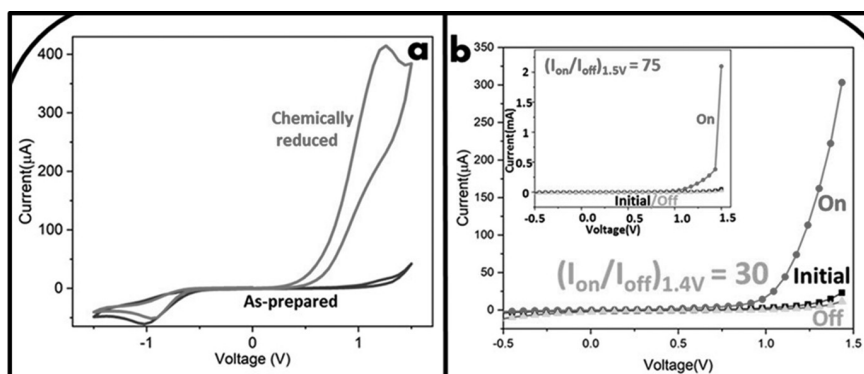


Figure 12.5 (a) CV of originally prepared extract vs chemically reduced extract using NaBH_4 as reducing agent, (b) I - V curve of liquid state extract in a distinct state of memory.

levels were generated by an external electrical bias. If bias-dependent switching was possible, this might potentially serve as a resistive memory⁴⁴ (memristor) component. To investigate the same, the I - V curve for original extract was recorded by varying the bias in the range of +1.5 to -5 V with 100 mV/s. Initially, the I - V curve showed the solution remains in high resistance stage (Initial state), when it swept up to -5 V (ON state), the resistance shifts to lower value, as the consequence of a bias-dependent reduction of the active compounds present in aloe vera flower extract to a higher conducting phase similar to the memory element's "write" activity. Following the step, the I - V curve was recorded again in potential window 5 to 0 V, which restored the low resistance state (OFF state). The ratio was then calculated for the current value in ON and OFF state. For the readout voltage of 1.4 V, current ratio was found to be 30. Conversely when calculated for 1.5 V, the ratio was found to be 75 (Figure 12.5b). The calculated values were outstanding while considering a resistive memory element. Without significantly compromising stability, several ON and OFF states can be possible. Hence, a natural resistive memory type behaviour was successfully investigated using aloe vera flower by adapting the simple extraction process in methanol. Further, a solid-state device was fabricated by mixing the aloe vera flower extract in an appropriate gel like poly (ethylene oxide) to obtain a botanical resistor device.⁴²

12.2.3 Using extraction of henna leaves and turmeric roots as yellow emission source

The henna leaves, also called mehendi,⁴⁵ are used as a hair and palm colorant and have a number of therapeutic benefits, including antifungal and antibacterial qualities. Turmeric,⁴⁶ in addition to being a ubiquitous culinary colouring ingredient in Indian homes, also possesses a number of medical

benefits, including antiseptic and antibacterial properties. The optical characteristics of the extract from these two herbal materials were studied, and a successful attempt was made by Sahu et al. to produce yellow emission by employing a blue LED as an excitation source.⁴⁷ In the reported work, henna leaves and turmeric roots were collected from the matured plants and extracted in methanol solvent. Roughly, 10 mg of henna leaves and turmeric root was washed thoroughly using DI water and allowed to dry in the room. After completely drying, roots and leaves were finely chopped/crushed and kept in a separate clean beaker containing 20 mL of methanol. The beaker was covered with aluminium foil and soaked overnight to fully extract the active component of henna leaves and turmeric root into the methanol. Next day, the soaked solution (extract) was filtered with Whatman filter paper. Afterwards, the extract was transferred to separate glass vials and stored in the fridge. The extract was used within 2 weeks to perform all the experiments.⁴⁸

The prepared extract of henna and turmeric appeared to be green (dark grey in Figure 12.6a) and yellow (light grey in Figure 12.6a) in visible light colour (Figure 12.6a), respectively, which was due to the presence of its active components. Curcumin⁴⁶ is the active component present in turmeric which is responsible for the yellow colour of turmeric. Similarly, the green colour of henna extract is due to the chlorophyll present in the leaves. To see the emission properties from both the extracts, the samples were kept under UV light and the extract of henna and turmeric appeared to be red and greenish-yellow in colour, respectively (Figure 12.6b) where red color is represented by dark grey and greenish-yellow color by light grey color, respectively.

To examine their optical characteristics, spectroscopic methods were used. Firstly, the samples were characterized using UV-Visible spectroscopy (Figure 12.7) considering methanol as the baseline, as the extract has been prepared in methanol. Hence to avoid the interference of solvent, that is, methanol, it was essential to take methanol's absorbance as baseline. From Figure 12.7, the henna extract's absorbance spectrum showed two peaks around red (less intense) and blue regions (highly intense). As the extract of henna absorbs red and blue colour, it indicates that green colour is being

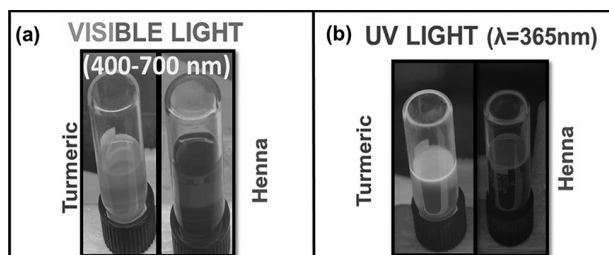


Figure 12.6 The prepared extract of turmeric and henna under (a) visible light, (b) UV light.

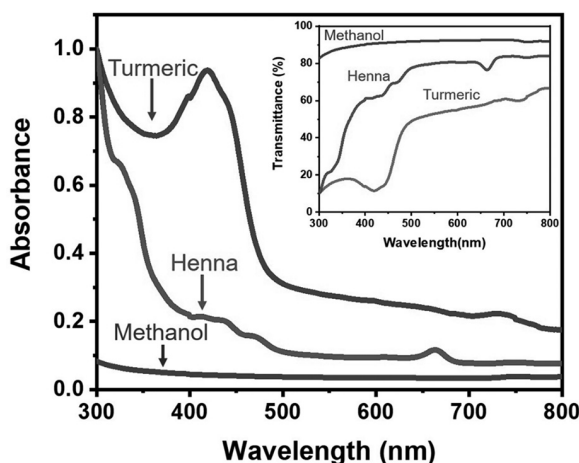


Figure 12.7 Absorbance spectra of turmeric extract and henna extract with methanol as baseline along with transmittance spectra (inset).

transmitted. The same has been confirmed when seen under room light as the extract shows green colour in room/visible light (Figure 12.6). One can also observe from the absorbance spectra of the turmeric extract that it displayed a strong peak in the blue band. According to the RGB scheme, it must be transmitting yellow colour since it was absorbing the blue colour. The primary cause of the extract's yellow colour was likewise verified when observed in a room/visible light. Additionally, as both extracts absorb UV light, they might be used as natural sunscreens and UV filters. As observed from the absorbance spectra, both the extracts showed highly absorbing blue colour, hence studying the emission phenomena, blue colour has been chosen as excitation wavelength. The PL spectra were recorded to investigate emission phenomena using blue colour wavelength of 400 nm as excitation source. In the PL spectra of henna extract, it was observed that when excited by 400 nm wavelength, the henna extract was emitting red colour by giving peak in the red colour band, which was in accordance when same extract was observed under UV light. Again, when the 400 nm excitation wavelength was used to capture the PL spectra, the turmeric extract exhibits a broad peak in the greenish-yellow region. As both the extract demonstrated luminescent properties, it showed their potential for biomarkers⁴⁹ and bioimaging applications.⁵⁰

Further, as observed from the PL spectra in Figure 12.7, the henna extract was exhibiting red luminescence and turmeric extract was showing green luminescence, therefore from the RGB scheme of mixing colours, once both the extracts are mixed appropriately, they should exhibit yellow luminescence. To get the yellow emission from henna and turmeric extract, both

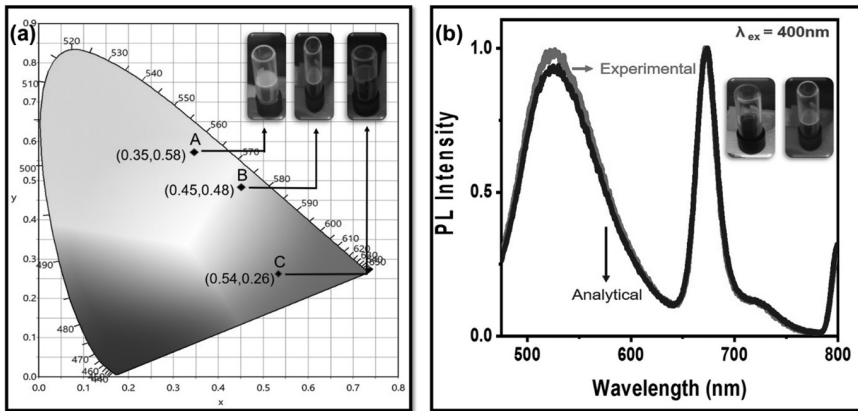


Figure 12.8 (a) CIE with originally prepared extract of henna and turmeric, and mixed extract under UV light (A denotes turmeric extract, B denotes mixture solution and C denotes henna extract), (b) emission spectra of analytical data and experimental data.

the extracts were mixed in equimolar concentrations. First, to identify the optical properties of the mixture, these samples were investigated by seeing it under UV light and the corresponding International Commission on Illumination (CIE) coordinate was plotted to see what colour was emitted from the extracts (Figure 12.8). When seen under UV light, as expected the emission appeared to be yellow. The same was characterized by recording PL spectra of the mixture solution. PL measurements of mixture (Figure 12.8b) depicted that both the analytical and experimental data were in accordance with each other. Here, the analytical data was obtained by adding the individual PL spectra of henna extract and turmeric extract and experimental data was obtained by first mixing the solution and taking the data by exciting it with 400nm wavelength. The experimental data fully overlapped the analytical data, which confirmed that the mixture solution was completely following the nature of individual spectra of henna and turmeric extract. Further, to demonstrate the concept in real-life application, a blue LED source was used as excitation source to excite the molecules present in the mixture solution of both henna and turmeric extracts. For the setup, a small cuvette was filled with the mixture solution containing henna and turmeric extract in equal proportion (1:1). Now blue LED was dipped in the mixture solution and very small bias was applied to the LED as schematically represented in Figure 12.9. As expected from the PL spectra, the emitted light from blue LED turned to be yellow in colour when dipped in the mixture solution of extract. Hence, by using the mixture solution of henna and turmeric root extracts in appropriate proportion, yellow light source was obtained using blue LED as excitation source. As per the

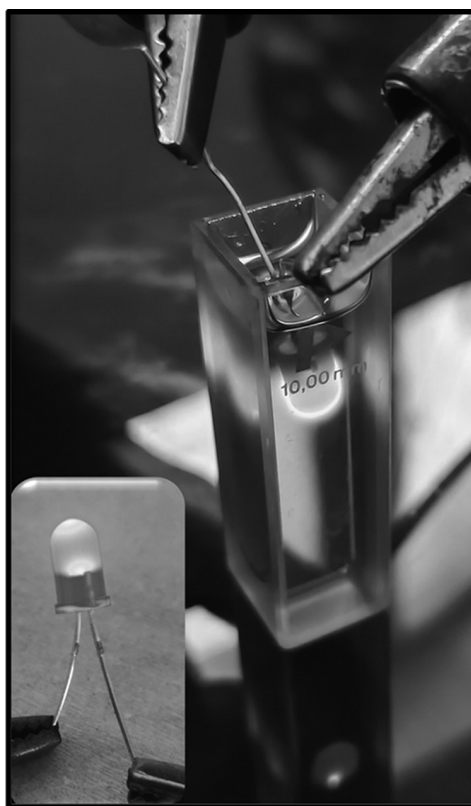


Figure 12.9 Blue LED as an excitation source for yellow emission from the mixture solution of henna and turmeric when mixed in 1:1 ratio by molar.

relation $E = hc/\lambda$, the yellow light possesses lower energy and blue light has high energy, so due to the minimum energy in the yellow light, it is good for eye and skin. Overall, yellow light can be emitted by mixing the two naturally occurring herbal materials, henna and turmeric extract, for its application in everyday life using blue LED as excitation source.

12.2.4 Application of pomegranate seed and turmeric root extraction as white light source

The white light emission from natural dyes, namely, pomegranate and turmeric, was produced in the lab by extracting the active component and utilizing an easy and environmentally friendly method. Pomegranate and turmeric, like all other fruits and vegetables, have antioxidants that neutralize free radicals and shield cells from harm. Singh et al. demonstrated a

novel application of pomegranate and turmeric seeds as a white light source. The process was started by collecting the extraction of both the plants, for which an eco-friendly and easy method was adapted.⁵¹ The freshly bought red pomegranate was purchased for the preparation of extract. To obtain the extract solution, the seeds of red pomegranate were squeezed and centrifuged for few minutes at 5000 rpm. The clear precipitate was obtained after centrifugation having anthocyanins and polyphenols as main components. In order to extract curcumin from the root of *Curcuma longa*, it was first grinded using mortar and pestle utilizing ethanol as a solvent for extraction, followed by centrifugation at 5000 rpm for few minutes. The yellow colour clear precipitate was obtained after centrifugation having curcumin as major component present in the extract.⁵²

The pomegranate and turmeric extracts as prepared were mixed in a proportion such that the solution was used as a white light source. In the process, the prepared extracts were diluted by adding 1% HCl in the ethanol. To study the optical properties of both the prepared extract, absorbance spectra was recorded followed by PL study keeping the excitation wavelength at 380 nm. The absorbance spectra of turmeric indicate a prominent peak in blue colour band while the turmeric extract was absorbing the blue colour and transmitting the yellow-orange colour. Due to the red colour of the initially prepared pomegranate extract, one can expect that it must be absorbing green colour band, as transmitting the red/magenta colour, giving red colour to the pomegranate extract. The same was observed in the absorbance spectra of pomegranate extract containing 1% HCl in ethanol. Following the RGB scheme, to get the white light emission, an appropriate mixing of red, blue, and green colour was required. When the pomegranate extract was seen under UV light, it was observed to be showing magenta colour, which is the combination of blue and red colour. In PL curve, it was expected that it must be giving emission in blue and red band, the same was observed in the curve. As we are getting blue and red emission from the pomegranate extract, the green emission must come from the turmeric extract to get the white light from the mixture solution. As expected from the PL curve, the turmeric extract was giving emission in the green band, and the same was confirmed by seeing the turmeric extract under UV light. As both the extracts are fluorescent in nature they can be used in making biomarkers.⁴⁹ Finally, to obtain the white light emission from the prepared extract of pomegranate and turmeric, the extracts were mixed in 1:0.05 molar ratio, and PL spectra were recorded showing the broad peak in the whole visible region. When the mixture solution was seen under UV light, as expected they were emitting white light. The successful white light has been emitted by using the two natural materials pomegranate and turmeric extract using simple extraction method and mixing in appropriate molar ratio of 1:0.05. The production of white light from such inexpensive and ecologically friendly materials may be significant for lighting and sensing applications.

12.2.5 Yellow ginkgo leaves as natural piezoelectric device

The fan-shaped ginkgo leaves, mainly found in China, have various therapeutical properties as they are rich in antioxidants, and are used to treat blood disorders and memory issues. Apart from the medicinal use, ginkgo leaves can be used as natural piezoelectric device. The piezoelectric device is the device which can create piezoelectric effect,^{53,54} the property of certain materials to produce electricity when small force is applied on it. The main reason for the ginkgo leaves to show piezoelectric effect is due to the naturally driven self-polarization during leaf growth, the internal piezo-phase cellulose crystals of natural leaves are able to align themselves in a highly desired manner, to produce an electric field when small force is applied. Shao et al. reported a study providing the application of yellow ginkgo tree as potential piezoelectric application.⁵²

In the extraction process, the gathered yellow ginkgo leaves were washed thoroughly with DI water and added to silica gel, which was already kept in a beaker. The gel was then left for 36 hours for the silica gel to soak the main components of ginkgo leaves completely at room temperature. Afterwards, the dried ginkgo leaves were removed from the gel. They were utilized straightaway for the fabrication of the device without any additional chemical processing. The dried yellow ginkgo leaves were employed directly as a piezo active layer for the easy fabrication of an environmentally friendly, mechanically flexible, self-polarized piezoelectric nanogenerator, without the need for chemical treatment or surface removal. For the fabrication of device, the dried ginkgo leaves, aluminium electrodes, and polyurethane tape were used to create a piezoelectric nanogenerator. Dried ginkgo leaves were sandwiched between aluminium electrodes, and then the aluminium electrodes were covered with polyurethane tape. The main purpose of aluminium electrode was to obtain piezoelectric signals. At last, the piezoelectric nanogenerator device was attached to the acrylic (poly-methyl methacrylate) plates in order to provide a seamless shock throughout the process of piezoelectric testing. The same acrylic resin was also used to make the impact head of the measurement system in order to prevent any potential triboelectric charge disturbance. The piezoelectric nanogenerator based on ginkgo leaves is prepared and measures 20×20 mm in size with the thickness of approximately 0.125 mm.

A piezoelectric device reacts very quickly to changes in the applied external force; one such ginkgo leaf device can function as a piezoelectric sensor in practical applications to detect different environmental mechanical and biomechanical activities. The ginkgo leaf device can function as an ultrasensitive, self-powered piezoelectric sensor in practical applications to detect various physical and biomechanical events occurring in the environment. For application purpose, the prepared ginkgo leaves piezoelectric device has been studied by applying it to various parts of body and the

developed electric field by the different forces were recorded. For the same, firstly, the prepared ginkgo leaves piezoelectric device was attached to the heels of different weighted peoples. It was observed that a heavy-weight person can produce an output of 70 V just by normal walking, on the other hand, a lightweight person can produce an output of 55 V. As the voltages developed by lightweight and heavy-weighted people were different, this demonstrated a sensing range of the ginkgo leaves piezoelectric device. Secondly, the prepared ginkgo leaves piezoelectric device was implanted on human forefinger and arm which showed that at a fixed angle the bending and stretching of the forefinger or arm exerted a controlled stress on the ginkgo leaves piezoelectric device. As the bending angle increases, a large stress was developed and thus produced the large piezoelectric output voltage. When the bending angle of forefinger ranged from 30° to 90°, the developed output voltage also varied from 0.07 to 0.15 V. Similarly, while bending angle of the arm changed from 30° to 90°, an increase in output voltage was observed from 0.16 to 0.4 V. In the next step, the prepared ginkgo leaves piezoelectric device was placed over an electric fan to monitor the air flow associated with daily living. It was found that when the fan was turned off, there was no electrical output voltage, but when the fan was running at 1300 rpm, there was an output voltage of 2 V. The ginkgo leaf device, in particular, demonstrates significant shape modification and high mechanical flexibility. In this way, it possessed the capacity to detect minute physiological stresses and pressures in humans. Effectively a self-polarized, mechanically flexible, environmentally friendly piezoelectric voltage generator was successfully fabricated by employing the leaves of the ginkgo tree, which naturally serve as an effective piezo active layer.

12.2.6 *Tinospora cordifolia* and *Cassia siamea* extract: a comparative emission study

Giloy,⁵⁵ an antipyretic herb, is frequently used to lower blood sugar and increase platelet counts in dengue infections. *Cassia siamea*,⁵⁶ another herb, has a variety of benefits like treatment of constipation, typhoid fever, and hypertension. Both the plants extracts appear green in colour due to the presence of chlorophyll. But they illuminate different colours when seen under UV lamp. A comparative study was performed by Ghosh et al., and has briefly demonstrated the different illuminating properties by studying their optical properties.⁵⁷ The simple extraction method in generic solvent methanol was utilized to get the extract. *Tinospora cordifolia* (aka giloy) and *C. siamea* (aka cassia) were gathered and cleaned thoroughly with tap water followed by distilled water. The cleaned leaves were left in open atmosphere for completely drying. After that, approximately 5 g of leaves of giloy and cassia were chopped finely into small pieces and were placed in separate cleaned beakers. Approximately 10 mL of methanol was taken

and poured to the beaker containing leaves. The separate beakers containing leaves of giloy and gassia along with methanol were left overnight to get the extract into the methanol. The resulting extract was filtered using Whatman filter paper and kept in two separate glass vials at 10°C in the refrigerator for later use.

The above prepared two extracts when seen under visible light appeared to be green in colour due to the presence of chlorophyll in the plants (Figure 12.10). The same extract when seen under the UV light, the giloy leaf extract was illuminating red colour whereas the cassia leaf extract appeared to be illuminating green colour. A comparison analysis was conducted here to better understand the unusual illuminating behaviour of the cassia leaf extract since the green colour illumination from the leaves is a very unusual observation. To study the optical properties of these two extracts solution, absorbance spectra were recorded (Figure 12.11). The absorbance spectra of both the leaf extract are highly absorbing the UV region, and can be used to make natural sunscreen.⁵⁸ Also, both the leaves were absorbing blue and red colour bands, thus transmitting the green colour, which was the original colour of the prepared extract. As both the extracts were highly absorbing the blue colour band, therefore 300 nm wavelength has been taken as the excitation wavelength to study the luminescence spectra of both the extracts (Figure 12.12).

The giloy leaf extract was seen to be giving two peaks in red and green region with different intensities. The intensity in the red region was very high, thus illuminating red colour when seen under UV light. Usually due to the presence of chlorophyll, the leaf extracts show red luminescence. Cassia leaf extract was also observed to be giving peaks in red and green region, but unlike the giloy leaf extract, the cassia leaf extract has higher intensity in the green region, thus giving green colour luminescence when seen under UV light. The unusual green colour luminescence of cassia extract was due to the high presence of mesophyll and lower concentration of chlorophyll.

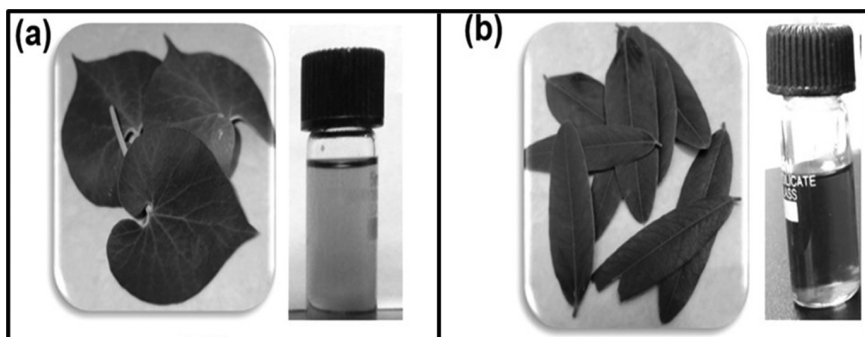


Figure 12.10 Original photograph of leaves and prepared extracts: (a) giloy, (b) cassia.

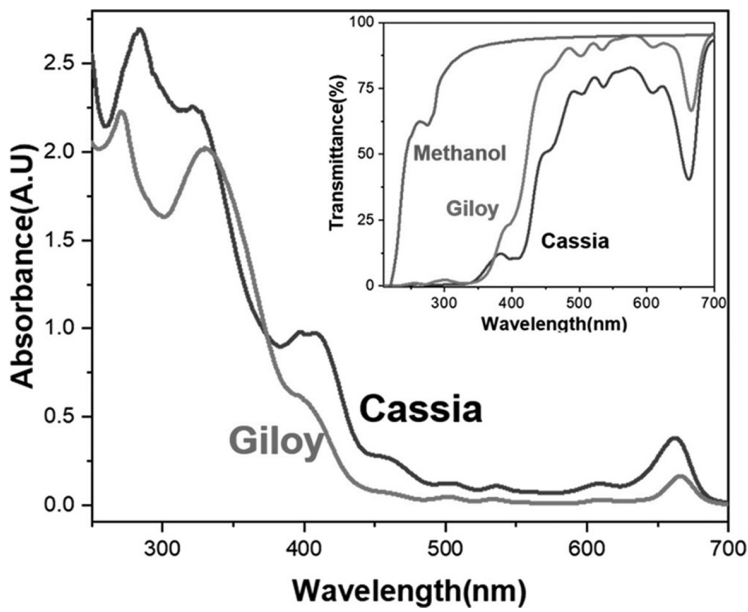


Figure 12.11 Absorbance and transmittance (inset) spectra of cassia and giloy leaf extract.

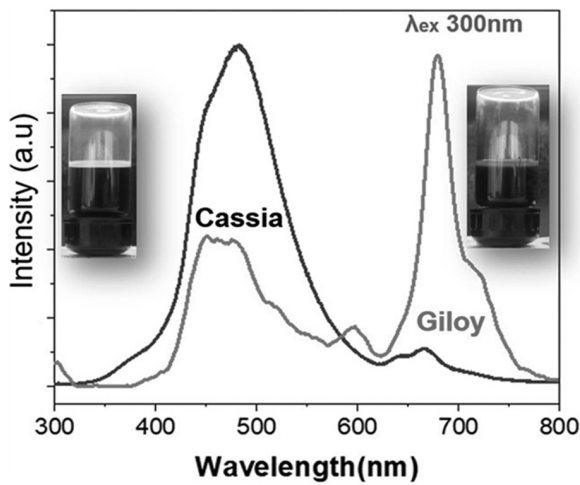


Figure 12.12 PL spectra of cassia and giloy leaf extracts.

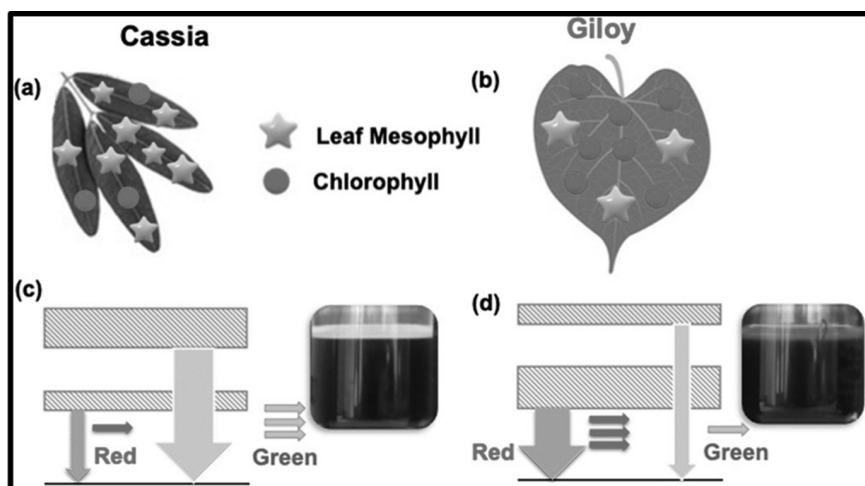


Figure 12.13 Schematic showing (a, b) varying concentration of chlorophyll and mesophyll in cassia and giloy leaves, (c, d) green and red emission from leaf extracts.

This can also be understood using the band diagram (Figure 12.13). According to the band diagram of giloy leaf extract, when the molecules were excited, they reach the excited state, and go to the metastable state present between the ground state and excited state. There were two metastable states present, but the majority of the molecules were coming to the ground state from the lower metastable state, that is, the order of the red light, thus giving high intensity in red region (Figure 12.12). In the case of the cassia leaf extract, most of the molecules coming back to the ground state from the higher metastable state correspond to the green light, thus giving high intensity in the green region (Figure 12.12). This observation can also be concluded as the cassia leaves lacking in chlorophyll.

Additionally, similar to other herbs, cassia and giloy have antioxidant qualities that counteract free radicals^{59,60} found in the human body. Accordingly, to investigate the redox activity of both the leaves, CV measurement was done in the liquid state using sodium acetate as the supporting electrolyte (Figure 12.14). The three-electrode setup contained platinum wire, glassy carbon, and Ag/AgCl as counter, working, and reference electrodes. The CV curves of cassia and giloy leaf extracts were taken in the potential window -2 to 0 V at different scan rates. The reduction peak of both extracts was observed at -1 V, indicating their reducing characteristics.

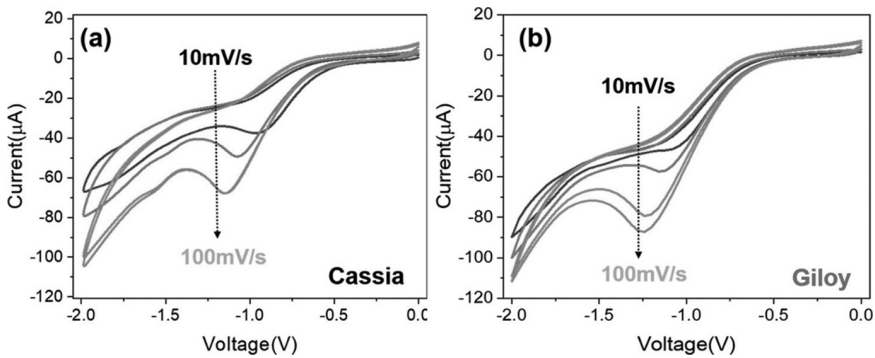


Figure 12.14 CV curve of extracts: (a) cassia, (b) giloy.

This attribute further suggests that there is a flow of electrons occurring in the extract solutions, which may have applications in solid-state electronics manufacturing.

Overall, it was shown that both leaf extracts were effective UV absorbers, producing green and red luminescence based on the amounts of mesophyll⁶¹ and chlorophyll present in the leaves. Electrochemical analysis showed that although the two extracts have distinct primary colour centres, they have equal antioxidant activities.

12.3 CHALLENGES IN GREEN ELECTRONICS

As plants are natural living things and dynamic, they react to changes in the environment. The properties of plant extracts change over a while as it reacts easily with the environment. Such a reaction can affect the functionality and stability of electronic components. So, the major challenge is guaranteeing the stability and compatibility of electronic devices with plant tissues over an extended period of time. For sustainable applications, it is crucial to create herbal electronic devices that are both eco-friendly and biodegradable. One of the main challenges is to find materials and manufacturing techniques that are both environmentally responsible and functional. A major difficulty can come into the picture when moving from lab-scale prototypes to large-scale production. The key to the widespread adoption of herbal electronic devices is the development of scalable, repeatable, and affordable production processes. Apart from establishing approaches to handle this kind of electronic waste, additional difficulties can be found concerning preserving and recycling rare elements, limiting down on the use of hazardous materials and solvents in electronics

processing, and utilizing less energy in fabrication processes. The compromise among the energy effectiveness and device performance is another difficulty, since the objective of lowering energy consumption and increasing demand for high-performance devices collides with one another. It also takes cooperation from all parties involved, including producers, buyers, and legislators, to create a circular economy for electronics, where materials are recycled and reused.

12.4 CONCLUSION

This chapter discussed the various applications of plant-based materials for producing “green electronic” with a strong dedication to environmental responsibility. “Green Electronics from Fabrication to Its Application” proves to be a priceless resource for scholars, engineers, and legislators working in the dynamic field of electronic technologies. This chapter promotes a dramatic change in the electronics industry’s paradigm in favour of more environmentally friendly practices in addition to offering a thorough manual. This chapter supports innovation and sustainability simultaneously by dealing with fabrication processes and applying its insights to the application of electronic technologies. It serves as a beacon, pointing stakeholders in the direction of a future in which technological innovations coexist peacefully with the protection of the environment.

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Sustainability and circular economics

Effective way for e-waste management

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13.1 INTRODUCTION

The electronics industry is responsible for 4% of global greenhouse gas emissions, having a considerable impact on environment. The cascade effect is now fuelling a wave in electronics manufacturing that will improve sustainability and reduce the vulnerability to changing energy prices [1]. The creation of electronics in a sustainable manner is the way to increase productivity, lower waste and make advancements at cost [1]. To reach these objectives, manufacturers are experimenting with new techniques. For example, moving to additive printed circuit board (PCB) manufacturing reduces water consumption by up to 95%. This change could mean the industry saves hundreds of millions of litres of water [1]. Further, smart digital manufacturing methods like artificial intelligence (AI) and Internet of things (IoT) technology enable companies to automate processes and cut down on waste [1].

The electronics industry is changing fast, with big money going into bringing back electronics manufacturing to Western economies. Companies now see access to green energy as crucial when they set up new factories [2]. Samsung, for example, now uses 100% renewable energy at all its sites in the United States and China, and other big players are jumping on this bandwagon. There is a pressing demand for electronic devices to be energy efficient. To meet environmental goals, makers must design electronic products with sustainability in mind from the inception. This applies to every part of the product and every step of its life. Designers should think about the environment from the start to the finish of a product's journey.

One big hurdle in making electronic devices last longer is planned obsolescence, which has become a major roadblock to the circular economy and lifespan of electronics [3]. People often throw away and replace products too soon because manufacturers design them to stop working. To solve this problem, companies can create new products with parts that can be disassembled. This helps people reuse or remake these parts. This idea doesn't just make things last longer. It also helps when we're running low on raw materials because we can use recycled materials instead. When electronic devices stop working, we can still save

materials to make new products. Recycling beats throwing things away because it helps the environment more [4]. It keeps us from using up our limited natural resources and cuts down on how much mining harms the climate. Recycling electronics must overcome many obstacles such as moving them around, gathering them up, dealing with dangerous stuff inside, and using processes that can harm the environment [5]. A lot of people think recycling should cost nothing and paid for by selling the materials found in gadgets. However, as technology gets better, devices use cheaper parts, which means we cannot get as much money from the bits that are saved. Further, we need to think about how much it costs when we don't recycle. This includes the money we spend to get rid of waste as well as the bad effects on our health and the environment. It might cost money to recycle some devices that aren't worth much, but it's the right thing to do for everyone's benefit.

Recycling and reuse of materials and metals from electronic waste (e-waste) is a major challenge, in terms of both technical separability as well as the cost associated with getting these into secondary markets. However, with current approaches, as highlighted by Ellen MacArthur Foundation a significant amount of value is lost when electronic products end up in landfills or are being burned [6]. Many countries have now EPR (extended producer responsibility) programmes in place to deal with this issue [5]. These initiatives are intended to address the consumer responsibility (or lack thereof) of waste management onto producers.

13.2 CIRCULAR ECONOMY: A NEW APPROACH TO GROWTH

The concept of circular economy allows for an alternative perspective on resource management to the traditional "take-make-dispose" approach [7]. Figure 13.1 depicts the process of circular economy for sustainable e-waste management. This concept focuses on reducing wastage and enable efficient use of resources by prolonging, the materials, parts and products in circulation for longer period. As the electronics industry expands, with the global consumer electronics market valued at about US\$1 trillion, a circular approach becomes more crucial [8].

A. Key Principles

The circular economy in electronics relies on a few key ideas [9]:

- i. **Designing with circularity in mind:** The design stage decides about 80% of a product's effect on the environment. This means creating products that last, can be fixed, upgraded and recycled when they're no longer useful.

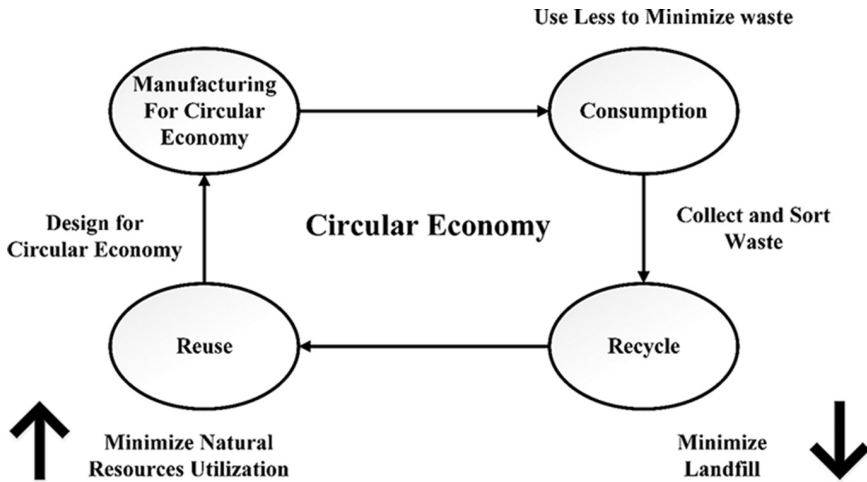


Figure 13.1 Circular economy for sustainability.

- ii. **Using things longer:** People keep products and their parts working for more time by giving them lots of chances to be used again, fixed, sold, spruced up or made like new.
- iii. **Responsible recycling:** When products no longer serve a purpose, companies collect, sort and recycle them using responsible methods and standards.
- iv. **More recycled materials:** New products contain higher amounts of recycled and recyclable components, which cuts down the need for raw resources.

B. Advantages

Embracing a circular economy in the electronics industry has many upsides [10]:

i *Environmental benefits*

The company's reduced consumption and/or emissions are considered environmental advantages. Reducing resource consumption, which includes using recycled or repurposed resources to save raw materials and cutting waste emissions, is the foundation of environmental performance. Scarcity of resources is a major consideration for any business wishing to apply circular economy strategies. Reusing manufacturing residues like ash and separating precious elements like metals from waste helps optimize resource cycles and boost material utilization. Businesses may support a more sustainable use of materials and lessen the strain on natural resources in this manner. The benefits of the circular economy for the environment have been illustrated

by the case of Kalundborg, Denmark [11]. By sharing water and other byproducts, they have reduced annual consumption of groundwater by 3 million cubic metres and the release of CO₂, SO₂ and other greenhouse gases by 275,000 tonnes. The national industrial symbiosis programme in the UK prevented 47 million tonnes of industrial waste from ending up in landfills between 2005 and 2013 [12]. It also cut 42 million tonnes of CO₂ emissions, 60 million tonnes of raw material consumption and 73 million tonnes of water use in the industrial system. In addition, businesses in Poland's port of Gdansk experienced conversion in response to the 1970s economic crisis. To address this issue, other strategies have been implemented, such as the circular economy. The metallurgical and petrochemical industries, which dominated the port of Gdansk, had a detrimental impact on the environment in numerous capacities. Encouraging other businesses to establish themselves in the biotechnology and nanotechnology industries was the solution; these fields are skilled at decomposing trash and hazardous materials and recycling things that have reached the end of their useful lives. This presented a chance for the port's businesses to advance their environmental management in an environment where they are being forced to adhere to European environmental requirements [13].

ii *Environmental protection*

Industrial processes are primarily driven by economic factors. The circular economy has piqued their interest due to its potential to provide economic benefits, create value and present lucrative prospects. Businesses can increase customer loyalty and their sense of corporate social responsibility by using circular economy techniques. Initiatives focused on the circular economy can, in fact, draw in new business, enhance ties with current clients and increase their dedication to the company's ability to satisfy their demands. Circular products that are well-made and of superior quality guarantee that customers will be just as satisfied, if not more so, as with typical linear products. The cost/benefit ratio is crucial for producers who consent to exchange flows in this regard. Recycled materials can be used in place of raw materials to achieve economic performance. Recycled or repurposed materials are typically less expensive than virgin resources. The expenses related to garbage disposal are eliminated when waste is sent to other industrial facilities. The selling of waste to other manufacturers and resource sharing generates some cash. The Huatai chemical industry generated an annual economic gain of US\$24.29 million, according to a study by Guo et al. [14]. The same can be said for two steel industries: one in Kawasaki, Japan, which saved \$54 million, and another in Liuzhou, China, which gained over \$36.55 million in revenue [15]. The donor can lower outgoing flow processing expenses thanks to

the circular economy, and they also get a financial boost from sales. Furthermore, Agyemang et al. discussed the advantages of applying the circular economy to Pakistan's auto sector [16]. The most significant factors influencing a firm, according to the writers, are economic factors including profitability, market share, earnings, and cost containment. According to Foroozanfar et al., the adoption of circular economy principles can revitalize already-existing companies and launch new service ventures [17]. This is made possible by new information management systems and increased accessibility to data pertaining to the circular economy. These systems include platforms that increase a business's supply chain visibility, making it possible to make more educated decisions about waste management and procurement as well as better understand the origins of materials, how they are utilized and how to recover them at the end of their lives. An enhanced comprehension of the supply chain can result in increased productivity, decreased expenses and heightened competitiveness for the enterprise.

iii *Social benefits*

The circular economy model promotes social cohesion and even the settlement of interpersonal disputes [17]. It facilitates the establishment of connections between companies via previously unimaginable exchanges as well as between companies and the community. In rising economies, the circular economy is advantageous to all parties involved. Businesses are urged to leverage data and information sharing to develop recyclable and reusable parts for new products, supporting socially conscious production and satisfying stakeholders [17].

C. Obstacles

The electronics industry that employs circular economy benefits from inherent advantages; however, there are barriers delaying its true realization [18]:

- i. **Design limitations:** Electronic appliances come mostly from the linear economy school of thought where it is harder to reuse, fix or recycle them without significant resources and work.
- ii. **Facilities for disposal:** Some regions lack proper recycling infrastructure and companies are unable to deal with e-waste responsibly in a circular fashion.
- iii. **Rapid obsolescence:** When technology changes so quickly, devices become old and useless in a short period of time, making it difficult to maintain gadgets for long durations.
- iv. **Consumer trends:** Changing buying habits and the urge for the newest may easily get in the way of groups trying to push eco-friendly, circular practices.

- v. **Recycling technology limitations:** It is very challenging to recycle different types of e-waste because they are made from ever newer materials and complicated gadgets.
- vi. **Financial hurdles:** The high costs associated with using circular economy practices and worries about losing repeating customers due to abandoning the products design or packaging may discourage businesses from adopting a circular model.

Implementing a circular economy in the electronics industry is a complex endeavour, hindered by numerous hurdles. We must ensure that the future of this sector is both sustainable and resource efficient.

13.3 SUSTAINABLE DESIGN APPROACHES

The development of sustainable design strategies helps to address the environmental problems caused by the creation of e-waste [19]. Such approaches strive to develop products that require fewer resources, generate less waste and last longer. The electronics industry can reduce its detrimental effects on the environment based on the new manufacturing methods and material selection while increasing energy efficiency [19].

A. Modular Construction

The future of sustainable electronics design lies with modular construction. Components are built in a factory setting under controlled conditions and then assembled on-site during the construction process. The benefits of modular construction are enormous for the environment, and few are listed below [20]:

- i. **Lower carbon footprint:** Modular building reduces greenhouse gas emissions by up to 47% compared with traditional site-built housing.
- ii. **Resourceful material utilization:** Modular projects lay emphasis on pre-construction design through software tools for a Computer-Aided Design (CAD) model. This method helps reduce waste by allowing the right quantity of materials to be utilized in a factory environment that can be observed and controlled.
- iii. **Waste reduction:** Regular building sites often waste about 30% of materials. This happens when they order too much or change designs. Modular building cuts this waste down a lot. It does this by keeping better track of supplies and reusing leftover materials.
- iv. **Better building quality:** Factories offer a controlled setting. This lets builders use dry materials. As a result, they avoid problems like water damage and mould.

- v. **Less site disruption:** Modular construction has a smaller impact on project surroundings. It cuts down on the need for vehicles and heavy equipment at the site. This leads to reduced pollution and less disturbance to the area.

B. Eco-friendly Materials

The electronics industry is now going green by choosing sustainable materials to minimize environmental impact, discussed as under [21]:

- i. **Recycled plastics:** The material is derived from post-consumer waste, and it has a beneficial effect of cutting down the plastic waste in landfills and oceans. Since less demand on new plastic sources will be done, the recycling will also contribute to lower the toxic pollution of environment.
- ii. **Bamboo:** The fastest growing dry wood can be harvested every 3–5 years, and it is considered as sustainable because of its high availability and consequently low prices. The material is becoming increasingly used as the alternative to a standard conductive wood in electronic engineering.
- iii. **Sustainable metals:** Aluminium and copper are replacing more harmful environment metals such as beryllium. Being more recyclable and causing less ecological damage, new metals also tend to bring some benefits in terms of decreasing the cost of production.
- iv. **Organic materials:** Biodegradable and biocompatible materials, consisting of silk, resins, gums, saccharides, cellulose, gelatine, peptides and others, are employed in making sensors, signal transducers and other devices. These materials also represent an environmentally friendly alternative to the traditional synthetic conductive polymers.

C. Energy Efficiency

The most important aspect of sustainable electronics design is improved energy efficiency. Various techniques and systems have been executed to decrease electricity usage like [22]:

- i. **Advanced semi-conductors:** Both gallium nitride (GaN) and silicon carbide (SiC) have relatively better electronic characteristics than conventional semiconductor devices which is even more so the case in terms of electrical properties, power quality and cost performance ratio.
- ii. **Power management circuits:** These systems allow the best distribution of energy inside the device, minimize waste and make it possible to increase battery life.

- iii. **Dynamic voltage and frequency scale (DVFS):** This technique adapts the voltage frequency of a processor to meet its workload, substantially reducing energy under periods where no activity is conducted.
- iv. **Energy efficient displays:** Technologies such as Organic LED (OLED) and electrophoretic electronic ink consume 40% less electricity than the traditional devices.
- v. **Low-power connection:** The protocols, such as Bluetooth Low Energy (BLE) and Zigbee, are built to achieve low power consumption for consistent connectivity.
- vi. **Energy-conscious devices:** ENERGY STAR labelled devices like washing machines which use less energy can save as much as 25% of the electricity of more comparable traditional models.

By implementing these sustainable design strategies, in the field of electronics industries can hugely improve their environmental footprint and thereby further a circular economy.

13.4 INNOVATIVE BUSINESS MODELS FOR ELECTRONICS

A. Rental and Leasing

Technology rentals and sustainability can go hand in hand when managed and executed thoughtfully. Rental services can contribute to sustainability as under [23]:

- i. **Reduction in e-waste:** Tech rentals push for the reuse of electronics. People and companies can rent devices and give them back when they're done instead of buying new ones each time they need them. This cuts down on e-waste in oceans and being dumped in landfills.
- ii. **Renting durable products:** Companies that rent high-tech knowledge assets have the incentive to maintain and repair those tools. This leads to devices having a longer life and reduces the rate of replacements.
- iii. **Newer technology:** Rental services can ensure that their inventory features the newest energy-efficient models. That way customers can use the latest tech without scrapping older tools, cutting down on e-waste.
- iv. **Sharing economy principles:** With the technology used being given on rent, it very well synchronizes with that of a sharing economy, roots of which are aimed at optimum resource utilization. Instead of every

one person having their own device, you can just share a few between all the users and lower production rates, which means less waste.

- v. **Recycling programmes:** Many environmentally conscientious tech rental companies will develop procedures to recycle outdated models. They ensure these gadgets are recycled, which ultimately reduces damage to the environment.
- vi. **Green energy and carbon balancing:** Some tech rental businesses work with clean energy or invest in carbon-balanced projects. This can offset the shipping and movement of their products at least to some extent.

B. Repair Services

Repair maintenance services have become essential in the consumer electronics industry for survival. These services may aid in preventing the replacement of devices with faulty or outdated components, hence prolonging their lifespan [23]. It may significantly reduce power consumption and eliminate the need to purchase additional electrical devices. The proliferation of technological advancements will result in an ongoing accumulation of digital trash. There are several approaches to address this issue, but one effective one is via maintenance. Maintenance involves repairing damaged or malfunctioning equipment, which enables the reuse of parts that would otherwise be unsuitable or too expensive to use. Furthermore, repairing and conserving an object enhances its durability over time while using less resources. This promotes the practice of refraining from disposing of electronic trash in landfills. Furthermore, the energy-intensive processes involved in manufacturing electronic devices emit greenhouse gases during both production and transportation. Consequently, they are less inclined to substitute non-operational items, resulting in less demand for new products and, subsequently, fewer carbon emissions [23].

C. Trade-In Programmes

In the electronics sector, trade-in programmes are important features of new business approaches promoting sustainability and e-waste management [24]. Majority of the trade-in programmes accept all kinds of used tech items irrespective if they are old or new, and from any brand. Certain stores will also offer consumers the ability to recycle or trade in their old electronics. Furthermore, there are some services that provide mail-in for those who need not physically be at a place [24]. Trade-in programmes thus enable consumers to responsibly dispose of their old electronics while also giving them something for the trouble.

13.5 TECHNOLOGY-DRIVEN SOLUTIONS

A. Smart Recycling Systems

The electronics sector is using innovative technology to tackle e-waste management challenges. Smart recycling solutions integrated with IoT and Deep Learning have the ability to revolutionize the management of electronic trash [25]. This is anticipated to provide an enhanced e-waste management system that, in turn, bolsters green city activities centred on sustainability. State-of-the-art object detection (OD) models, including YOLOv5s, YOLOv7-tiny and the newly released You Only Look Once version 8 (YOLOv8), are part of the popular OD family [26]. YOLOv8s has shown the best results, with a mean average precision of 72% at 50% Intersection over Union and 52% at 50%–95% IoU [26]. This accuracy helps identify and sort e-waste items better, making recycling more efficient. Using Convolutional Neural Networks like YOLO in e-waste management has improved recycling in many ways. Sorting e-waste correctly at the start helps recycling centres work better and spend less. It also ensures that dangerous materials in some e-waste are handled safely, reducing risks to the environment. The TOMRA AUTOSORT Fines machine is another smart recycling tool made for e-waste [27]. It's so precise that it can find and sort tiny precious metal pieces as small as 1–2 mm. It uses four advanced sensors [27]:

- i. Very high-resolution near-infrared spectrometer
- ii. Camera detection
- iii. High-resolution metal sensors
- iv. Deep Laser OD with AI

These sensors help the machine make clean mixed metal groups, collect clean circuit boards, improve aluminium sorting, and even sort plastics like ABS, PS, and PC.ABS, including black plastics.

B. Digital Product Passports

Digital Product Passports (DPPs) is an innovative solution that collects and documents product information during its entire lifespan [28]. They emphasize factors such as the product's sustainability, its environmental effect and its recyclability. When DPPs gather and disseminate product data obtained from the whole supply chain, including information on the origin of raw materials and manufacturing processes, it benefits everyone involved. These DPPs may be seen as the digital representation of a physical item in the manufacturing process. They effectively record all the events and transactions related to the product, as well as its sustainable characteristics throughout its lifespan. The digital copy is often linked to the real goods via a QR code, barcode or sometimes NFC tags [28].

Consumers may access information about the product's sustainability claims, its prior owner and proper recycling methods using a smartphone app. The Sustainable Products Regulations specify specific criteria for DPPs, including the utilization of open standards. The data must be in a format that can be easily read by machines and transferred through an open network for data exchange often without any fees. Additionally, the data should be compatible with other systems to the greatest extent possible.

C. Blockchain for Traceability

Blockchain has the potential to completely transform supply chains. This enables efficient and cost-effective product delivery, improved monitoring throughout the whole process, alignment with partners and access to finance [29]. In a particular transaction, a blockchain has the ability to merge information streams pertaining to the item or thing being transacted, track the movement of inventories from one location to another and provide detailed records of trade finance support. This surpasses the capabilities of existing systems. By leveraging the potential of blockchains via creative solutions, organizations may effectively streamline their supply chain processes. This will facilitate the management of electronic trash more effectively and promote the establishment of a more sustainable circular economy for electronics. Blockchain-based DPP solutions provide many major advantages [30]:

- i. **Data security:** The use of robust encryption in blockchain ensures that data is cross verified in a manner that greatly reduces the possibility of tampering, hence minimizing the risk of fraud or unauthorized alteration of existing information.
- ii. **Immutable records:** Blockchains provide exceptional assurance in the integrity of their data, since they consist of genuine digital records that are impervious to alteration.
- iii. **Openness:** Blockchain transactions exhibit a high level of transparency since they can be proven, tracked and traced back on the chain.
- iv. **Efficiency:** Blockchain facilitates swift data transmission and verification among parties involved, eliminating the need for intermediaries and simplifying operations.

13.6 E-WASTE MANAGEMENT POLICY FRAMEWORKS

In recent years, there has been a significant increase in the utilization of electronic devices, leading to changes in communication, information access and entertainment. The United States currently has an average of 24

electronic devices per household, and the annual sales of electronic products in the country exceed \$206 billion [31]. The exponential rise in consumer electronics acquisitions has resulted in an expanding influx of pre-owned devices requiring suitable handling. As per the U.S. Environmental Protection Agency, the amount of e-waste discarded in 2009 was about 2.4 million tonnes, which represents a growth of over 120% compared to 1999 [31]. Out of this quantity, just 25% were gathered for recycling. The remainder was disposed of in landfills and incinerators. These items encompass computers, televisions, stereos, printers, copiers and mobile gadgets. While the proportion of used electronics in the total waste stream is very modest, their disposal raises many concerns. The manufacturing of electronic gadgets necessitates a substantial quantity of resources such as metals, polymers and glass, many of which can be reclaimed through recycling. As an illustration, the manufacturing process of a single desktop computer requires a minimum of 530 pounds of fossil fuels, 48 pounds of chemicals and 1.5 tonnes of water [31]. Cell phones are resource-intensive devices that include valuable metals including silver, gold, palladium and copper. Retrieving these and other commodities by means of recycling requires only a small portion of the energy than required for mining fresh metals.

A. Regulations

Governments worldwide have made policies to deal with growing e-waste. For example, in the 25 states of United States and the District of Columbia legislations have been enacted establishing a statewide e-waste recycling programme [31]. Legislation around the world typically follows two basic models for e-waste disposal. Under the EPR model the manufacturer takes responsibility by paying to collect and recycle the products covered under law, with the products covered varying widely from state to state. Under the second type of programme, known as the advanced recycling fee model, consumers pay retailers a nominal fee at the time of purchase which is deposited into a statewide recycling fund. The Waste Electrical and Electronic Equipment (WEEE) Directive in the European Union aims to minimize the environmental impact of e-waste [31]. It mandates electronic product collection, recycling and proper disposal, holding manufacturers responsible for their products' entire life-cycle. The Basel Convention is an international treaty that governs the movement of hazardous wastes across borders, including e-waste [31]. It outlines guidelines for the environmentally friendly management of hazardous wastes, aiming to reduce their production and promote sustainable alternatives.

B. Incentives for Following Rules

To enforce the e-waste management rules, authorities and organizations offer different kinds of incentives. These kinds of incentives are built into the programme to try and incentivize consumers as well as businesses alike, properly dispose electronic equipment so it does not end up in landfills. Usually, there are financial rewards involved. Some governments around the globe offer tax exemptions or rebates for businesses that establish e-waste recycling plants and are sustainably managing their e-waste. For example, in the country of India, subsidy to tune of 50% is offered by the government for setting up new e-waste recycling plants [32]. Other stimulants are certification programmes such as e-Stewards or R2 (Responsible Recycling) [33]. They are the most effective means into ensuring a particular company stands out above others in meeting e-waste recycling regulations. As many large corporate and government agencies are mandated to only use a Recycling Partner who is R2 or E-Steward Certified, having company certified elevates it above others in the marketplace. An indirect incentive is educational and awareness programmes. These public education programmes highlight the advantages of proper management (and the environmental and health risks associated with poor disposal practices) to achieve voluntary compliance.

13.7 THE ROLE OF CONSUMERS IN THE CIRCULAR ECONOMY

A. Responsible Purchasing

Consumers play a vital role in driving the circular economy within the electronics industry through their buying decisions. Growing awareness of environmental, social and governance (ESG) factors has led to increased demand for sustainable products [34]. A 2020 McKinsey U.S. consumer sentiment survey found that over 60% of respondents were willing to pay more for products with sustainable packaging [35]. Additionally, a NielsenIQ study revealed that 78% of U.S. consumers consider a sustainable lifestyle important [36]. This shift in consumer preferences has significant implications for the electronics industry. Products with ESG-related claims accounted for 56% of all growth over a 5-year period, showing 28% cumulative growth compared to 20% for products without such claims [34]. Various demographic groups, including higher-income households, urban and suburban residents, and households with children, have shown a greater likelihood to purchase products with ESG-related claims.

When making purchasing decisions, consumers increasingly consider factors such as [34]:

- a. Energy efficiency
- b. Carbon footprint
- c. Use of eco-friendly materials
- d. Fair labour conditions
- e. Ethical business practices

Notably, products with multiple ESG-related claims have shown faster growth rates than those with single claims. In nearly 80% of product categories, there was a positive correlation between growth rate and the number of distinct types of ESG-related claims made [34].

B. Proper Disposal

It is important to dispose of e-waste in a responsible manner, to avoid environmental damage and health problems. E-waste is considered to be hazardous waste as it may contain lead and mercury and can pose significant human health risks if improperly managed [37]. The constant upgradation of technology is the main reason for increments in e-waste that can impose huge hazards in adverse disposal/landfills.

To ensure responsible e-waste disposal, consumers should follow these guidelines [37]:

- i. Do not dispose of e-waste in regular household trash; it is illegal and detrimental to environment.
- ii. Do not smash or shred e-waste, indoor air quality can be contaminated by destroying them.
- iii. Transport e-waste to authorized certified recycling centres (or) collection systems that can process electronic equipment in a safe and sound way.
- iv. Explore options for reusing or donating functional electronic devices to extend their useful life and minimize waste generation.

C. Engagement in Take-Back Initiatives

Consumer take-back initiatives across the world have proven to be one effective way of allowing consumers to recycle their electronic products responsibly and support the circular economy. Implemented by manufacturers and retailers, often set drop-off points at stores or other locations allow consumers to return used electronic products for recycling, environmentally safe disposal in landfills and refurbishment [38].

Several states in the United States have enacted legislation to promote e-waste recycling through take-back programmes [39]:

- i. California enacted the Cell Phone Recycling Act of 2004, mandating cell phone retailers to implement a take-back programme for used cell phones.
- ii. Connecticut requires municipalities to provide collection services for covered electronic devices (CEDs) from residents.
- iii. The District of Columbia mandates manufacturers of covered electronic equipment (CEE) to collect and recycle e-waste generated in the District at no cost to the consumer.

Numerous major retailers and manufacturers have established their own take-back programmes [38]:

- i. Best Buy has a free recycling service that lets customers recycle up to three old electronic items every day, regardless of where they were bought, at any participating store. Customers who qualify for Best Buy's Trade-In programme may also trade in or recycle any qualified consumer electronic goods by using the mail-back option. A Best Buy gift card will be used as payment for the transaction if the item has a trade-in value. Consumers may use kiosks at Best Buy U.S. retail shops to freely dispose of used mobile phones, rechargeable batteries and inkjet cartridges.
- ii. By obtaining an online shipping label, users in the United States may recycle their Canon goods via the Canon Recycling Programme. Binoculars, camcorders, cameras, small picture printers, film, scanners, inkjet printers, multifunction all-in-one devices, fax machines, personal computer copiers and other bulky equipment may all be recycled by customers.
- iii. Circuit City clients are eligible to receive cash for trading in any qualified consumer electronic device, such as gaming systems, mobile phones, PDAs, iPods, digital cameras, camcorders, computer displays, servers, audio receivers and GPS navigation systems. Cash, PayPal, charitable contributions and other methods may be used as forms of payment.
- iv. Any qualified consumer electronic device may be recycled or traded in by RadioShack customers. MP3 players, mobile phones, cameras, camcorders, GPS units, vehicle audio systems, computers, game consoles and game media are among the electronic goods that may be traded in. Consumers may get an online appraisal for their equipment via RadioShack's Trade-in Programme website or in-store. A RadioShack gift card will be used as payment for the deal.

Customers may send the things to the business for free by using the pre-paid postage label that will be given.

- v. Verizon gathers old cell phones and accessories for domestic abuse organizations around the country. Verizon gathers and safely cleans donated phones via HopeLine, repairs and sells reusable phones, recycles broken phones and gives the money raised to organizations that support victims of domestic abuse.
- vi. Apple provides free mail-in recycling for iPhones and iPads in addition to recycling for desktop, laptop, Mac, and PC computers and monitors. Additionally, Apple provides free mail-in recycling for iPods and mobile phones. Batteries for Mac computers and iPods may be recycled for free at Apple Retail Stores.
- vii. Dell Reconnect programme provides a variety of recycling alternatives, including as mail-back and take-back choices at any collaborating Goodwill shop. Additionally, they provide recycling choices for several brands of electrical devices.
- viii. Most Epson devices, such as printers, scanners, cameras, laptops, PCs and projectors, have a mail-back scheme available via Epson's Recycling scheme. FedEx sends pre-paid shipping labels to customers via mail.
- ix. HP's Recycling Programme provides many choices for reuse and recycling, such as returning any brand of computer hardware for refurbishment, recycling or donation, and trading in to upgrade to a new HP product.
- x. Sony EcoTrade allows consumers to trade in qualified non-Sony and Sony items for credit towards the newest models. Sony offers free recycling for unwanted old items.

13.8 CONCLUSIONS

Sustainable electronics is one of the tenets driving e-waste management and fostering resource conservation worldwide. Through circular economy principles and innovative design strategies, the industry is changing to minimize its environmental footprint with technology-driven solutions. This change towards modular components, sustainable supplies and power-efficient applied sciences suggests an imaginative and prescient to supply an environmentally pleasant services or products designed for lengthy life. This change needs to be driven by consumer participation. The individual-based sustainability solutions include making wise purchasing decision, effective e-waste disposal and engagement in Take-Back Programmes that contribute significantly to the circular economy. With policy changes and stricter regulations coming in, together with many new environmentally friendly business practices being followed there is a chance that the environmental

footprint of an average electronic device will be decreased substantially. Thus, joint collaboration among all stakeholders will lead towards a greener and fairer electronics industry.

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The future of sustainable electronics

Innovations and trends

Haider Mehraj and Farkhanda Ana

14.1 INTRODUCTION

The electronics industry sustainability movement started in the mid-1970s when global standards were applied to limit electronic waste (e-waste) disposal. In 1976 the Resource Conservation and Recovery Act (RCRA) established a national ban on landfills accepting e-waste in the United States [1]. This law foretold the attitude change which would soon arise on e-waste recycling. However, struggles with dumping e-waste persisted and grew even more pronounced until the 1980s when a series of global events exposed the importance of proper disposal of e-waste. A case in point is the notorious vessel *Khian Sea*, a Liberian ship that dumped 14,000 tons of ash from burned e-waste traced to Philadelphia [2]. While the ship's final voyage saw some of its ash illegally dumped in one place after another, enraging public throughout, it is also credited with catalyzing the start-up a year later of The Basel Convention. This treaty outlined international laws banning the transfer of e-waste to developing countries [2]. The recycling industry sprang up as a response to these problems, with an emphasis on salvaging recyclable materials from e-waste. Since then, this growing industry has provided thousands of jobs and helped to alleviate the environmental effects by combating the scourge of e-waste around the globe.

The electronics industry has experienced exponential growth, with the global consumer electronics market now estimated at \$1 trillion [3]. However, this growth has brought significant challenges. E-waste generation is increasing by 3%–4% annually and is expected to reach 74 million tons by 2030 [4]. Although e-waste represents only 2% of solid waste streams, it accounts for 70% of the hazardous waste in landfills [4]. Today, sustainable electronics is marked by a growing awareness for ecological integrity at each phase of the electronic product life cycle. From production to disposal, manufacturers and consumers are aware of the environmental impact of electronic devices. The responsible sourcing of materials is a key challenge faced by the industry. The sourcing and production of the materials required to make electronics, including items like batteries,

can have significant environmental and ethical impacts. The mining of lithium, cobalt and nickel for batteries – which are used in electric vehicles as well as many electronic devices such as laptops – has been linked to habitat destruction and water pollution [5]. However, energy consumption continues to be an important issue in terms of both production and use. The industry is actively looking for opportunities to improve energy efficiency and cut greenhouse gas emissions across the product life cycle.

Sustainable electronics is about adopting principles of a circular economy and innovative thinking to solve the current problems. That is the reason manufacturers are now adopting sustainable strategies to be more environmentally friendly right from the design phase of their production. The utilization of recyclability and reusability in product design is one of the most popular trends. The idea is to mitigate increasing waste and pressure on virgin resources by using electronics or parts of them for longer duration in a potentially upgradable form. A classic example of this is the high-performance/Internet-of-Things (IOT) shuffle – where components are being repurposed from high-performance applications into lower end ones [6]. There are more take-back programs, where consumers can bring in old devices to be properly disposed of and/or recycled. This keeps e-waste out of the landfills and allows some valuable resources to be recovered for use in new products [7]. Refurbishment and re-commerce streamlines are carving out even larger roles in the life cycle management strategy for responsible manufacturers. These markets refurbish functional electronics to extend their device life cycles and thereby reduce the manufacturing of new products. This is where innovations in recycling processes will help move the needle, especially closed-loop systems that recycle recovered materials back into production. There is an increasing emphasis in educating consumers and to make them aware about correct disposal of e-waste. In the coming years, manufacturer collaboration with governments and NGOs will be key to materializing a circular economy for electronics that also meets resource scarcity bottomlines alongside waste management and environmental impact concerns.

14.2 INNOVATIVE DESIGN APPROACHES

14.2.1 Biomimicry in electronics

Biomimicry is a methodology that draws inspiration from nature to discover innovative and environmentally friendly solutions to human problems [8]. Biomimicry has parallels with biomimetics, making it a viable approach for tackling the challenges of the 21st century. So far, biomimicry has resulted in several technical breakthroughs across various fields such as industrial design, building, innovative materials and biomedicine, among others. Several discoveries, like the bullet train in Japan, Velcro and the Shard skyscraper in London, have successfully transitioned into genuine commercial uses [9].

Biomimicry not only leads to technical advancements, but also inspires innovative and sustainable ideas. For example, it encourages the development of scientific research that may be conducted in low-resource laboratories, creates opportunities for the discovery of new and useful functions, and facilitates the exchange of information across different technological and cultural domains. Unlike conventional scientific research, biomimicry primarily relies on the environmental and social consequences, while also delivering performance and economic benefits. This is achieved via strategies such as optimizing resource utilization and developing context-specific solutions.

Engineers are responsible for the design and operation of electronic industries, whereas biomimicry aims to promote cooperation between biologists, who possess a profound understanding of the natural world, and engineers, to achieve a sustainable future. One notable example of collaboration between scientists and engineers in electronics is the development of sharkskin-inspired surfaces [10]. Scientists have replicated the microscopic structure of sharkskin, which consists of countless overlapping scales called dermal denticles, to create more efficient designs. These bio-inspired surfaces have found applications in various electronic components, potentially improving energy efficiency and reducing parasitic growth [11].

The principles of sustainable manufacturing, process intensification and industrial ecology are the same principles that nature has used to sustain the earth throughout its existence [12,13]. These principles are inherent rules for sustainability and have been incorporated into the biomimicry design lens by the Biomimicry Institute [9]. The incorporation of these concepts into the design and operation of industrial processes requires seeing nature as a model, a mentor and a measure, which are referred to as the 3Ms of biomimicry. Nature provides models that may be used or modified to address various challenges encountered by humans. Novel solutions need to replicate or draw inspiration from nature's patterns, mechanisms and ecological systems. This will guarantee the development of long-lasting and environmentally friendly advancements. Nature's principles may serve as a standard to assess the sustainability of any invention. Additionally, nature, with its billions of years of experience, is regarded as a valuable mentor.

14.2.2 Minimalist product architecture

One of the major movements currently happening in sustainable electronics is for those products to be designed as minimally as possible. They diverge from the typical strategy of feature-heavy products to focus on things that will provide “invisible” products for end users. The premise behind this is to create products for which there does not exist a distinction between form and function, like modular product architecture in the design space. This “modularization” results in products consisting mostly of modules or components, which can be swapped for improved capability. Advantages of modular architecture [14] are as follows:

- i. **Adaptable:** Manufacturers can quickly adapt to the changes in markets without a compromise on principal quality.
- ii. **Fast:** Due to the modular construction, modules can be manufactured simultaneously which makes a fast production process.
- iii. **Modification:** Specifications of a product can be quickly changed to meet the needs of certain customers or markets without much rework in manufacturing.

Manufacturers could even take a page out of the minimalist design book to enable an ecosystem of these fragile electronics items that they loan, participate in and exchange components with each other. That will allow the product to last longer and functional, thus easing manufacturers on their end of maintaining, upgrading or recycle their product. This sits alongside a circular electronics production model which offers longer-life products and less waste.

14.3 MATERIAL SCIENCE ADVANCEMENTS

Organic technologies, which are based on carbon, aim to resolve the energy and cost inefficiencies associated with inorganic technologies. Organic electronics, which use conjugated polymers or small molecules as the primary semiconductor component, emerged in the scientific area during the mid-1970s and early 1980s [15]. This technology showed enormous potential for producing affordable and energy-efficient materials and devices. Despite the scientific community's extensive efforts over the last 30 years, the performance and stability of organic semiconductors continue to be significant obstacles to their progress as viable alternatives to inorganic equivalents [16]. Therefore, we currently do not envision the prompt substitution of inorganic components, like those found in high-speed processors, integrated circuits and solar cell modules, with organic alternatives on a broad scale. However, carbon-based materials have a significant advantage over inorganic materials due to their soft nature [17]. This allows for the creation of electrical devices that are incredibly flexible, highly conformable and even invisibly thin.

Organic light-emitting diode (OLED) technology is widely regarded as the most sophisticated platform for organic devices. OLED technology is poised to rival liquid crystal and plasma technologies in the display industry, with distinctive features including vibrant colors and energy efficiency. Organic active layers, an emissive layer and transport layers sandwiched between a cathode and an anode are the fundamental components of OLED devices [18]. Electrons are provided to the electrodes by the cathode, which emits them into the emissive layer, and the anode, which removes them, leaving holes in the whole transport layer. The applied cell potential

causes the electrons and holes to move toward the boundary between the emissive and transport layers [18]. The emission of light occurs when the electron-hole couples combine. Holes have higher mobility than electrons in organic semiconductors. Recombination often occurs inside the emissive layer. While OLED technology has transitioned from the research and development stage to the scale-up stage, the main focus now is on processing yields. However, there is still unresolved scientific inquiry regarding the stability of the active layer when subjected to high current densities for long periods of time. OLED devices may be manufactured using either polymer or small-molecule ingredients. Polymer-based technologies, with their potential to cover vast areas, have been the primary focus of current scientific research. Small molecules, due to their low solution viscosities, are not suitable for forming smooth, conformal coatings in these applications. Lately, there has been a growing interest in solid-state lighting. In this scenario, the criteria for resolving patterns are less strict. Both the architecture and display industries provide significant possibilities for innovative product ideas. Before these devices become widespread in the market, difficulties such as device lifetimes, color changes, and deep blue electroluminescence need to be addressed.

Organic photovoltaics is another platform for organic devices. These devices, known as solar cells, are gaining significant attention due to favorable government policies in alternative energy and the growing economic prospects resulting from improvements in cell performance. Organic solar cells function in the opposite manner compared to OLEDs. The diagram in Figure 14.1 depicts the operational mechanism of an organic solar cell. These devices consist of diode structures that usually consist of a light-absorbing semiconductor that donates electrons and a semiconductor that accepts electrons. They are designed with a mixed microstructure or bilayer to create a heterojunction at the interface. The cell functions by first absorbing photons by the excitation of an electron from the highest occupied molecular orbital (HOMO) energy level to the lowest unoccupied molecular orbital (LUMO) energy level. Conjugated systems, which include the delocalization of π electronic orbitals, often exhibit a π - π^* transition [18]. An exciton is generated when an electron and hole pair is linked together. This exciton may then go from the electron donor domain, where it was created, to the interface with the organic electron acceptor semiconductor. Due to the comparatively lower LUMO energy level of the electron acceptor semiconductor, the transfer of the electron to the electron acceptor semiconductor is energetically advantageous. In an ideal system, separated charges are subsequently directed toward the electrodes by the inherent electrical potential of the cell. Clearly, a higher number of photons being absorbed lead to an increased production of charge, resulting in a bigger power output. Considerable research efforts are focused on expanding the absorption spectra of electron donor semiconductors toward

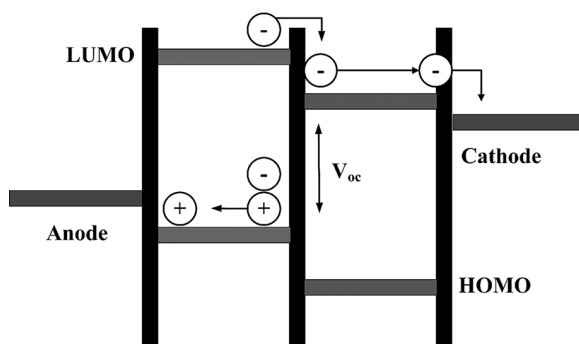


Figure 14.1 Heterojunction energy diagram of an organic photovoltaic cell.

longer wavelengths. This is because a notable portion of photons within this energy range are now not being absorbed. Bulk heterojunction photovoltaic systems consist of light-absorbing semiconductor polymers that transport holes and electron-transporting semiconductors. These materials separate at the nanometer scale throughout the manufacture process. These gadgets show great potential, and Brabec et al. provide an overview of advancements in this field [19]. The devices strike a balance between power conversion effectiveness and compatibility with the manufacturing methods that allow for cost-effective manufacture. Device efficiency is being enhanced by prioritizing the use of novel materials with precisely engineered electronic energy levels. These materials are capable of producing higher cell voltages, absorbing more light, enhancing charge separation, minimizing losses from charge recombination and possessing optimal transport properties. Researchers are currently developing electron donor polymers with low-bandgap and lower-lying HOMO energy levels. These polymers are intended to be employed in conjunction with soluble fullerene derivatives. These polymers have the ability to absorb longer wavelengths of light in the infrared region of the solar spectrum. Additionally, their low HOMO energy levels allow for the production of a higher open circuit voltage. The process of separating p and n semiconducting components into distinct nanoscale domains, which occurs during thin-film processing, may be improved by using processing additives. This enhancement results in the production of more efficient devices. The study of molecular orbital energy levels and geminate recombination processes is gaining significance in understanding the factors that restrict the effectiveness of separating photogenerated charges at interfaces. Recent research indicates that thiophene-containing polymers with delocalized energy levels, often employed in organic photovoltaics, need higher energies than previously anticipated for efficient charge dissociation.

The exploration of electrode materials is a significant area of study, with a specific emphasis on replacing indium tin oxide (ITO) with more affordable printable inks. Thin-film organic transistor devices are attracting significant attention and are on the verge of being commercially available, alongside organic solar cells and organic light-emitting diodes. Organic-transistor active-matrix backplanes are being used by many startup businesses to develop tiny monochrome electrophoretic display (EPD) devices. These displays use electrophoresis to generate an image. Electrophoresis involves the movement of charged pigment particles in a liquid medium of contrasting color, which is powered by applying an electric field across the pixel cell. Recent advancements in picture contrast, resolution and speed, together with decreased driving voltage, have sparked interest in the field. Companies like E Ink and SiPix have already released commercial devices using monochromatic front plane EPD effects. Advanced displays with more complexity need improvements in transistor performance and extended operational lives. Therefore, substantial efforts in the development of novel materials and manufacturing techniques are still required. Radio-frequency identification (RFID) tags and logic applications are hindered in their commercialization due to challenges in adopting standards, integrating systems and operating at high frequencies. Organic transistors have intriguing potential for sensing applications.

Green materials are a developing idea in the category of carbon-based materials. They have the purpose of achieving more ambitious objectives, such as incorporating electronics into living tissue to enable biochemical monitoring, diagnostics, drug delivery and the creation of technologies that are safe for humans and the environment. Green materials and green technologies are being used to achieve sustainability in the electronics industry. This is done by identifying organic precursors that are abundant and low-cost, and by using economically feasible synthetic routes that can produce electronic grade materials without the need for toxic solvents [18]. In addition, it is crucial for the synthesized electronic grade materials to ensure cost-effective processing methods in practical devices [20]. Ideally, these methods should be performed at room temperature using harmless solvents or at low sublimation temperatures. Moreover, the produced electronics should be biodegradable under mild degradation conditions at the end of their life cycle. Alternatively, they should be capable of performing intricate biological functions, such as transduction, sensing, recognition and event triggering. This would enable them to serve as a means of connecting electronics with different life forms. Due to the current stage of development of green materials and technologies, it is difficult to provide a definitive definition of “greenness”. This is because the production of green organic materials using environmentally friendly technologies, which meet all the specified criteria, is currently quite challenging. Many harmless dyes and pigments used in textile, cosmetic and food coloring industries are

made using cost-effective and efficient methods. However, the production of these substances often leads to the creation of environmentally harmful by-products and waste. Scientists are motivated by the simplicity and complexity of nature as they strive to address the energy shortfall and environmental crisis to attain sustainability in electronics. The goal is to imitate natural processes to create a new category of engineered materials that can perform complex functions. Examples include creating a synthetic leaf that replicates the process of photosynthesis, using 3D biomimetic polymers to fabricate artificial compound eyes, replicating the intricate structure of natural photonic fibers, developing self-assembled peptide sequences for use in electronics, designing surfaces with super-hydrophobic (lotus effect), super-adhesive (gecko effect) or self-healing properties, reproducing the natural infrared camouflage coatings found in cephalopod proteins, and harnessing the motion of spermatozoa in a hybrid micro-bio-robot [20].

Nature is a highly proficient energy utilization mechanism that may serve as an endless source of inspiration. The wide range of natural materials provides researchers with several unknown phenomena to investigate and has already begun to pave the way for new advancements in the domains of chemistry, physics and materials engineering. Organic bioelectronics is an emerging research area that highlights biocompatible materials in the development of electronic devices, which can interface with living tissue. Research in the field of bioelectronics deals with a highly interdisciplinary subject to which chemists, physicists, materials scientists as well as electrical and mechanical engineers contribute their efforts. Their contributions involve creating new biocompatible materials, designing device and circuit layouts, and selecting packaging strategies. The goal is to achieve seamless integration and interaction between bioelectronics and living organisms. Organic bioelectronics is expected to serve as a supplementary technology in the near future, creating electronic interfaces in developing disciplines and new markets. This will reduce the need for conventional electronics in those growing areas. The successful demonstration of organic bioelectronics has been observed in a range of applications. These include ultra-thin electronic platforms used in surgical procedures, point-of-care diagnostics and implants. Additionally, organic bioelectronics has been utilized in ambient intelligence systems for daily life assistance, as well as in soft robotics [15]. Furthermore, it has been employed in the development of conformable and self-sustaining bioelectronic components for sports and recreation. Lastly, organic bioelectronics has been used in the creation of disposable (biodegradable) electronics for food packaging and other throw-away applications. The integration of innovative electrical components with biosensing elements will enable the development of disposable diagnostic and medication delivery devices. The area of organic bioelectronics is well-suited for incorporating natural and nature-inspired organic materials. It also provides a promising platform for realizing the ambitious objective of a future with environmentally friendly and sustainable electronics.

14.4 ENERGY INNOVATIONS IN ELECTRONICS

The requirements for improvement in energy production arise for both direct and indirect reasons. Directly, we are seeing a steady increasing demand for energy due to population growth and increasingly Western lifestyles, and secondly (and arguably more significant) the incidental effects of fossil fuel energy on the biosphere, of which global warming is the most important. The pressure to keep costs low is an essential feature of future innovations given the fact that 2 billion people live in poverty, and energy poverty itself is a feature of most Western countries. COVID-19 has also put strong pressures on the public purse, and if we are to have better energy outcomes then they must be cost-effective. This situation has been further complicated by the fact that energy R&D spending has been relatively flat over extended periods in OECD countries [21]. Moreover, Acemoglu et al. have argued that in countries with strong use of fossil fuel energy, which they designate as dirty energy, research spending tends not to be directed to clean energy, and it is possible to find explicit statements in the literature that regulations in many countries continue to shelter big fossil fuel companies from free competition due to their strong lobbying power [22]. However, there are several technologies which might change the current energy dynamics listed as under:

14.4.1 Ambient energy harvesting

Energy harvesting (power harvesting or even energy scavenging) has developed as an important idea for sustainable electronics. It is a method of gaining energy from outside sources like solar power, thermal energy, wind power and even kinetic to store up for application in tiny wireless self-directed tools [23]. Energy harvesters are designed to provide limited amounts of power for small, low-power electronics by harnessing energy from different available background energy sources in the environment. Energy harvesting has been motivated by its ability to power sensor networks and other intermittent-demand mobile devices without reliance on batteries that require external charging or service [23]. This methodology is considered much more sustainable and cost-effective than traditional battery-powered systems, with implications of longer system lifetime, lower manufacturing costs and environmental impact. Modern energy harvesting technology has allowed the creation of devices that can charge themselves from repeated user interactions. For example, researchers have developed battery-less toys, where a user pressing button or turning the knob generates energy for powering toy itself. These developments demonstrate the possibilities of devices to work on rechargeable and renewable energy sources, reducing dependency on conventional battery power.

14.4.2 Ultra-efficient power management

Power management has been a critical part of the equation for unleashing the full potential of harvested energy technologies. A key advance in this area has been the development of low quiescent current (IQ) technologies [24]. Quiescent is term that refers to how much power is consumed while the device is on, albeit not actively; it's also known as standby mode or sleep mode. Most battery-powered devices sit in standby mode around 99% of the time during their life cycle, which is why IQ must be kept to an absolute minimum for any reasonable efficiency. The amalgamation of devices with low IQ with proprietary BiCMOS process technologies allows for novel circuit designs that result in best-in-class low IQ and energy efficiency to extend battery life without sacrificing system performance [24]. One such device, the BQ76952 (industrial high-accuracy battery monitor), can drive active power down to 1–10 μA in standby mode, a 98% reduction as compared to traditional devices of standby power consumption [25]. Process technology breakthroughs have also enabled design engineers to reduce current leakage from battery-management devices. Large digital circuits, memory and high-power field-effect transistors (FETs) contribute most to the leakage current. However, high-density resistors and capacitors together with an innovative circuit design result in a smaller digital circuit thus reducing the leakage as well IQ. One key provision enabling ultra-efficient power management is the ability of such devices to make rapid and efficient transitions between standby load modes and higher-power loads.

14.4.3 Wireless charging advancements

Wireless charging technology is growing as the next big thing where the technology of charging electronic gadgets offers hassle-free solution by eliminating tangling wires while ensuring a smooth and efficient way to charge devices. Wireless charging technology has evolved a lot since it came into existence and wireless chargers do improve the overall experience of recharging devices. Inductive charging is the method that was most widely used in early wireless chargers, where energy is transferred between two coils (one on the charger and another built into a device). Though simple, inductive charging was also inefficient, the device had to make either direct contact with it or be perfectly aligned.

Wireless charging technology has managed to revolutionize the way devices work and are used, and as such has many advantages, some of which are unique to today's market. Wireless charging technology has become incredibly improved over time, offering drastically better efficiency levels, faster charge times and the ability to be used and applied to a much wider range of devices. The key and the most contributing factor for improved efficacy is the common European standard of wireless charging, Qi, established in 2008 by the Wireless Power Consortium (WPC) [26]. This allows

any compatible wireless charger and product to adhere to certain guidelines so that they can be used with products of any brand or model. This creates greater user convenience for switching across devices while also ensuring that the charging standard remains consistent. Wireless charging offers several advantages [26]:

- i. **Convenience:** One of the things that is no longer needed when charging a device is to look for a charging cable. With wireless charging, smartphone or tablet is to be placed on a charging pad to initiate charging.
- ii. **Less wear and tear:** Wireless charging eliminates the regular requirement to connect and disconnect charging cables, which would inevitably be damaging in the long run to either the cable or the charging port of gadgets. Thus, by going wireless, gadgets will be shielded against this wear and tear, which would otherwise shorten their life.
- iii. **Minimal cable clutter:** With wireless charging, not many charging cables will be strewn about in home or office as in the past.

14.5 THE IMPACT OF 5G AND IoT ON SUSTAINABILITY

As the telecommunications industry moves toward 5G and the Internet of Things (IoT), the opportunities and challenges around sustainability are also reshaping. However, this transformation also presents significant risks and benefits to the telecom sector in terms of energy efficiency and environmental impact.

14.5.1 Smart device longevity

Longevity is an important piece of the sustainability puzzle in electronics. Smart devices have an immense environmental footprint, with 82% of their emissions coming from the production stage [27]. As a result, extending the device lifespan has huge benefits for the environment. Today, manufacturers are starting to design phones for longer usage, repairability and modular upgrades. In the United States, mobile customers now hold on to a phone for a record-high average of 6 years before purchasing a new one, compared with a 3-year life cycle in 2012 [27]. There are several reasons why we're now using our phones for longer:

- i. Changes in pricing models, with carriers adopting equipment installment plans.
- ii. Increasing costs of high-end smartphones.
- iii. Reduced planned obsolescence and improved software support for older devices.

14.5.2 Efficient data centers

Increasing efficiency in process optimization is essential for operators of hyperscale data centers. The integration of 5G and IoT technologies, as well as the migration of cloud-native 5G applications into hyperscale data centers, represent a true game-changer. IoT via 5G and hyperscale computing not only enables many use cases for remote and unmanned data center operations, but also allows real-time monitoring of Computer Room Handler (CRAH) units to quickly correct issues in the cooling profiles and lower data center power usage [28]. Data centers are adopting an increasing number of IoT applications as part of an overall strategy to monitor, optimize and lower costs. For example, data centers deploying IoT sensors in their infrastructure gain real-time visibility into critical metrics such as temperature, humidity, power, current, water pressure and asset-utilization levels. That data can be used to identify problems and identify possible inefficiencies that can be corrected.

14.5.3 Optimized energy consumption

The use and implementation of 5G and IoT technologies can take up the potential of optimizing energy use across a wide range of sectors. To start, the manufacturing sector, which contributes 24.2% of all greenhouse gas emissions can benefit from IoT, data analytics and the understanding of consumption at a detailed level, thus being able to fine-tune operations [29]. For example, prominent strategies for energy optimization could be:

- i. Virtual twins and simulation processes to model alternative configurations.
- ii. 5G-enabled machine sensors for predictive maintenance.
- iii. Comprehensive organizational views using 3DEXPERIENCE solutions.
- iv. IoT-enabled tracking of sensitive materials to reduce waste and rework.

However, industry itself accounts for approximately 2% of annual CO₂ emissions worldwide, although that figure is likely to grow without an unwavering commitment to renewable energy in 5G roll-out. In response, the telecom industry has started to explore some solutions, such as [29]:

- i. Incorporation of renewable energy sources such as solar and wind power.
- ii. Improved data center efficiency through virtualization and economies of scale.
- iii. Deployment of data centers in colder, remote locations for built-in cooling benefits.
- iv. Pledges by major tech companies to achieve carbon neutrality by 2030.

Therefore, as the 5G and IoT space evolves and develops, the sustainability of their operations will depend on whether telecoms have a foothold in best environmental practices to offset innovative technology wave. Essentially, the industry has an opportunity to work toward greater sustainability by upholding the idea that there is inherent value in device longevity, that data centers can run efficiently and that energy can be consumed effectively.

14.6 CHALLENGES AND OPPORTUNITIES IN SUSTAINABLE ELECTRONICS

The emergence of sustainable electronics means a new dawn with more seriousness from all stakeholders, vibrant convergence possibilities and endless innovations. The challenges and solutions in the field of sustainable electronics are discussed in this section.

14.6.1 Supply chain complexity

The electronics supply chain stands out in having a unique global reach and complex network of suppliers, manufacturers and distributors. Due to this complex value chain the entire process of tracking and maintaining ethical practices is highly challenging. A key concern here is the responsible sourcing of materials, since extraction and processing can severely impact nature (and society). In addition, the industry's reliance on rare metals and hazardous chemicals only adds to the complexity when considering questions of sustainability. However, sourcing replacement materials that are also low impact is a challenging equation to master without sacrificing quality. Moreover, the energy-intensive production of electronics accounts for a major portion of carbon emissions in the industry, demanding that this is changed by moving toward renewable energies and more efficient manufacturing.

14.6.2 Consumer adoption barriers

In the face of increased awareness about our environment, consumers are still cold to sustainability in electronics due to several reasons. One common perception barrier is that products made from sustainable, recycled resources will be of a lesser quality than those produced using virgin raw material. The only way to dispel this myth is through extensive consumer education, as quality remains the highest concern. One more obstacle is the linear model of electronics' consumption; goods are made with built-in obsolescence and thrown away soon. The radical technological advancement when combined with the linear business model is created for disposable products (like razors), and ultimately very short product life cycles. Changing this will require consumer attitudes and industry habits to be more in line with circular economy practices.

14.6.3 Technological limitations

Electronic devices are difficult to recycle and manage at end-of-life due to their current design and composition. Electronics are not recyclable by design, a complex mixture of materials that includes heavy metals and toxic compounds. This complexity means recycling is a resource-intensive process that relies on specialized equipment and methods to separate and recover valuable materials. This is further complicated by fast new technologies that evolve into existence compared to the pace with which sustainable solutions develop. Waste management strategies are slow to keep up with new market technologies that arise and gain acceptance from the public. This discrepancy highlights the necessity of continued research to develop solutions capable of not just correcting the problem at hand, but in doing so fully applying a circular economy model.

However, this new era also carries an opportunity wave for the sustainable electronics sector. The smart materials that are either biodegradable or made of earth-abundant components have a chance at revolutionizing existing devices. Furthermore, novel manufacturing technologies such as additive manufacturing (3-D printing) will create and facilitate more clean ways to manufacture both product and prototypes.

14.7 CONCLUSIONS

The sustainable electronics movement to shift to more environmentally friendly practices affects every part of the electronics life cycle, from design and manufacturing all the way down to end-of-life management. Incorporating organic materials, biodegradable substances and energy-saving technology is a step toward sustainable electronics of the future. Additionally, businesses are adopting circular economy principles that include take-back and remanufacturing programs to extend product usefulness and reduce the related waste. While notable strides in the development of sustainable electronics have been made, there are still many hurdles that need to be overcome. The intricacy of global supply chains and consumer adoption barriers as well as technical shortfalls remains. But the challenges also provide opportunities for more innovation and an increasingly collaborative industry. Rapid advances are paving the way for breakthroughs in materials, manufacturing practices and recycling technologies. However, reaching there will require a decisive combination of action from manufacturers and consumers to shift the electronics sector toward becoming much more sustainable and responsible.

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