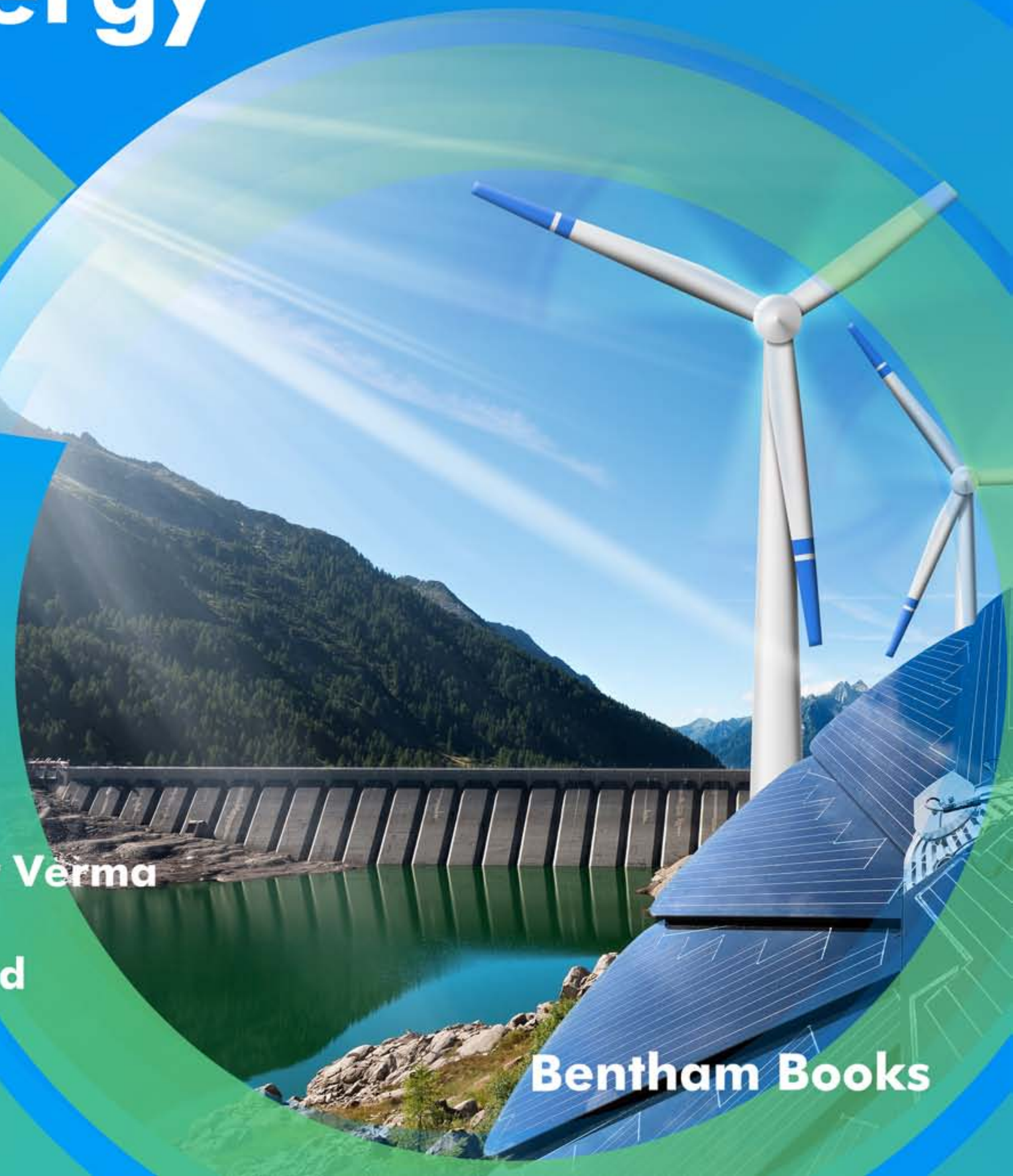
Sustainable Composites for Future Trends in Renewable Energy



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FOREWORD

In an era where sustainability is the primary goal for scientific research and international policy, materials science is essential for advancing progress. The demand for sustainable, cost-efficient, and eco-friendly materials for renewable energy technologies has become increasingly urgent. ***Sustainable Composites for Future Trends in Renewable Energy*** addresses this pressing issue, offering an in-depth examination of advanced composite materials and their transformative potential in the renewable energy sector.

An important contribution to the growing field of sustainable energy materials is this publication. It covers topics like the design, manufacturing, and performance improvement of composites for energy generation, storage, and conversion, thereby bridging the gap between basic research and practical applications. The book offers an in-depth overview of the prospects and difficulties associated with developing a sustainable future by combining perspectives from a wide range of areas, such as energy systems engineering, nanotechnology, and polymer science.

In order to cover disciplines like bio-based composites and new materials for use in photovoltaics, fuel cells, and wind energy systems, the editors have expertly arranged chapters written by prominent experts. This book stands out for its emphasis on sustainability and dedication to promoting cutting-edge scientific research, which makes it a priceless tool for academics, business leaders, and legislators. This book provides direction and motivation as the world transitions to renewable energy. It highlights the revolutionary potential of sustainable composites and the vital role that collaboration, innovation, and moral responsibility have in addressing the world's energy problems.

The dedication and foresight of the editors and contributors in creating this work are commendable. I hope that ***Sustainable Composites for Future Trends in Renewable Energy*** will motivate future researchers and practitioners to contribute to a cleaner and more sustainable world.

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PREFACE

Our modern world's persistent demand for energy has elevated sustainability to the forefront of industrial and scientific innovation. The development of materials that adhere to sustainability principles has become crucial as we struggle with the critical issues of climate change and the depletion of natural resources. A timely response to these issues is this book, Sustainable Composites for Future Trends in Renewable Energy, which explores the potential of composites to transform the renewable energy industry. Composites are becoming increasingly essential in renewable energy applications because of their adaptable qualities, lightweight design, and variable performance. Sustainable composite materials are essential in challenging the limits of what is feasible in a variety of applications, including wind turbine blades, sophisticated solar systems, and next-generation energy storage devices. We achieve the demands of performance while also addressing environmental imperatives by emphasizing materials produced from renewable resources and environmentally friendly manufacturing techniques. The objective of the book is to present an extensive overview of the most important recent developments, discoveries, and studies in the field of Sustainable Composites for Future Trends in Renewable Energy. Numerous subjects are covered in the chapters, such as life cycle evaluation, application-specific optimization, fabrication techniques, and material design. In order to ensure that the insights provided here are both innovative and useful, the goal is to bridge the gap between scholarly research and industrial applications. Without the diligent efforts of researchers, professionals, and entrepreneurs who are dedicated to establishing a sustainable future, this book would not have been possible.

I sincerely appreciate everyone who contributed by sharing their expertise and perspectives. Their endeavors give us hope that we can overcome the obstacles of the twenty-first century and achieve an environmentally friendly and more sustainable future by working together and using our creativity. For students, researchers, scientists, and government officials interested in the nexus between materials science and renewable energy, I hope this book will be a useful resource. We can make the idea of a greener world a reality by utilizing the potential of sustainable composites.

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CHAPTER 1

Background, History, and Introduction to Sustainable Polymer Nanocomposites for Future Trends in Renewable Energy

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Abstract: Magnetic nanocomposites are among the most significant categories of materials because they have excellent magnetic, thermal, and mechanical characteristics for use in various professions. The progress made in the last half decade has stemmed from the preparation of new nanocomposites that display enhanced performance in healthcare, environmental treatment, the energy industry, and electronics. Various synthesis methods for producing M-TiO_2 have been enhanced effectively, including co-precipitation, sol-gel processes, and hydrothermal synthesis to possess the required structural and functional characteristics. Magnetic nanoparticles, which have been approved for targeted drug delivery combined with polymers, ceramics, and metal matrices, offer expanded functionality in applications such as MRI and catalytic systems. Nevertheless, some problems of the approach include the problems of scalability, stability, and environmental impact that may require further inquiries. In this chapter, we focus on the recent progress, including computational modeling, artificial intelligence, and green chemistry. The last one is devoted to present trends, where the roles of bioinspired and hybrid magnetic nanocomposites in shaping future technologies are described.

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Keywords: Advanced materials, Biomedical applications, Energy storage, Environmental remediation, Green chemistry, Hybrid composites, Magnetic nanocomposites.

INTRODUCTION

Magnetic nanocomposites are a relatively new generation of multifunctional advanced materials possessing both magnetic characteristics and nanoscale size, as well as the advantages of composites. These materials have recently attracted the interest of researchers in both scientific studies and industries because of their unique physical, chemical, and mechanical characteristics [1]. Due to their exciting ability to selectively control the magnetic properties on the nanoscale, they are potential candidates for multifaceted applications such as drug delivery, pollutant removal, energy storage, and nanoscale electronics [2]. Recent developments in nanotechnology have seen improvements in the synthesis, as well as the manipulation of properties of numerous magnetic nanocomposites, leading to improvements in their properties and applications [3]. The inclusion of magnetic nanoparticles with polymers, metals, and ceramics has enabled the design of materials with specific characteristics of use, for example, superparamagnetism, high thermal stability, and biocompatibility [4]. These materials are especially important in new scientific disciplines, including biomedicine, where they are used as diagnostic imaging tools or components of drug delivery systems and hyperthermia therapy devices. The natural polymers and derivatives that the BioPol4fun research group uses include chitosan, agarose, alginate, cellulose, gelatin, *etc*., to design materials [5].

Magnetic nanocomposite synthesis has advanced towards techniques such as co-precipitation, sol-gel processing, and hydrothermal techniques, which provide the adaptability for larger-scale production and result in lower costs [6]. Additionally, there has been a development of innovative remedies in green-synthesis engineering that allow for operation under environmentally sensitive conditions and offer high efficacy. These developments have provided opportunities for the green synthesis of magnetic nanocomposites for global sustainable production and proper utilization of natural resources [7]. Characterization techniques such as X-Ray Diffraction (XRD), Scanning Electron Microscopy (SEM), TEM, and Vibrating Sample Magnetometry (VSM) have played a vital role in the characterization and manipulation of properties in these materials [8]. These techniques have proved helpful to researchers in acquiring information on the structural, morphological, and magnetic characteristics of nanocomposites and their enhancement for particular applications [9]. However, magnetic nanocomposites are not exempted from some issues like scalability, stability during operation, and toxicity effects that may be incurred on the environment and human beings [10]. These are problems that will need to be solved at the interface of materials, engineering, and computation. AI and ML in the recent past have come up as essential tools in enhancing the identification and designing of magnetic nanocomposites by providing behavioral and performance forecasts.

This chapter is intended to give a brief account of some recent progress made in the synthesis of magnetic nanocomposites, their characterization, and multifarious fields of applications. It also highlights the challenges associated with these materials and discusses the prospects and directions for development, including trends such as bioinspired designs, hybrid nanocomposites, and knowledge of the use of AI-driven approaches. In targeting a parallel between research and application, this chapter aims to encourage more research and application of magnetic nanocomposite materials in innovative technologies.

SYNTHESIS TECHNIQUES OF MAGNETIC NANOCOMPOSITES

Nanocomposites are widely used in the medical sector for various applications, such as in orthopedics, cardiovascular implants, and the fabrication of implants. Recent progress in synthesis techniques has been widely seen to have a large impact on the development of magnetic nanocomposites. These methods seek to provide accurate and reproducible control over aspects such as size, shape, magnetic characteristics, and distribution of nanoparticles in the host matrix. All of the synthesis techniques present certain advantages and are suitable for solving certain problems; this is why the choice of the synthesis method is critical.

Co-precipitation

Magnetic nanocomposites prepared by the co-precipitation method are discussed in this section because this technique is quite general and inexpensive. In this technique, magnetic nanoparticles are separated from a solution containing metal salts at a specific pH and temperature [11]. Normally, Fe^{2+} and Fe^{3+} salts are precipitated by using a base, especially ammonia solution or ammonium hydroxide. Although this technique offers the benefits of large-volume production and precise control over particle size and size distribution on the nanoscale, it has limitations in that the crystallinity and, conversely, uniformity of the produced nanoparticles may be low and require additional post-synthesis treatments like annealing.

Sol-gel process

Another general approach to obtaining magnetic nanocomposites is the sol-gel process, which becomes crucial for obtaining target materials with high purity and homogeneity [12]. This process involves the reaction of metal alkoxides or metal

CHAPTER 2

Processing, Characterization, and Classification of Polymer Nanocomposites in Sustainable and Renewable Energy Sector

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Abstract: The potential of Polymer Nanocomposites (PNCs) to enhance energy systems' performance and efficiency while providing sustainability advantages has drawn a lot of interest in the field of renewable energy. These materials' mechanical, thermal, and electrical properties are improved by the integration of nanoparticles into a polymer matrix. The usefulness of polymer nanocomposites is greatly influenced by their processing, with methods like melt mixing, solution casting, and in situ polymerization being often employed. The structural, morphological, and mechanical characteristics of these materials are evaluated using characterization techniques such as spectroscopy, microscopy, and thermal analysis. PNCs are also categorized according to their composition and use, with an emphasis on technology for energy conversion, storage, and harvesting. PNCs have been investigated for use in solar cells, batteries, fuel cells, and supercapacitors in the field of renewable energy, which will improve durability, energy efficiency, and environmental sustainability. The production, characterization, and classification of polymer nanocomposites are covered in this paper, along with how they contribute to the development of sustainable and renewable energy systems. PNCs' success in the renewable energy industry depends on resolving issues of cost-effectiveness, reliability, and scalability.

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Keywords: Characterization methods, Energy conversion, Energy storage, Nanomaterials, Polymer nanocomposites, Processing techniques, Renewable energy applications, Renewable energy, Sustainable energy, Sustainable materials.

INTRODUCTION

The mechanical, thermal, and electrical properties of Polymer Nanocomposites (PNCs), a class of sophisticated materials, are greatly improved by the addition of nanoscale fillers to a polymer matrix [1]. Because of their potential to enhance the sustainability and efficacy of energy systems, these materials have garnered a lot of interest across several industries, including renewable energy [2]. PNCs offer improved efficiency, lightweight constructions, and ecologically favorable features in a variety of renewable energy applications, including energy storage, energy conversion, and energy harvesting technologies [2]. To modify polymer nanocomposites' characteristics to satisfy the unique requirements of renewable energy applications, processing is essential [3]. To successfully incorporate nanoparticles into polymer matrices, a variety of processing methods have been investigated, including melt blending, solution casting, and *in situ* polymerization [4]. These techniques have an impact on how nanofillers disperse, which has a direct impact on the material's overall performance [5]. For example, the mechanical strength and electrical conductivity of the composites—both crucial for energy applications, including solar cells, batteries, and supercapacitors—can be greatly impacted by the shape and distribution of nanofillers inside the polymer matrix [6].

Understanding the structure-property relationship of polymer nanocomposites is crucial for characterization, which enables researchers to evaluate the materials' suitability for a range of applications [7]. The morphology, crystallinity, and thermal stability of the nanocomposites are frequently examined using methods including Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), X-Ray Diffraction (XRD), and Thermogravimetric Analysis (TGA) [8]. The accurate assessment of PNCs' mechanical, chemical, and physical characteristics is made possible by these characterization technologies, guaranteeing their efficient deployment in energy-related applications [9]. The classification of polymer nanocomposites is often based on the composition, the kind of nanofillers, and the application for which the nanocomposite is intended [10]. PNCs have been studied for application in energy harvesting gadgets, energy conversion technologies like organic photovoltaics, and energy storage systems such as lithium-ion batteries and supercapacitors in the field of renewable energy [11]. It is established that the introduction of nanoparticles such as metal oxides, inorganic nanoparticles, and carbon structures (graphene, carbon nanotubes) into the polymer matrix increases the strength, conductivity, and thermal stability of the material, whichis essential for enhancing the relevant device performance and energy conversion efficiency [12]. With an emphasis on their uses in energy storage, conversion, and harvesting technologies, this study attempts to investigate the processing, characterization, and classification of polymer nanocomposites in the renewable energy field. The difficulties with PNCs' scalability, stability, and cost-effectiveness will also be covered, along with potential future research and development avenues. Several kinds of nanofillers for nanocomposites are made of polymers, in which nanofillers are mainly classified into organic and inorganic composites [13].

PROCESSING POLYMER NANOCOMPOSITES

Polymer Nanocomposites (PNCs) are a class of sophisticated materials that improve the properties of polymers by combining them with nanoscale fillers. Their processing, characterization, and classification are critical to their use in renewable energy systems [14]. Optimizing their performance for particular uses, such as energy harvesting, energy conversion, and storage, requires an understanding of these factors [15]. A discussion of several processing, characterization, and classification-related topics is provided here, along with the relevant references [16].

Processing of Polymer Nanocomposites

The structural and functional characteristics of polymer nanocomposites are significantly influenced by their processing [17]. Nanomaterials are frequently added to polymer matrices using a variety of processing techniques, including melt mixing, solution casting, and *in situ* polymerization [18]. The performance of the composite material is directly impacted by each method's effects on the homogeneity and dispersion of the nanofillers [19]. Green polymeric nanocomposites for supercapacitors can be seen widely in the literature [20].

a. **Melt Blending:** By combining the polymer with molten nanoparticles, this method enables the filler to be evenly distributed throughout the polymer matrix [19]. Its ease of use and scalability make it one of the most used techniques for processing PNCs. However, controlling the dispersion quality of nanofillers can be difficult [21].
b. **Solution Casting:** This entails adding the nanomaterials after the polymer has been dissolved in an appropriate solvent. After that, the solution is dried and cast into a thin layer. For the production of thin, flexible films for energy devices like solar cells and supercapacitors, this technique offers improved control over filler dispersion [22].

CHAPTER 3

Piezoelectric Polymer Composites: A Comprehensive Study on Energy-Harvesting Applications

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Abstract: Piezoelectric energy harvesting is a promising technology; basically, this technology is used to convert ambient waste energy into usable electrical energy. This technique is typically employed to transform diffuse wasted energy into usable electrical energy. For energy harvesting applications, polymeric piezoelectric composites are regarded as a key study area because they provide the convenience of mechanical flexibility. The nature of the piezoelectric phenomena, the fundamental theory underlying Piezoelectric Energy Harvesting (PEH) devices, and the configuration used to fabricate PEH are explained at the outset.

Keywords: Energy harvesting, Piezoelectric Composites, Semiconductor.

INTRODUCTION

Over the past three decades, advancements in semiconductor manufacturing technologies have resulted in remarkable progress in tiny/small devices (electronic), including portable devices such as sensors, electronics, and transmitters. These advancements have significantly expanded functionality, improved energy efficiency, and drastically reduced device sizes. Furthermore,

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the continuous improvement in battery energy density has enabled numerous devices to operate for extended periods using battery power alone. However, certain applications, like sensors installed in remote areas or within the human body, pose challenges regarding individual power connections. Consequently, batteries have been widely used for their convenience, despite their power cost drawbacks. Nevertheless, it is impractical to repeatedly replace batteries on a large scale, such as in the Trillion Sensor Universe.

Consequently, researchers and engineers have been driven to explore alternative power solutions for small electronic devices. Several potential solutions have emerged, including the following.

i. Energy Harvesting (EH): This method involves capturing and converting ambient energy sources, such as light, heat, vibration, or radio waves, into electrical energy to power the devices. Energy harvesting techniques offer the potential for a continuous or intermittent power supply, reducing reliance on batteries.
ii. Wireless Power Transfer (WPT): Technologies like inductive charging and resonant inductive coupling enable devices to receive power wirelessly, eliminating the need for physical connections or frequent battery replacements.
iii. Micro-scale Power Generation (MPG): Researchers are investigating the use of micro-scale power generators, such as micro fuel cells or micro wind turbines, to generate electricity and provide self-sustainability for small devices.
iv. Power Management and Optimization: Enhancements in power management techniques, low-power design, efficient power conversion circuits, and intelligent power management algorithms can help extend battery life and reduce overall power consumption.

These alternative power solutions offer potential pathways to overcome the limitations of battery dependence and pave the way for long-term, sustainable power solutions for small electronic devices in various applications.

Currently, numerous wireless sensor nodes rely on battery power and operate with a limited energy budget. The sheer scale of networks, consisting of thousands of physically embedded nodes, makes it impractical to continuously replace batteries [1]. Notably, the WiseNET platform, created by the Swiss Centre for Electronics and Microtechnology (CSEM) [2, 3, 4], serves as an example of such wireless sensor networks. In order to ensure the longevity of sensor nodes, it is essential to focus on the low-power characteristics of the components and the system architecture design.

ENERGY HARVESTING

Power generation, also known as energy scavenging, encompasses the process of gathering and accumulating diverse amounts of energy from the immediate surroundings. This energy can be harnessed from sources like solar radiation, thermal gradients, wind, and electromagnetic waves. The objective of power generation or energy scavenging is to capture and utilize these available energy sources, enabling a sustainable and efficient power supply for various applications. This collected energy is then transformed into electrical power, which can be stored for future utilization. Mechanical Vibration (MV), mechanical strain and stress, and thermal energy are derived from the heat sources. In addition, the biological and chemical reactions are frequently employed as power sources in this process.

Energy harvesting is not only essential for sustaining self-powered systems, but it also offers a viable and economically applied alternative to batteries. Moreover, it plays a crucial role in reducing greenhouse gas emissions and preserving the environmental situation [5]. Characteristically, an Energy Harvesting System (EHS) comprises three key components [6].

i. Energy source: This refers to the origin of the energy from which the electrical power is harvested. The energy source can either be ambient, existing in the surrounding atmosphere (such as heat, sunlight, wind), or external, involving explicitly deployed energy sources (such as vibrations, lightning, human heat) [7].
ii. Harvesting mechanism: This component encompasses the structure or mechanism responsible for converting ambient energy into electrical energy. It facilitates the extraction and transformation of energy from the chosen source.
iii. Load: The load represents the destination or recipient of the electrical energy generated through harvesting. It either consumes the energy directly or stores it for future use.

By understanding and optimizing these three components, energy harvesting systems can effectively harness available energy, reduce dependence on batteries, mitigate greenhouse gas emissions, and contribute to the sustainability of our environment.

A burgeoning area of research focuses on energy harvesting methods from road infrastructure, which involve capturing and storing lost energy from pavements for future utilization. What makes these methods particularly attractive is that they leverage existing extensive paved surfaces. Recent examples of such energy harvesting technologies include the use of conductive pipes, piezoelectric sensors, nanomaterials, thermoelectric generators, phase change specimens, barriers,

CHAPTER 4

Highly Stable Nanocomposite PVDF-Based Energy Harvesting Piezoelectric Devices

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Abstract: The topic of energy harvesting is very important because of the rising power consumption and environmental concerns. Extensive research is being done on Poly (Vinylidene Fluoride) PVDF and its copolymers for the purpose of developing energy harvesting devices. This chapter deals with the various types of piezoelectric devices and their working principle, along with their applications. The use of PVDF and its nanocomposites in piezoelectric devices makes them promising due to their outstanding properties, such as ease of processing, good flexibility, good biocompatibility, high stability, *etc*. Also, the applications of PVDF-based piezoelectric materials in energy harvesting devices such as sensors, biomedical science, flexible and hybrid nanogenerators, *etc*., are discussed.

Keywords: Energy harvesting, Nanocomposite, Piezoelectric applications, Piezoelectric effect, Polymer composite.

INTRODUCTION

Energy sources (solar, thermal, wind, and mechanical vibrations) can be harnessed using specific materials that are capable of generating electricity or collecting charges [1]. Thus, to harness mechanical energy, piezoelectric materials are prominent candidates, manifesting greater potential, higher power density, and increased life span [1, 2]. In 1880, the Curie brothers first discovered the piezoelectric effect. *Piezoelectric* is a Greek word meaning “pressure electricity”

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[3]. Piezoelectricity is observed in materials that are non-centrosymmetric (their crystalline state lacks a centre of symmetry), and this phenomenon is generally attributed to the electric dipole [3, 4]. Dipoles provide a macroscopic polarization vector, P, when they are mutually aligned in specific spatial areas (Weiss domains). Such alignment can occur spontaneously, or it can be induced in some materials (ferroelectrics) by either a mechanical drawing technique or an externally provided, strong electric field (poling method). Following a mechanical stress (σ), both the strain (ε), which is induced in the material, and the direction of P and/or intensity may change. The electro-mechanical behavior of the material is then described as a piezoelectric coefficient, d_{ij} = Di/j, where Di denotes the electric displacement's components and the direction denoted by 3 is recognized as the direction of pristine polarization (poling process). In d_{ij}, the j subscript signifies the direction of applied stress (for j = 1-3), as well as whether shear stress is present (for j = 4-6). The subscript i in d_{ij} denotes the direction (*i.e.*, x, y, or z) of the electric displacement resulting in the piezoelectric material, *i.e.*, the direction along which a voltage bias is produced [5 - 7]. The variable design of a system can benefit greatly from shear piezoelectric response, which has been demonstrated in numerous uniaxially oriented systems.

Piezoelectric materials are desirable for their use in Energy Harvesting (EH), actuators, sensor devices, and a variety of other fields of technology because they can directly generate electrical and mechanical energy [8, 9]. Due to its high energy conversion efficiency, simplicity of use, and miniaturization, the piezoelectric effect has been widely utilized to convert mechanical energy into electricity [10]. Due to their piezoelectric behavior, several materials can be used in harvesting energy, as well as in the fabrication of piezoelectric sensors and actuators. Barium Titanate ($BaTiO_3$) and Lead Zirconate Titanate (PZT) are traditionally popular Piezoelectric Materials (PEM) [11]. However, these are brittle and toxic. PEMs that are non-toxic, flexible, and simple to fabricate are therefore in demand for commercial applications [12, 13]. Fig. (**1**) depicts the various piezoelectric materials and their atomic structure. Although the piezoelectric effect is frequently linked to ceramic materials, numerous polymers also exhibit piezoelectric behavior. Despite frequently being less piezoelectric than their ceramic counterparts, piezoelectric polymers are frequently preferred for particular applications because of their flexibility, simplicity of production, and biocompatibility [14, 16]. Many different polymer families exhibit piezoelectric effects. In addition to the well-known ferroelectric polymer Polyvinylidene Fluoride (PVDF), various polyureas, polyamides, polypeptides, and polyesters also exhibit piezoelectric behaviour [17]. Piezoelectric technology is often used to generate electricity. Due to its high electro-mechanical coupling factor and piezoelectric constant, PZT is the most widely utilized piezoelectric material. However, due to its fragility, high cost, high density, and environmental risks, the development is incomplete at this point [11, 18].

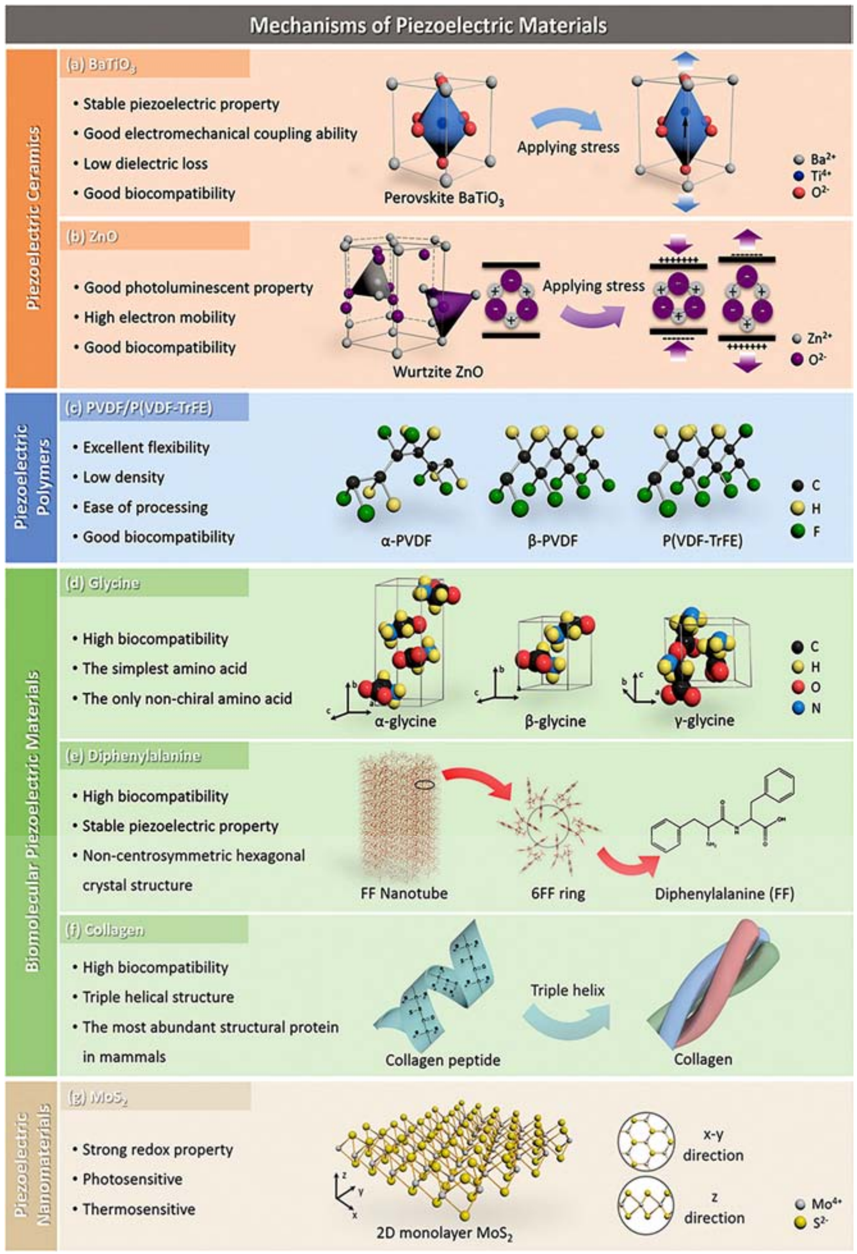

Fig. (1). Various piezoelectric materials and their atomic structure [3].

CHAPTER 5

Innovative, Cutting-Edge Technologies for Energy Harvesting Using Polymer Nanocomposites

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Abstract: This chapter discusses the cutting-edge polymer nanocomposite energy harvesting technology. Attention has been drawn to polymer nanocomposites, which combine polymers and nanoparticles, for their potential for effective energy conversion. Polymer nanocomposites are used in piezoelectric, thermoelectric, and photovoltaic systems to transform mechanical, thermal, and light energy into electrical energy. Techniques like nanofillers and interface engineering maximize the effectiveness of energy conversion. Improvements in characterization, modeling, and manufacturing techniques are essential for commercialization. Polymer nanocomposites can potentially be used for energy harvesting in self-powered sensors, Internet of Things (IoT) devices, and wearable electronics. In order to advance sustainable energy solutions, this chapter outlines current research initiatives and future uses of polymer nanocomposites.

Keywords: Applications, Challenges, Electronics devices, Energy harvesting, Innovative technologies, Piezoelectric materials, Polymer nanocomposites.

INTRODUCTION

It is possible to “harvest” a small portion of dissipating energy from the environment with minimal effort to utilize it as electrical energy. This concept is referred to as “energy harvesting”. Recently, it has attained enormous attention as an alternative/source for achieving Sustainable Development Goals (SDG) [1, 2, 3].

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The Internet of Things (IoT) technology provides more sophistication to society, and as a result, it is envisioned to enter the Trillion-Sensor Universe (TSU). Generally, the challenging task is to link these sensors to an individual energy supply, and for this purpose, batteries are used despite their disadvantages, like high power costs. However, it is difficult to change the batteries often, especially for a TSU. So, the communal application of energy harvesting techniques becomes unavoidable.

From the literature, it has been identified that the term harvesting has been explicitly used for photovoltaic applications [4]. Different energy harvesting methodologies were reported by researchers [5, 6]. The overall outline of the technologies is shown in Fig. (**1**) for different environmental targets. In general, energy harvesting may include one or all of the following:

a. Harvesting: Generally in small quantities
b. Conversion: Harvested energy to electric energy
c. Processing: Preferably in power conversion circuits
d. Utilizing: For different applications

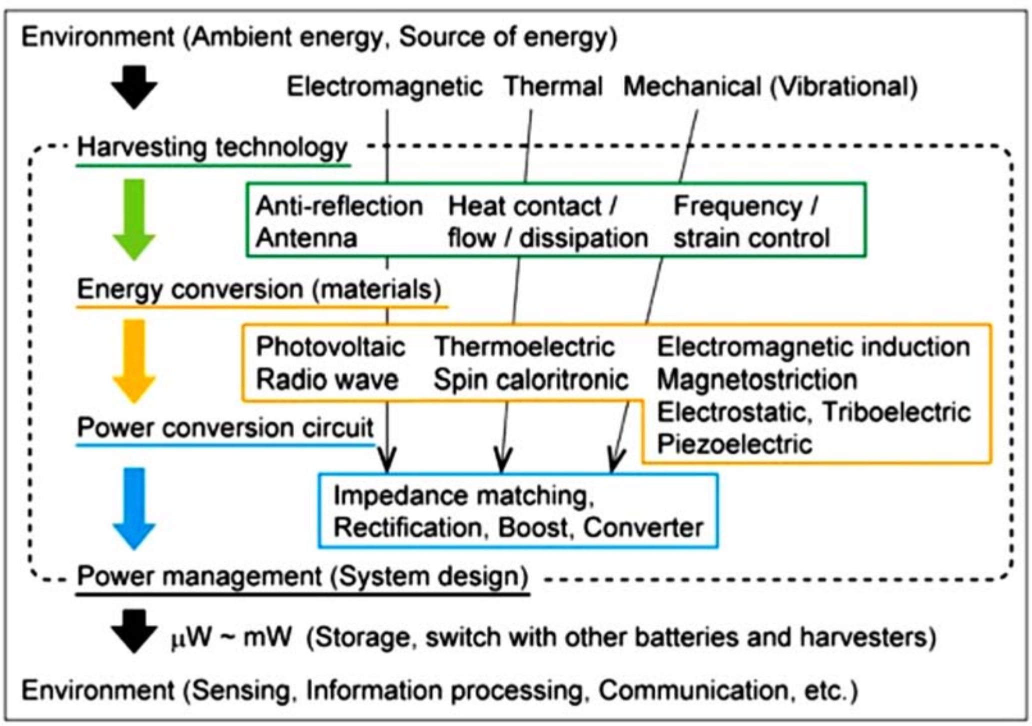

Fig. (1). Energy harvesting techniques [7].

Throughout this chapter, all the above are referred to as energy harvesting. Among the various technologies, solar cells have wide popularity due to their high yield output, and they have already been in practice for a long time. Still, it is necessary to harvest the energy from indoor and outdoor light [8, 9, 10]. Thus, standardization is essential for the different solar cell types for further development.

Besides solar energy, vibrational energy, radio wave energy, and thermoelectric energy are also essential sources/techniques. The factors to be considered while implementing the energy harvesters are reliability, durability, environment, and operational cost.

CLASSIFICATION

According to the matrix, nanocomposites can be categorizedinto ceramic, metal, and polymer nanocomposites.

Ceramic-Matrix Nanocomposites (CMCs)

Industrial ceramics are inorganic, non-metallic compounds composed of borides, oxides, nitrides, silicides, *etc*. Since ceramics are fragile, their toughness is one of the most interesting research areas. For this reason, more pliable metal phases are usually interspersed in a ceramic matrix. To achieve unique nanoscopic qualities, it is ideal for both the metallic and ceramic components to be properly circulated within one another. Moreover, information on improved qualities, including optical, electrical/magnetic, tribological, and corrosion resistance, has been distributed [11].

Since a metallic constituent can freely react with ceramic and lose its metallic properties, protective layers must be formed to prevent chemical reactions between the two components. Finding a metal that is miscible with the ceramic matrix is one of these measures. For instance, Cu is miscible with TiO_2 in the Gibbs' triangle of Cu-O-Ti in vast sections.

Ceramic-matrix nanocomposite films can be produced utilizing gas current sputtering with the resonating cathode method in thin-film (thicknesses from a few nm to tens of m applied to a connecting substrate). High deposition rates and the growth of nanoparticles in the gas phase are associated with this vacuum-based deposition technology. The technique forms nanocomposite layers consisting of TiO_2 and Cu that have admirable corrosion resistance, low friction, and high mechanical hardness.

CHAPTER 6

Methodologies Exploited in the Synthesis of Conducting Polymer Nanocomposites: Concept, Strategies, and Development

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Abstract: This book chapter provides a comprehensive overview of conducting polymer nanocomposites, including their types and potential applications. The article highlights six types of conducting polymer nanocomposites, which include metal nanoparticles, carbon nanotubes, graphene, metal oxide nanoparticles, nanocellulose, and clay nanoparticles. Additionally, the chapter discusses the various methods available for the synthesis of conducting polymer nanocomposites, which include *in situ* polymerization, solution blending, *in situ* reduction, electrochemical deposition, and layer-by-layer assembly. Overall, this chapter serves as a valuable resource for researchers interested in the synthesis and application of conducting polymer nanocomposites.

Keywords: Conducting polymer nanocomposites, Functional polymer, Fabrication techniques, Hybrid nanomaterials.

INTRODUCTION

Conducting polymers, also known as conjugated polymers, are a class of organic materials that have the ability to conduct electricity. They are formed by linking together small molecules called monomers, which form long chains. The unique structure of conducting polymers allows for the flow of electrons, making them attractive for a variety of applications, such as electronics, optoelectronics, and

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energy storage. The properties of conducting polymers can be tailored to suit specific applications by modifying their chemical structure, leading to the development of different types of conducting polymers.

Types of Conducting Polymer Nanocomposites

Conducting polymer nanocomposites are a type of composite material that combines conducting polymers with nanoparticles or nanofibers to enhance their electrical and mechanical properties. The addition of nanoparticles to conducting polymers can result in increased electrical conductivity, improved thermal stability, and enhanced mechanical strength. There are different types of polymer nanocomposites, such as

1. Polymer nanocomposites with metal nanoparticles

Conducting polymers can be combined with metal nanoparticles such as silver, gold and copper to create materials with high electrical conductivity and antimicrobial properties. These materials have potential applications in electronic devices, sensors, and medical devices.

Polymer nanocomposites incorporating metal nanoparticles exhibit antibacterial activity through a synergistic combination of physical and chemical mechanisms:

a. Physical membrane disruption: The high surface area-to-volume ratio of nanoparticles facilitates strong interactions with bacterial cell membranes. These interactions may involve direct contact, surface adhesion, or even partial envelopment of bacterial cells, ultimately leading to membrane destabilization and increased permeability.
b. Metal ion release: Certain metal oxide nanoparticles, such as Zinc Oxide (ZnO) and Copper Oxide (CuO), release metal ions into the surrounding environment. These ions can compromise membrane integrity, disrupt vital enzymatic processes, interfere with nutrient uptake, and inhibit DNA replication, collectively impairing bacterial viability.
c. Generation of Reactive Oxygen Species (ROS): Noble metal nanoparticles, including Silver (Ag) and Gold (Au), can catalyze the formation of reactive oxygen species. ROS such as superoxide anions, hydroxyl radicals, and hydrogen peroxide induce oxidative stress, damaging bacterial DNA, proteins, and lipid membranes, ultimately resulting in cell death.

Polymer Nanocomposites With Carbon Nanotubes

Conducting polymers can also be combined with Carbon Nanotubes (CNTs) to create nanocomposites with high electrical conductivity, thermal stability, and mechanical strength. CNTs are one of the strongest materials known to man, and their addition to conducting polymers can significantly improve their mechanical properties. These materials have potential applications in flexible electronics, energy storage devices, and aerospace applications.

Polymer Nanocomposites with Graphene

Graphene is a two-dimensional material consisting of a single layer of carbon atoms arranged in a hexagonal lattice. Conducting polymers can be combined with graphene to create nanocomposites with high electrical conductivity, thermal conductivity, and mechanical strength. These materials have potential applications in energy storage devices, electronic devices, and sensors.

Polymer Nanocomposites with Metal Oxide Nanoparticles

Conducting polymers can also be combined with metal oxide nanoparticles such as titanium oxide, zinc oxide, and iron oxide to create nanocomposites with improved electrical conductivity, thermal stability, and mechanical strength. These materials have potential applications in sensors, electronic devices, and energy storage devices.

Polymer Nanocomposites with Nanocellulose

Nanocelluloses are biodegradable materials that can be extracted from plant-based sources such as wood, cotton, and hemp. Conducting polymers can be combined with nanocellulose to create nanocomposites with high electrical conductivity, thermal conductivity, and mechanical strength. These materials have potential applications in flexible electronics, biomedical devices, and packaging materials.

Polymer Nanocomposites with Clay Nanoparticles

Clay nanoparticles such as montmorillonite and kaolinite can be combined with conducting polymers to create nanocomposites with improved mechanical strength, thermal stability, and flame retardancy. These materials have potential applications in electronic devices, coatings, and flame-retardant materials.

Advantages of Conducting Polymer Nanocomposites

Conducting polymer nanocomposites offer several advantages over pure conducting polymers, including:

- Enhanced electrical conductivity: The addition of nanoparticles to conducting polymers can significantly enhance the electrical conductivity of the material by providing additional charge carriers.

CHAPTER 7

Biodegradable Nanocomposites for Energy Harvesting Devices, Piezoelectric Sensors, and Fuel Cells

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Abstract: The growing demand for sustainable and eco-friendly technologies has spurred significant interest in the development of biodegradable materials with multifunctional capabilities. Biodegradable nanocomposites have emerged as a promising solution to address various environmental challenges while enabling advanced applications in piezoelectric sensors, fuel cells, and energy harvesting devices. This comprehensive review delves into the recent advancements and key considerations in the design, fabrication, and application of biodegradable nanocomposites for these vital technologies. In conclusion, the development of biodegradable nanocomposites presents a transformative opportunity to merge sustainability with cutting-edge technologies. This review underscores the pivotal role of these materials in piezoelectric sensors, fuel cells, and energy harvesting devices.

Keywords: Biodegradable nanocomposites, Energy harvesting, Environmental technology, Fuel cells, Piezoelectric sensors.

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INTRODUCTION

The pressing environmental challenges have spurred substantial research endeavors in both industrial and academic sectors, with the aim of developing "green materials" derived from natural resources. These efforts encompass the exploration of biodegradable and biopolymer-based materials as sustainable alternatives. Polylactic Acid (PLA) stands out as the most promising biopolymer due to its biodegradability and its derivation from agricultural resources. Nanocomposite materials offer several advantages over conventional composites, including superior barrier and thermal and mechanical properties, even with minimal reinforcement levels. Additionally, nanocomposites exhibit enhanced recyclability, transparency, and reduced weight compared to their counterparts [1]. Nanocomposites can be categorized into various types, including polymer nanocomposites, metal nanocomposites, bio-nanocomposites, and more. Polymer nanocomposites consist of a polymer matrix containing uniformly dispersed organic or inorganic fillers that serve as additives [2]. In recent years, biopolymers have garnered significant attention as polymer matrices of interest. Commonly used conventional polymers such as polypropylene, polyethylene, polystyrene, and polymethylmethacrylate are non-biodegradable, posing significant challenges for their recycling and reusability [3]. Consequently, an enormous amount of non-biodegradable waste is generated worldwide, including the composites derived from these polymers. The utilization of biodegradable polymers sourced from alternative renewable origins in polymer composite technology is captivating. On the other hand, substituting them for commercial synthetic polymers poses significant challenges. A few of these challenges include low thermal stability, brittleness, and inadequate barrier characteristics [4]. The incorporation of nano-fillers into polymer matrices not only results in selective developments in performance and characteristics but also impacts the biodegradability of the polymer within the nanocomposite. Hence, it is crucial to assess the biodegradability of the nanocomposite. However, when it comes to specific applications such as biomedical applications, no individual biodegradable polymer can accomplish every single one of the necessary requirements. Consequently, a trend has emerged in recent years, focusing on the fabrication of multi-component polymer systems. This approach aims to develop innovative biomaterials that are multifunctional in nature [5].

Biodegradable nanocomposites have captured considerable interest across diverse domains such as piezoelectric devices, fuel cells, sensors, and energy harvesting systems. These materials present the advantage of both functionality and environmentally friendly properties. Piezoelectric substances generate an electric charge under mechanical stress. It is feasible to design biodegradable nanocomposites to display piezoelectric characteristics, enabling them to transform mechanical power into electrical power. The application of biodegradable nanocomposites extends to the construction of environmentally friendly sensors. These sensors possess the capability to identify and quantify different variables, encompassing temperature, humidity, pressure, and chemical analytes [6]. Through the integration of functional nanoparticles or nanowires into biodegradable matrices, these sensors acquire the ability for real-time monitoring, all the while maintaining their eco-friendly nature. Fuel cells transform chemical energy into electrical energy by means of electrochemical reactions. Biodegradable nanocomposites can serve as electrolyte membranes or electrode materials in fuel cells. These materials must exhibit commendable proton or ion conductivity, substantial surface area, and exceptional chemical stability to enhance the fuel cell's efficiency and productivity [7]. Biodegradable nanocomposites can be utilized in energy harvesting systems to capture and convert surrounding vibrations into electrical energy. This technology exhibits a range of applications, including self-sustaining wearable devices, wireless sensors, and remote monitoring systems. The development and commercialization of biodegradable nanocomposites for these applications are still in early stages, with scientists focused on enhancing their characteristics, performance, and scalability for specific needs. This review offers a synopsis of notable progressions in biodegradable nanocomposites that have taken place in recent years. This content encapsulates the authors' contributions to the development and characterization techniques, accompanied by the presentation of typical examples that demonstrate the improved material properties [8]. These developments possess significant promise for a wide range of applications in areas of human interest.

Fig. (**1**) provides an outline categorizing bio-polymers into four distinct groups. The initial three classifications contain bio-based polymers, while the polymers in the final group are ecological but not of bio-based origin. Additionally, the polymers belonging to the last three groups share the common feature of being aliphatic polyesters in the structure.

Polylactic Acid (PLA)-Based Nanocomposites

Polylactic Acid (PLA) has garnered significant attention from researchers due to its exceptional biodegradability, compatibility, and high strength. Furthermore, as an aliphatic polyester derived entirely from renewable resources, PLA has emerged as a highly capable substance for synthesizing biodegradable nanocomposites. By incorporating various nanoparticles into the PLA matrix, the material's mechanical and thermal properties can be significantly enhanced, expanding its range of applications. This key aspect explains the considerable focus of several studies on this procedure [10 - 12]. Zhuang *et al*. [13] employed

CHAPTER 8

Advanced Materials with Carbon Nanostructure-Based Composites for Environmental Energy Harvesting

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Abstract: In recent years, carbon-based nanostructured materials have emerged as promising candidates for addressing the challenges associated with increasing energy demand and environmental degradation. These materials exhibit exceptional properties such as enhanced electrical conductivity, mechanical strength, and thermal stability, making them attractive for various applications in energy harvesting and environmental remediation. Carbon-based nanostructured materials have garnered significant attention from the scientific community due to their superior electrical, mechanical, and electronic/optoelectronic properties. In this chapter, we present a systematic overview of the advancements in carbon-based nanostructured materials for environmental and energy harvesting applications. Furthermore, we discuss their practical applications in environmental remediation and energy technologies. Specific focus is given to their roles in supercapacitors, solar cells, and batteries.

Keywords: Carbonn nanostructured specimen, Electronics devices, Environmental application, Energy harvesting applications.

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INTRODUCTION

A significant portion of the scientific community has recently raised concerns about the extraordinary challenges posed by the rise in energy demand. Rapid industrialization, technical advancement, and population increase are the primary factors contributing to the increasing energy demand. Currently, the world's per capita energy consumption has increased due to the increase in population density. Additionally, by 2035, energy demand is expected to increase by up to 40% from its current level. As a result, the manufacture of energy from sustainable sources is attracting a lot of interest in the context of global energy demand. In general, the term “carbon” refers to a unique element that can be found in both microscopic and macroscopic structures and compounds. The periodic table only has one element that can arrange four valence electrons under various hybridization conditions (sp, sp^2, sp^3), leading to both strong covalent and weak π-π bonds. Overall, about ninety-five percent of known chemical compounds can be categorized as carbon-based. Carbon has four valence electrons (namely 2s and 2p) that play an important role in bond formation (single, double, and triple). Further, it can react to form some stable substances by means of many electronegative and electropositive elements. The resultant massive variety of the specimen compounds and nanostructures is improved through a huge range of different physical, chemical, and biological features. These key features make carbon the most extensively researched specimen element in both research and materials science domains [1 - 6].

At the end of the 20th century, carbon technology and chemistry were marked by noteworthy technological and scientific progress. It led to the further establishment of novel kinds of nanosized carbon and emerging carbon specimens/nanostructures/nanomaterials.

Furthermore, Carbon Nanostructured Materials (referred to as CNMs) have received considerable attention because of their numerous uses in many domains (namely, environment, energy, biomedicine, water, and so on). The CNMs form various allotropes in different dimensions (namely zero-, one-, two-, and three-dimension) at the nanoscale, such as fullerene, carbon nanotubes (referred to as CNTs), graphene, and porous carbon/ diamond, respectively [7]. Moreover, carbon materials also have novel utilities due to their physical, chemical, optical, and electrical characteristics, which can be achieved through the architecture or assembly with different functional materials/nanomaterials [7]. The same material can be produced in several forms, such as oxide nanomaterials, carbon nano-coatings comprising functional metal elements, and graphene modified with carbon compounds.

To address new global concerns like environmental degradation, enormous energy production, and the need for improved agricultural and nutrition, novel technology solutions are needed. New advanced technologies must be developed to improve and automate operations that can independently monitor infrastructures, the environment, and process effectiveness in order to increase productivity while reducing the emission of pollutants [8 - 15]. The potential offered by sensing technologies has implications in this context.

NANOCOMPOSITES AND CARBON NANOSTRUCTURE MATERIALS

The demand for the commercial utilization of transformed carbon-based specimens is on the rise in today's technology-driven fields of agriculture, medicine, and the environment. Considering numerous characteristics exhibited by such carbon-based organisms, a group of researchers and businessmen has become highly concentrated, enabling the development of novel methods of manufacturing for significant industries [16]. One of the stimulating specimens with the ability to generate an extensive range of arrangements, typically with different qualities, is the element named “carbon” [17]. One or two of the most noteworthy allotropes of carbon are “soft” graphite and “hard” diamond [18].

In general, a composite material is a specimen that is formed from two/more constituent specimens. These element specimens have characteristics that are particularly distinct from the different constituents in terms of their physical or chemical composition. The various components become distinct and separate inside the completed structure, distinguishing composites from other interactions and solid solutions.

Multi-phase materials termed nanocomposites have at least one phase with a size in the nano range (10–100 nm) [19, 20]. Due to the high surface-to-volume ratio, contact between the matrix and reinforcement in nanocomposites is quite high. The characteristics of each component, the proportions between them, and the overall shape of the nanocomposites all affect how well they perform. In recent years, the scientific world has paid more attention to nanocomposite specimens. There are many phases in it, all of which have at least one, two, or three dimensions that are in the nanoscale range.

The innovative constituents of carbon elements are Carbon Nanotubes (CNTs), graphene, fullerenes, *etc*. They show excellent characteristics that serve as encouraging opportunities in rich application domains upon closer examination by the scientific industries because of their superior abilities. This element is therefore classified as an ensemble of “wonder materials” [21]. Fullerene, an allotropic form of carbon, is usually a chemical constituent of carbon. Sixty

CHAPTER 9

Evolution of Advanced Polymer-Based Nanogenerators for Energy Harvesting Applications

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Abstract: The burgeoning demand for sustainable and renewable energy solutions has accelerated advancements in Nanogenerators (NGs) based on polymers. These innovative devices harness piezoelectric, triboelectric, and pyroelectric effects for energy harvesting, offering transformative solutions in wearable electronics, biomedical applications, and the Internet of Things (IoT). With their unique ability to convert mechanical and thermal energies into electrical power, polymer-based nanogenerators exemplify the synergy between nanotechnology and material science. This review delves into the evolution of these devices over the last two decades, highlighting key advancements in materials, fabrication techniques, and application domains. Additionally, challenges such as scalability, energy conversion efficiency, and environmental impact are discussed alongside strategies for addressing these limitations. By emphasizing the sustainable potential of polymer-based nanogenerators, this work aims to provide insights into their role in the future of energy technology and their application in diverse fields, from healthcare to smart cities.

Keywords: Energy harvesting, IoT applications, Piezoelectric effect, Polymer-based nanogenerators, Sustainable technology.

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INTRODUCTION

The escalating global energy crisis and environmental concerns have prompted researchers to explore renewable energy harvesting technologies [1 - 3]. Traditional energy sources such as fossil fuels are rapidly depleting, and their continued use poses significant environmental challenges, including climate change, air pollution, and resource scarcity [4]. These issues have catalyzed the urgent need for alternative energy solutions that are not only sustainable but also adaptable to a wide range of applications [5].

Nanogenerators represent a groundbreaking approach in this domain, offering the capability to convert ambient mechanical, thermal, and other forms of energy into electrical power [6]. This ability to harvest energy from ubiquitous sources, such as human motion, environmental vibrations, and temperature gradients, positions nanogenerators as pivotal in addressing the growing energy demands of the modern world [7].

Polymer-based nanogenerators, in particular, have emerged as a promising subset of this technology due to their unique combination of properties [8]. Polymers are inherently lightweight, flexible, and cost-effective, making them suitable for applications in wearable electronics, biomedical devices, and the Internet of Things (IoT) [9]. Additionally, the ability to engineer polymers with tailored properties has enabled the development of multifunctional materials that combine energy harvesting with other functionalities, such as sensing and actuation [10].

Since their introduction in the early 2000s, polymer-based nanogenerators have undergone significant evolution, driven by advancements in material science, nanotechnology, and fabrication techniques [11]. Researchers have focused on enhancing the energy conversion efficiency, mechanical robustness, and environmental stability of these devices [12]. Innovative approaches, such as the incorporation of nanostructured fillers, hybrid composites, and advanced surface engineering, have propelled this field forward, enabling the realization of highly efficient and durable devices [13].

This review aims to provide a detailed examination of the evolution of polymer-based nanogenerators over the past two decades. It delves into the fundamental mechanisms underlying their operation, the innovative materials that have been developed, and the cutting-edge fabrication techniques that have enabled their deployment in diverse applications. Furthermore, this review highlights the challenges that remain in the field, such as scalability, energy output optimization, and environmental impact, while exploring future directions that can unlock the full potential of this transformative technology in addressing global energy challenges.

POLYMER-BASED NANOGENERATORS: MECHANISMS AND MATERIALS

Polymer-based nanogenerators operate primarily on piezoelectric, triboelectric, and pyroelectric principles. Each mechanism leverages specific material properties to convert mechanical or thermal energy into electrical energy [14].

Piezoelectric Nanogenerators (PENGs)

PENGs utilize piezoelectric polymers such as Polyvinylidene Fluoride (PVDF) and its copolymers. These materials exhibit high piezoelectric coefficients and mechanical flexibility [15]. Advanced fabrication techniques, including electrospinning and 3D printing, have enabled precise control over material morphology, enhancing energy conversion efficiency [16].

Recent innovations include the integration of nanoscale fillers such as carbon nanotubes, graphene, and metal oxides, which significantly enhance the piezoelectric response and mechanical durability of PVDF-based devices [17]. Additionally, the introduction of piezoelectric polymer blends and composite structures has improved the coupling efficiency, making these devices more efficient in converting mechanical stress into electrical energy (Fig. **1**) [18]. Research has also explored high-performance ferroelectric polymers to expand the range of applications in both flexible electronics and large-scale energy harvesting systems [19].

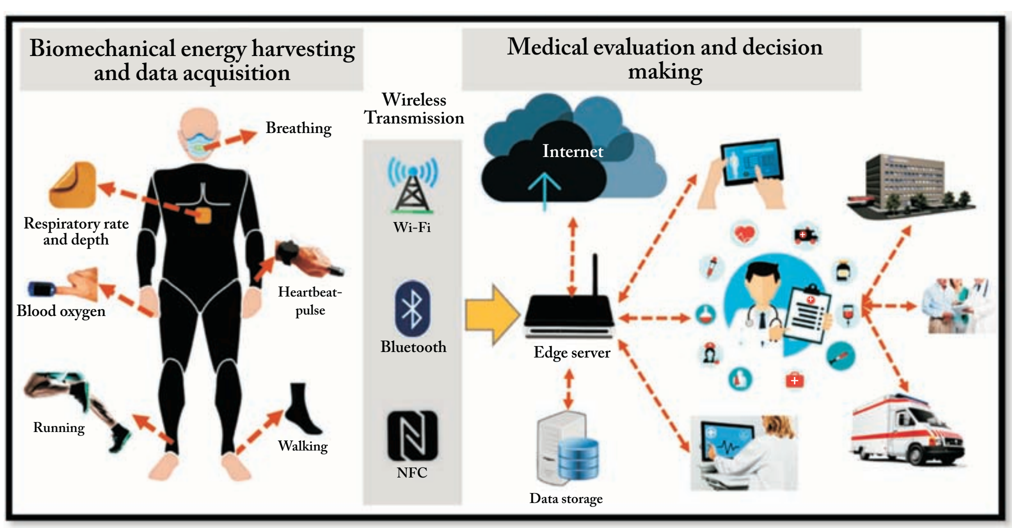

Fig. (1). Potential application of piezoelectric and triboelectric nanogenerators to change biomechanical energy into electrical energy [45].

CHAPTER 10

Polymeric Energy Materials: Development, Challenges, and Future Benefits for Industrialization

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Abstract: Polymeric active materials have emerged as a promising class of materials that will likely lead the way in energy conversion and storage. Materials such as conductive polymers, polymer composites, and polymer electrolytes are being processed to enhance energy-delivery devices like batteries, supercapacitors, and photovoltaic cells. The challenges in polymeric energy materials are related totheir stability, scalability, and behavior under extreme operating conditions. It calls for extraordinary solutions in designing materials, manipulating methods of processing the material, and enhancing properties like electrical conductivity, mechanical properties, and flexibility. The prospects for industrializing polymeric energy materials offer advantages because they can be engineered to be lighter, more efficient, and eco-friendly for energy delivery. These new materials, if incorporated successfully into commercially viable products, can lead to the fourth generation of energy materials needed for further development of sustainable energy and non-renewable resources such as fossil fuels.

Keywords: Conductive polymers, Energy conversion, Energy storage, Industrialization, Material development, Polymer composites, Polymeric energy materials, Solar cells, Supercapacitors, Sustainability.

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INTRODUCTION

Polymer energy materials can now be recognized as one of the emerging themes in the search for adequate energy supplies. These materials, including conductive polymers, polymer composites, and polymer electrolytes, are considered more promising substitutes for traditional inorganic materials in energy storage and conversion equipment [1]. The use of polymeric materials in energy technologies, such as batteries, supercapacitors, and solar cells, has attracted a lot of interest because of their inherent advantages of flexibility, lightweight nature, and potential for cost-effective manufacturing processes [2]. Namely, conductive polymers possess certain distinctive features, including high electrical conductivity, ease of processing, and ability to be tuned, all of which have contributed to the increasing use of conductive polymers as materials for next-generation energy devices [3].

Nevertheless, the application of polymeric energy materials in the field of development and industrialization has various problems. Some of the main concerns are the ability of these materials to perform stably in practical applications, the lack of a wide range of manufacturing approaches, and the high demand for efficiency in storage devices, such as batteries and supercapacitors [4]. The problem of optimizing the relationship between electrical conductivity and mechanical properties, as well as some questions related to environmental issues, remainsrelevant for investigators [5]. However, despite these challenges, the constant improvement of the material and its processing methods is gradually eradicating these barriers [6].

In emerging areas, polymeric energy materials have massive potential for industrial applications. As recent trends in nanotechnology, polymer blends, and hybrid systems dictate, such materials are expected to play a major role in the generation of further improved, cleaner, and more cost-effective energy technologies [7]. Specifically, it has been pointed out that there is an opportunity for developing novel energy storage devices that can pave the way for change in industries, starting with electronics and moving to transportation, through the use of easy-to-fold, lightweight, and flexible wearable electronics, mobile power sources, and skin-like solar cells [8]. While the problems are being investigated today, polymeric energy materials are likely to become the cornerstone for advancing the future of energy storage and conversion, providing new opportunities for industrialization and environmental sustainability [9].

POLYMERIC ENERGY MATERIALS: APPLICATIONS IN MODERN INDUSTRY

Thermoplastic energy materials have been widely incorporated into contemporary manufacturing industries due to their versatility, lightweight nature, and potential for cost-effective conversion [10]. These are polymers, polymer composites, and polymer electrolytes that are critical to different technologies involving theconversion, storage, and management of energy [11]. They are used in almost all industries, including electronics, the automotive industry, renewable energies, healthcare, and many more. In this section, we also cover key industrial applications of polymeric energy materials such as energy storage, energy conversion, flexible electronics, *etc*.

Energy Storage Systems

Polymeric energy materials have emerged as critical components for new-age energy solutions, especially in the design of batteries, supercapacitors, and fuel cells. Copolymer and polymer composites are widely used in lithium-ion batteries, supercapacitors, and other energy storage technologies because of their high electrical conductivity, flexibility, and ease of processing. Conductive polymers, such as PEDOT, PANI, and polyacetylene, are among the most researched polymers owing to their conductive and charge/discharge properties, which can improve energy storage systems [12]. To illustrate this, conductive polymer composites can be blended with battery electrodes to enhance cyclability, discharge capacity, and energy density.

Flexible and lightweight energy storage devices can be built without the need for solid-state electrolytes in supercapacitors by incorporating polymeric materials. Supercapacitors that can be bent should be utilized in wearable electronic devices and portable gadgets because size and flexibility play a vital role in these products [13]. Conductive polymers combined with carbon-based nanomaterials exhibit good charge/discharge abilities, long cycling stability, and energy density, which primarily enhance the supercapacitor's performance [14]. The use of such materials in large-scale energy storage applications for grid-scale storage is also being investigated, which is beneficial for the use of renewable energy storage systems [15]. This chapter also explores theinterconnections among polymeric composites, bioeconomy, and Amazonian residues. With sections representing important components, including chemical interactions, sustainable resource management, material reuse, and the production of novel materials, the study illustrates the role of human activity in sustainable development, as studied in the literature [16].

CHAPTER 11

Enhanced Energy Harvester Performance by a Tension-Annealed Carbon Nanotube Yarn at Extreme Temperatures

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Abstract: Carbon Nanotubes (CNTs) are nanoscale cylindrical structures composed of carbon atoms with diverse applications in supercapacitors, artificial muscles, and intelligent textiles. An Incandescent Tension Annealing Process (ITAP) can significantly enhance their mechanical and electrochemical properties, improving energy harvesting capabilities. The experimental observations reveal that during the 1 Hz sinusoidal stretching cycle, the peak-to-peak Open Circuit Voltage (OCV) and Short Circuit Current (SCC) generated by ITAP yarn were more than 1.5 times that of pristine CNT. The densified surface of ITAP yarn results in about a 20% reduction in capacitance when it is stretched to about 30% strain. A noticeable negative shift in the values of the potential of ITAP yarn suggests greater charge injection when immersed in the electrolyte. Thus, the factors—namely, the pronounced changes in capacitance and the increased initial charge injection—are key contributors to the enhanced energy harvesting performance of ITAP yarn compared to untreated CNTs.

Keywords: Carbon nanotubes, Incandescent tension annealing process, Open circuit voltage, Short circuit current.

INTRODUCTION

CNTs have good electrical and thermal conductance with exceptional mechanical properties. Its nanoscale-based properties make it an ideal candidate for manufact-

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uring lightweight and flexible fibers, potentially overcoming the issues of bulkiness, heaviness, and low-density power output associated with conventional electromagnetic devices [1]. CNT yarns are currently produced in different continuous processes using a variety of important technologies, such as liquid-state and dry-state techniques [2 - 5]. Yarns spun from spinnable nanotube forests have excellent mechanical strength, low impurities, a strong nanotube line-up, and novel structural versatility. Twisting these yarns increases their strength, making them behave as high-strain conductors and high-performance artificial muscles for torsion and tension [6].

The ITAP process involves heating a vertically suspended nanotube yarn from a two-point suspension through a current of about 20,000 A cm^{-2} in a vacuum. This treatment solves several problems existing in single-coil CNTs due to the weak interfacial connection between adjacent nanotubes present in yarns [7].

1. Except under tension, coiled and twisted strings tangle.
2. To avoid irreversible untwisting, CNT yarns should be torsionally tethered as actuatable muscles. Some non-actuating parts are needed for torquing back; these non-actuating parts give spring action.
3. The strength of twisted nanotube yarns is still some orders of magnitude below that of the individual nanotubes.

Hence, many practical applications of CNT yarns are opened up by ITAP [8 - 10]. Therefore, it becomes essential to introduce more mechanical bonding inside the structure of the yarn because it offers both twist retention and mechanical strength [11, 12]. We are focused on precisely controlling the parameters of the Incandescent Tension Annealing Process (ITAP) itself to ensure reproducible performance for yarns treated under specific conditions. We describe the controlled conditions applied during the process, which are fundamental to achieving consistent results. The yarns were heated to a specific, extreme temperature of about 2000 °C. This was typically achieved by applying an electrical current (electrothermally). Temperature measurement methods were used, including spectroscopic measurements calibrated by resistance for smaller yarns, highlighting efforts to accurately control this parameter. The duration of the high-temperature treatment was controlled. Major property improvements were observed within seconds, and a standard annealing time of 2 minutes was typically employed for optimal results, as longer times could degrade properties. However, in this chapter, we have described the experimental methods and characterization techniques used for the specific samples studied; it does not detail quality control measures or data analysis methods used to verify consistency, which have yet to be explored.

An understanding of the working mechanisms for converting mechanical energy into electrical energy becomes a prerequisite for improved performance of CNT-based twist-based harvesters [13 - 16]. CNTs act as electrodes upon immersion in an electrolyte and cause the ionic species to adsorb onto their accessible surface area naturally through self-charge injection, driven by the chemical potential difference between the carbon atoms of the polymer and the ionic species within the electrolytes [3]. Mechanical deformation, such as twisting or coiling, decreases the available surface area, causing self-charge redistribution and alteration of capacitance [17 - 20]. According to the relation:

$$\Delta V = \frac{Q}{\Delta C}$$

where ΔV is the change in potential, Q is the total injected charge, and ΔC is the change in capacitance. This means that the variation of capacitance directly impacts the potential with fixed Q [21]. Strategies to modify the electrochemical surface area, such as infiltration with polymers or irradiating carbon double-walled nanotubes, often compromise its conductivity and restrict power output. High-temperature annealing corrects structural flaws to enhance conductivity and strength, though its effect on electrochemical capacitance has not yet been ascertained [22 - 25].

The ITAP significantly enhances the mechanical properties. Neat coiled yarns tend to untwist, whereas ITAP-treated yarns remain stable and straight and show minimal untwisting, demonstrating enhanced structural integrity. The process is described as solving issues of weak interfacial connection and improving twist retention as well as mechanical strength. The ITAP was developed to stabilize twisted and coiled CNT yarns, preventing irreversible untwisting, which was a problem for pristine yarns used in applications like artificial muscles. ITAP-produced inter-nanotube connections act as internal springs, allowing for fast, reversible, torsional, and tensile actuation without needing external springs or torsional tethering. The long-term stability of ITAP-treated yarns under repeated mechanical or electrochemical stress is discussed in terms of their observed reversibility and performance during cyclic testing. The ITAP-treated yarns exhibit significant stability under repeated mechanical and electrochemical stress. Reversible torsional and tensile actuation is achieved with guest-free ITAP yarns in response to vapor absorption and desorption cycles. Unlike pristine yarns, which untwist irreversibly, the ITAP-produced inter-nanotube connections act as internal springs, enabling these yarns to retwist after untwisting, thereby solving the problem of unwanted untwisting for torsional actuators. For example, when subjected to a load causing untwisting, an ITAP-30 yarn is fully retwisted upon

CHAPTER 12

Energy Harvesting: Innovating Advanced Technologies Through Polymer Nanocomposites

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Abstract: The demand for renewable and sustainable energy sources has made energy harvesting a crucial field of study. This study examines cutting-edge energy harvesting technologies with an emphasis on the application of polymer nanocomposites. Combining polymers with nanoscale components to create polymer nanocomposites offers special benefits such as improved thermal stability, electrical conductivity, and mechanical qualities. Because of these qualities, they are good candidates fordeveloping energy harvesting devices that effectively transform ambient energy sources—such as mechanical, thermal, and solar energy—into electrical energy that can be used. The review examines many processes for creating polymer nanocomposites and how they are used in energy harvesting devices. The usefulness of methods like electrospinning, solution casting, and melt blending in improving the efficiency of energy harvesting devices is highlighted. The electrical characteristics of polymer matrices are greatly enhanced by the use of nanoparticles, such as metal oxides, graphene, and carbon nanotubes, which raises energy conversion efficiency. The study also looks at certain energy harvesting uses for polymer nanocomposites, such as solar cells, thermoelectric devices, and piezoelectric generators. These materials are positioned as competitive substitutes for conventional energy harvesting technologies due to their ability to provide flexible, lightweight, and long-lasting energy harvesting devices. It is observed from the review study that by demonstrating the revolutionary potential of polymer nanocomposites in energy harvesting applications, the ongoing developments in materials science and nanotechnology open the door to the creation of novel solutions that can make a substantial contribution to the worldwide effort to achieve sustainable energy, tackling the problems brought on by environmental concerns and energy demand. Future research should concentrate on improving these technologies' scalability and performance to allow for broad adoption across a range of industries.

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Keywords: Energy harvesting devices, Nanocomposites, Polymer, Sustainable energy.

INTRODUCTION

The need for energy to sustain transportation, industrial development, and quality of life increases with an increase in the human population. Currently, the main sources of energy for the ecosphere are natural resources like coal, oil, and petroleum gas. Vestige fuels, on the other hand, have disadvantages like short supply, rapid depletion, and environmental issues, such as air or water pollution [1]. Low-cost, clean, and renewable energy sources are therefore highly desired. Notable decisions are being taken to develop sophisticated techniques for transforming solar, wind, or thermal hydropower energy into affordable electricity [2, 3]. One of these technologies that has received a lot of interest is organic Photovoltaics (PVs), which directly convert sunlight into power. Every year, the sun's energy illuminates the planet with approximately 3×10^{24} J, which is 10^4 times more than the world's entire energy consumption. The entire planet can be powered with just 0.10% of the Earth's surface covered with solar cells that are 10% productive. PV-generated electricity only makes up 0.1% of the world's energy production, despite its huge potential [4 - 6]. The Power Conversion Influence (PCE) has significantly improved as a result of advancements in modern light-emitting materials, creative device design, the emergence of applied science or nanotechnology, and breakthroughs in material blends (in the form of composites or copolymers) or the design of Organic-Based Photovoltaic (OPV) devices. Research on energy generation is a global concern that has a significant impact on both industrialization and the everyday quality of live in contemporary civilization. Finding sustainable power sources with lower carbon emissions and renewable energy technologies is crucial for green economics and the healthy advancement of human civilization in light of the current environmental degradation and global energy constraints. Furthermore, as the world enters the era of fifth-generation wireless networks (5G) and the Internet of Things (IoT), a variety of self-powered electronics are thought to be the fundamental components of the upcoming industrial revolution that will lead to a smarter world. A sustainable power supply solution is required to meet the demands of the future intelligent world, where traditional batteries are struggling because of their short lifespan, environmental impact, and frequent replacement. This is due to the advanced characteristics of electronic devices, which include miniaturization, light weight, and portability. The only way to overcome these problems is to create gadgets that can harvest energy from their environment. Mechanical-to-electrical energy transduction is a viable method for powering tiny devices, as mechanical energy is one of the most abundant and pervasive forms of energy in the environment. Numerous energy harvesting technologies, such as Electromagnetic (EM) induction, piezoelectric effect, and electrostatic effect, have previously been developed. In order to overcome these drawbacks, Zhong Lin Wang created the Triboelectric Nanogenerator (TENG) in 2012. Since then, it has garnered international attention and experienced substantial advancements, emerging as a promising technology for energy harvesting, particularly in the field of Nanoenergy and Nanosystems (NENS) [7].

The most versatile materials available today are polymers, finding applications in countless areas due to their unique properties. Among the essential benefits are flexibility, cost-effectiveness, processability, environmental stability, lightweight design, and tailorability. As early as the fifth century, polymers were discovered to be electrically insulating materials. Among other things, polymers have been used as switches, insulating gloves, electrical wire insulating covers, and a shielding layer on an electronic circuit pane [8]. These saturated polymer systems are isolating by nature due to the long covalent carbonchain. To move electrons from the valence to the conduction band in these kinds of polymers, the molecular orbital bandgap must be more than 10eV [9]. Consequently, the surface electric resistance of insulating polymers is often more than 10^{12} Ω-cm. Since conducting performance is contained within the appearance of a polymer, the elasticity of polymer materials is increased. Two primary methods canalso be used to create the physical phenomenon of conductivity in polymers [10], which is characterized by π-electron coupling in polymers and polymer composites of conducting nanoparticles (carbon nanotube, graphite, metal and inorganic hybrid salt, *etc*.) with insulating polymers. The primary one is known as an "intrinsically conducting polymer", and the other is known as an "ion-conducting polymer". Composites of polyethylene oxide compounds [11], polyethylene adipate [12], polyethylene succinate [13] with lithium salts, as well as polyacetylene, polyaniline, polypyrrole, *etc*., are examples of ion-conducting polymers [14]. Intrinsically conducting polymers are recognized as "synmet" or "synthetic metal" because they incorporate some particular metallic properties, such as conductivity and resistivity [15]. Since three scientists (Prof. Alan G. MacDiarmid, Prof. Alan J. Heeger, and Prof. Hideki Shirakawa) were awarded the Nobel Prize for the creation and enhancement of electrically conducting polymers in 2000, interest in this area has significantly expanded [16]. Conjugated double-bond polymers are electrically conductive. Lightly bound π-electrons in the conjugated polymer have the ability to delocalize along the polymer chain [17]. As a result, the conjugated polymers have a lower bandgap.

There are several covalent bonds in a chain of π-electron conjugated polymers. Every carbon atom or heteroatom undergoes sp^2 hybridization when a conjugated polymer chain is formed. It shows that all other p-orbitals continue to exist parallel to one another, whereas one unhybridized p-orbital per atom stays vertical to the polymer chain. Consequently, the p-orbitals are delocalized throughout the

CHAPTER 13

A Brief Overview of Energy Harvesting in Advanced Sustainable Polymers

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Abstract: Energy harvesting represents a transformative strategy for capturing ambient energy and converting it into usable electrical power, thereby enabling the operation of electronic systems without reliance on conventional energy supplies such as batteries or wired connections. Polymers have emerged as a pivotal class of materials in this domain owing to their structural versatility, tunable properties, and potential alignment with sustainability goals. With the growing global demand for renewable and decentralized energy solutions—particularly for autonomous, wireless, and portable electronics—polymer-based energy harvesters are gaining increasing prominence. Sustainable polymers, derived from renewable or recycled precursors, offer distinct advantages including mechanical robustness, corrosion resistance, and biodegradability, thus meeting both environmental and economic imperatives. Nevertheless, conventional synthetic polymer production and disposal practices remain environmentally unsustainable, exacerbating resource depletion and pollution. To address these limitations, current research is advancing the development of polymers engineered within closed-loop life cycles to minimize ecological burden. Emerging innovations, such as photovoltaic-integrated sound barriers, polymer-based nanomaterials, thermoelectric generators, and induction-driven energy systems, highlight the expanding scope of polymer applications in this field. This chapter concludes by critically evaluating key challenges—most notably the enhancement of energy conversion efficiency, scalability, and techno-economic viability—while underscoring the pivotal role of advanced sustainable polymers in shaping the next generation of energy harvesting technologies.

Keywords: Biodegradability, Energy harvesting, Polymer-based devices, Renewable energy, Sustainable polymers.

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INTRODUCTION

Energy harvesting, broadly defined, is the process of capturing and converting ambient energy—derived from sources such as solar radiation, wind, thermal gradients, and mechanical vibrations—into usable electricity for powering electronic systems. Against the backdrop of rising global energy consumption and its adverse implications for energy security and environmental sustainability, energy harvesting technologies have emerged as indispensable strategies for sustainable power generation. Often referred to as "energy scavenging," these systems capitalize on otherwise wasted or underutilized energy—including temperature fluctuations, ambient vibrations, or human motion—while ensuring efficient storage and regulated delivery, particularly in low-power or off-grid applications. Unlike narrow definitions restricted to transducer-level conversion, energy harvesting can be more comprehensively viewed as an integrated approach encompassing energy capture, storage, and power management to provide electricity in scenarios where conventional energy infrastructure is impractical or inefficient [1].

A wide spectrum of energy sources has been explored for this purpose, ranging from environmental vibrations and water vapor motion to atmospheric sunlight and even biological systems such as the human body. Recent advances in materials science have introduced hyperbranched polymers capable of photon absorption and inward energy transfer, mimicking capacitor-like behavior for efficient energy storage. Similarly, kinetic energy from vapor-driven motion and piezoelectric responses from structural vibrations have opened new avenues for harvesting dispersed ambient energy. Collectively, these innovations highlight the potential of polymeric and nanostructured materials to enhance efficiency and sustainability in energy conversion processes [2]. The impetus for energy harvesting research has been further strengthened by the rapid proliferation of wireless technologies and autonomous devices. Conventional batteries, with their limited lifespans, environmental hazards, and frequent replacement requirements, are poorly suited for long-term or remote applications. In contrast, energy harvesting enables wireless sensors and distributed devices to operate autonomously over extended durations, even in hostile or inaccessible environments. The integration of compact harvesters with advanced power management units not only reduces dependence on bulky conductors but also enhances the feasibility of remote operation, thereby disrupting conventional paradigms of energy sourcing [2].

As depicted schematically (Fig. **1**), a typical energy harvesting system comprises three fundamental components: (i) the harvester, responsible for converting ambient energy into electrical signals; (ii) a power management circuit, which regulates and conditions the output; and (iii) an energy storage module or direct load connection. While the architecture remains broadly similar across platforms, the specific technologies employed—such as photovoltaic, thermoelectric, piezoelectric, or triboelectric transducers—determine overall efficiency and applicability. Ongoing research is thus increasingly directed toward improving conversion efficiency, miniaturization, and cost-effectiveness, with particular emphasis on polymer- and nanomaterial-based solutions.

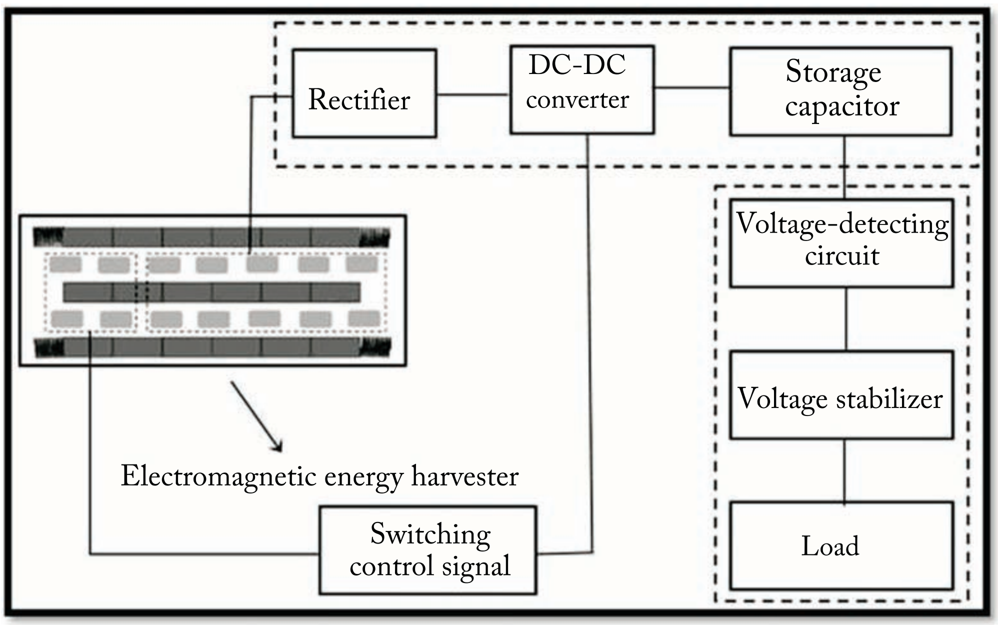

Fig. (1). Block diagram of an energy harvesting system [3].

SIGNIFICANCE OF SUSTAINABLE POLYMERS IN MODERN ENERGY APPLICATIONS

As shown in Fig. (**2**), energy harvesting enables the use of ambient energy sources to power small electronic devices. These sources include industrial heat, heat from vehicles (such as buses and motors), and even energy from the human body. Energy transducers convert this ambient energy into usable electrical power. The primary goals of energy harvesting are to extend the lifespan of energy storage devices, minimize the frequency of battery recharges, and ultimately eliminate the need for battery replacement or dependence on traditional power lines. One of the earliest large-scale applications is in building automation, particularly in self-powered light switches, commonly known as piezo switches. Future applications include structural health monitoring of large infrastructures and condition

CHAPTER 14

Biobased Resorbable Polymeric Nanocomposites for Sustainable Healthcare Applications

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Abstract: Biobased resorbable polymeric nanocomposites are the biggest breakthroughs in the search for green and eco-friendly healthcare compounds. These biobased materials incorporate biodegradability characteristics with good mechanical, thermal, and biological properties, which are attributable to the nanoscale reinforcements. These nanocomposites help meet the fast-emerging need for green and biocompatible materials in applications such as drug delivery systems, tissue engineering scaffolds, and medical implants. Their ability to not cause any harm upon being metabolized in the human body and maintain their structure during their utilitarian lifespan keeps their environmental footprint and healthcare visitors' waste level to a bare minimum. This paper aims to review the state of existing knowledge, limitations, and opportunities associated with the use of resorbable polymeric biobased nanocomposites in healthcare to establish them as a part of the sustainable future in medical technology.

Keywords: Biobased polymeric nanocomposites, Biodegradable polymers, Nanotechnology, Resorbable materials, Sustainable healthcare.

INTRODUCTION

Anticipating the growing importance of ecological materials and resources in contemporary medical practice, the healthcare industry has spurred a significant advancement in the biosynthesis of resorbable polymeric nanocomposites based

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on biobased materials [1 - 3]. These are new materials derived from renewable biological resources, which are unique and environmentally friendly as opposed to petroleum-based polymers [4]. Polymers, mainly obtained from renewable sources, are classified into biodegradable and non-biodegradable categories [5].

Among other polymers, resorbable polymers are equally preferable for uses in medicine since they can disintegrate in the body and do not need to be surgically removed [5]. As a result, they can be left in the human body for long periods as they end up being medical waste [6]. Polymeric nanocomposites are developed by identifying a nanoscale filler, which, when added to the biobased polymers, results in improved mechanical strength, thermal stability, and biological performance [7]. The combination of biobased polymers and nanotechnology enables the design and development of materials that conform to the strict test requirements of a medical device while also addressing sustainable environmental and application needs [8]. The application of these nanocomposites include drug delivery to control the release of therapeutic substances and tissue engineering scaffolds that enable cell growth and regeneration [9].

Additionally, the use of polymeric nanocomposites in medical products helps reduce the product's environmental impact; these polymeric nanocomposites break down into harmless substances after use [10, 11]. This biodegradability is of paramount importance for minimizing the stockpiling of medical waste and lessening the effects on the environment caused by disposable medical products [11]. However, there are some issues that require further investigation, including the maximization of the degradation rates, controlling the mechanical properties, and fabrication at a commercial scale [12, 13]. These issues must be addressed in order to properly integrate biobased resorbable polymeric nanocomposites into clinical practice. This chapter presents general features of the importance of biobased resorbable polymeric nanocomposites to enhance sustainable healthcare solutions [14]. With the help of renewable resources and nanotechnology applications, these materials provide a unique opportunity for the development of environmentally friendly yet high-performance medical materials.

BIOBASED RESORBABLE POLYMERIC NANOCOMPOSITES

The everyday emerging environmental and biomedical demands require healthcare to embrace sustainable materials. In these, biobased resorbable polymeric nanocomposites have proven to be revolutionary materials because of their biocompatibility, degradability, and increased functionality [15]. This chapter delves into the basic concepts and their development, ushering the reader through the possibilities of these materials, together with their weaknesses and the contemplated options for the future [16]. Biobased resorbable polymeric nanocomposites are nanocomposite materials that can be synthesized using renewable resources and are biodegradable and non-toxic in physiological environments [17]. Such materials are special in healthcare applications because biobased polymers are biodegradable, while nanoscale reinforcements improve structure and function [18]. This synergy has made them usefulin the development of drugs, engineering of tissues, and the production of medical implants [19]. This provides another stimulus for developing biopolymers that are dispatched worldwide, such as PLA and PHA, which can be functional with the help of nanotechnology. The study findings are relevant to the UN's Sustainable Development Goals (SDGs) regarding resource consumption and production in healthcare [20].

PLA, PHA, and Polycaprolactone (PCL) are examples of biopolymers that provide the basis of these composite materials [21]. These polymers are produced from renewable resources, for instance, corn starch and sugarcane, and through microbial feeding processes [22]. This reduces environmental problems associated with disposal, and in medical applications, the surgical expulsion of materials used is not required due to their non-biodegradability [23]. Nanofillers, such as nanoclays, carbon nanotubes, and hydroxyapatite, increase the mechanical properties, thermal properties, and biological activity of polymers. These nanofillers are also used to control the degradation rate of the composites to suit a given biomedical application [23, 24]. Resorbable polymeric nanocomposites based on biopolymers are a common element in controlled-release drug delivery systems. For instance, it is possible to develop nano clay-PLA composites that present effective drug delivery of anti-inflammatory medicines, with a reduced percentage of side effects and increased patient compliance [25]. There is increasing utilization of biobased nanocomposites in tissue engineering scaffolds because of their biocompatibility and promotion of cell attachment, growth, and differentiation. Nanocomposite scaffolds of PCL-hydroxyapatite have the potential to be used in bone tissue engineering [26]. Biodegradable implants, such as screws and plates prepared from poly lactic acid-carbon nanotube composites, have the benefit of degrading in the body if their function of holding the bone together is served without having to remove them through another operation [27].

APPLICATIONS IN HEALTHCARE

The uses of biobased resorbable polymeric nanocomposites in the healthcare field are broad and impactful, meeting modern medical needs while aiming for a greener world. Below are detailed explorations of their applications across various domains:

CHAPTER 15

Carbon-Based Nanocomposites (CBNs) for Environmental Energy Harvesting Applications

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Abstract: Rapid urbanization has a significant impact on various components of the environment, putting stress on energy reservoirs. These effects targeting human health risks, in particular, include air pollutants, wastewater load, poor sanitation, *etc*. Unsustainable urbanization has also led to a surge in energy requirements for domestic, industrial, road, and transport use. To address such issues, different methodologies have been employed to treat different wastewater types, remove gaseous pollutants, and develop technological interventions that lead to energy harvesting. In recent years, among several approaches, Carbon-Based Nanocomposites (CBNs) have been recognized by the scientific community in several fields, including energy and the environment, because of their increased "surface area to volume ratio", good chemical stability, higher conductivity, reduced toxicity, high dispersibility, excellent thermal, mechanical, and electrical properties, cost-effectivity, facile synthesis, the scope of surface functionalization, biocompatibility, *etc*.

This chapter draws attention to the application of various Carbon-Based Nanomaterials (CBNs) (such as polymer nanocomposites, graphene, Graphene Oxide (GO), reduced GO (rGO), graphite, activated carbon, *etc*.) (i) for the detection of heavy metals, pesticides, bacteria, *etc*., in contaminated water and their efficient removal, (ii) for the degradation and removal of organic species from wastewater, (iii) as environmental sensors for detecting toxic gases, and (iv) as mechanical sensors and energy-harvesting devices. Further, the latest developments, current challenges, and future scope of research in CBNs for enhanced environmental and energy-harvesting applications have also been discussed.

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Keywords: Carbon-based nanocomposites, Environment, Energy conversion, Energy storage, Wastewater.

INTRODUCTION

The major driving forces aiding water pollution include unsustainable urbanization, population growth, rapid industrialization, poor sanitation, climate change, *etc* [1]. Every day about two million tons of industrial, sewage, and agricultural waste are globally discharged into the water [2]. The major types of contaminants associated with water pollution include organic, inorganic, radiological, and biological, which are categorized into natural (higher than acceptable limits of nitrate, fluoride, arsenate, chloride, *etc*.), anthropogenic (heavy metals, dyes, pesticides, antibiotics, paints, oils, detergents, *etc*.), and pathogenic microbes (like viruses, bacteria, parasitic protozoa, and worms) [2]. As per the WHO, about 80% of human diseases are linked to water pollution [1]. Some of the reported diseases include cancer (liver, lungs, kidney, prostate, bladder, nasal passages, skin, *etc*.) and non-cancer ailments (diarrhea, vomiting, nausea, stomach pain, typhoid, severe headaches, cholera, skin discoloration, numbness in feet and hands, blindness, partial paralysis, *etc*.) [2]. The different techniques mentioned in the literature for the removal of physicochemical contaminants and disinfection of water from microbial pathogens are physical (sedimentation, filtration, boiling, distillation), chemical (chlorination, adsorption, coagulation, ozonation, flocculation), and biological methods (biologically-activated carbon, bioremediation, *etc*.). The above-mentioned techniques of wastewater treatment have both advantages and limitations. Apart from this, the magnitude of the problem is so vast that the above-mentioned selective treatments are not enough. Under such circumstances, exploring cost-effective and novel techniques for wastewater treatment has become a priority.

Nanotechnology-inspired routes have recently attracted attention among researchers, and in this direction, different types of CBNs (Fig. **1**) are prominent candidates due to their excellent structural and surface properties [3]. The diverse applications of CBNs are attributed to their high thermal conductivity, physical strength, current density, electronic conductivity, electron mobility, affinity binding, surface area, strong adsorption, ion absorption, catalysis support, light weight, strong and slim structure, metallic/semi-conductive properties, *etc* [4].

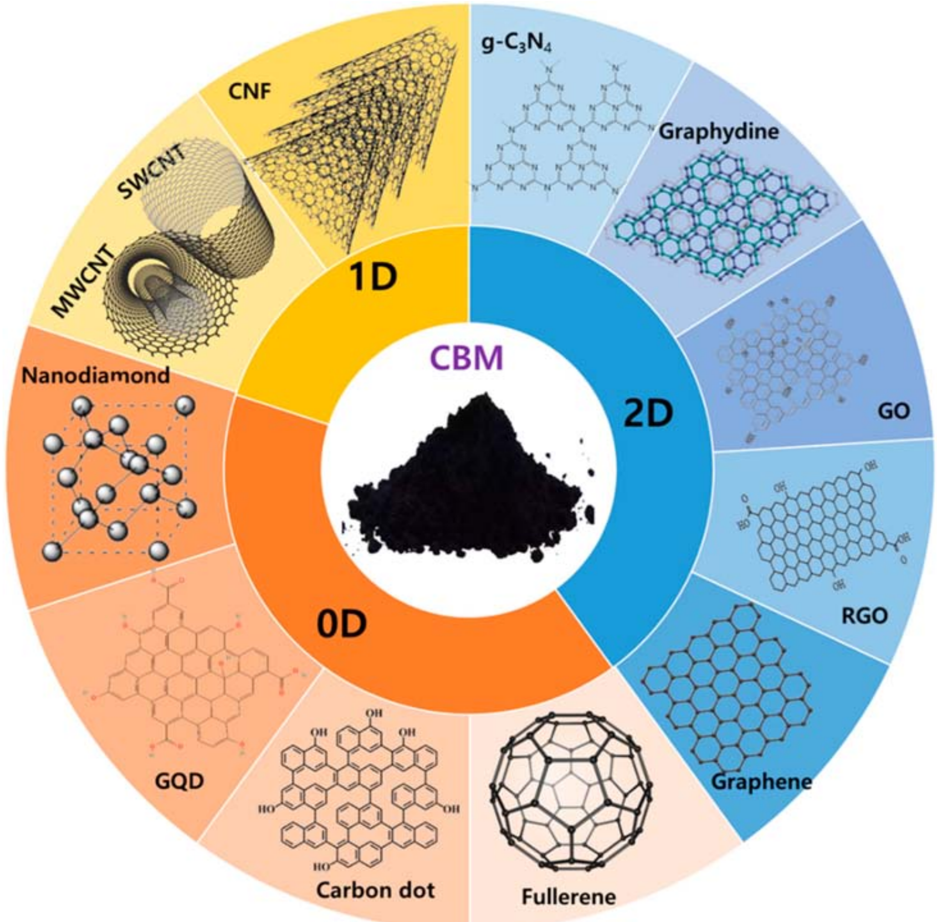

Fig. (1). Types of carbon-based materials [7].

Composites made of Graphene-based NMs (GNMs) can be used to absorb various water contaminants, including colors, heavy metals, antibiotics, and pesticides [5, 6]. The biocompatibility, pH sensitivity, and improved surface properties of CBNs qualify them as potential antimicrobial agents for water decontamination. Several studies have been reported on CBNs decorated with noble metals (Au, Ag, Pt, Pd, *etc*.) for enhanced heterogeneous photocatalysis, leading to the efficient treatment of dye-contaminated textile effluents. Carbon-based hybrid materials offer superior antimicrobial and photocatalytic properties compared to pure metal/metal oxide Nanomaterials (NMs). The capacity to manipulate the composition, structure, and morphology of CBNs to modify their attributes further enhances their performance and expands their application possibilities. Hence, developing

CHAPTER 16

Recent Advancements in Metal Oxide Nanocomposites for Energy Harvesting Applications

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Abstract: This chapter examines the latest developments in metal oxide nanocomposites and their uses in energy harvesting devices. The chapter begins with a brief overview of metal oxide nanocomposites, emphasizing their makeup and importance in improving energy conversion processes, including thermoelectric, solar, and piezoelectric ones. A thorough review of current developments exposes cutting-edge synthesis methods and the advantages of nanostructuring, which enhance the performance and characteristics of materials. Several forms of metal oxide nanocomposites are classified in this chapter, emphasizing the widely used materials such as ZnO, TiO_2, and SnO_2, along with novel hybrid systems that blend metal oxides with polymers or other materials for improved performance. A detailed discussion is also included regarding the fabrication processes and characterization methodologies that evaluate the performance of these nanocomposites, highlighting their potential applications in solar energy, waste heat recovery systems, and wearable technology. Additionally, the drawbacks and restrictions of metal oxide nanocomposites, including scalability and material stability, are also addressed in this chapter. Emerging materials and their potential integration into smart energy systems are highlighted below, along with future trends and research directions. A case study shows its practical applications and is included in the chapter's conclusion, along with consideration of these materials' sustainability and effects on the environment in the current situation. By comparing metal oxide nanocomposites with other nanomaterials, we highlight the advantages of these materials as well as potential market trends. This comprehensive study thus aims to shed light on the ground-breaking significance that metal oxide nanocomposites play in the search for durable and efficient energy harvesting technologies.

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Keywords: Characterization methodologies, Fabrication processes, Hybrid systems, Metal oxide nanocomposites, Nano structuring, Piezoelectric, Thermoelectric, Wearable technology, Waste heat recovery.

INTRODUCTION

Energy plays a crucial role in the creation and upkeep of almost everything around us. However, the production and consumption of energy account for two-thirds of global greenhouse gas emissions. In order to meet the constantly rising global energy demand, it is vital that we explore clean, affordable, and alternative energy sources, especially due to the impending depletion of fossil fuels like coal, oil, and gas. Additionally, the release of greenhouse gases such as methane and carbon dioxide by the industries, and the re-release of toxic organic pollutants like textile dyes, pharmaceutical contaminants, and antibiotics into the water system, pose serious environmental issues, which further cause water pollution, irreversible global warming, and climate change [1]. At the same time, ensuring access to energy is vital for enhancing economic development and quality of life, particularly in underdeveloped parts of the world. Currently, there is a global shift towards renewable energy resources, such as solar and wind energy, to achieve these particular goals. However, the difficulty in shifting away from fossil fuels lies in the efficient and economical harvesting and storage of energy generated from renewable resources. Unfortunately, renewable energy sources cannot be fully exploited at the time of their production and are intermittent in nature. Therefore, there arises an urgent need for effective energy storage systems in order to make green energy a viable option for the future [2]. Therefore, research is being done on nanocomposites, which are materials that incorporate nanoparticles (usually smaller than 100 nm) into a bulk matrix to improve the composite material's characteristics. These nanomaterials have special properties such as greater surface area, improved mechanical strength, enhanced electrical and thermal conductivity, and superior chemical stability compared to their bulk counterparts. Nanocomposites are very appealing for a variety of applications, especially in energy harvesting technologies, because the addition of nanoparticles to the matrix can result in synergies that improve the material's overall performance. The objective of energy harvesting is to transform ambient energy such as mechanical, thermal, or light energy into useful electrical power. In this context, nanocomposites are extremely useful as they may modify their properties to fit various energy conversion methods, thus improving efficiency and performance [3].

The development of energy harvesting systems, which rely on the efficient conversion of various energy sources, including vibrations, temperature gradients, and sunlight, into electrical power, is greatly aided by nanocomposites. These composites can harvest energy in a variety of ways, especially those having thermoelectric, photocatalytic, or piezoelectric characteristics. For instance, thermoelectric nanocomposites use temperature variations to produce power, whereas piezoelectric nanocomposites can transform mechanical vibrations or pressure into electrical energy. In contrast, photocatalytic nanocomposites are employed for the conversion and storage of solar energy. Considering the size, shape, and composition of the nanoparticles can be precisely adjusted to maximize the energy conversion process, nanocomposites are extremely adaptable for a range of energy harvesting applications [4, 5]. Among the most studied materials for energy harvesting are metal oxide-based nanocomposites because of their superior stability, electrical conductivity, and catalytic qualities. It has been demonstrated that adding metal oxide nanoparticles, such as ZnO, TiO_2, and CuO, to polymer matrices greatly increases the effectiveness of energy conversion devices. Energy harvesting systems perform better in terms of energy efficiency, mechanical durability, and environmental stability due to the cooperation of metal oxides and nanostructured materials [6]. Additionally, improved charge generation, transport, and storage are made possible by the nanoscale contact between the matrix and the nanoparticles, which improves device performance overall.

INTRODUCTION TO NANOCOMPOSITES IN ENERGY HARVESTING

Energy harvesting stands as a crucial innovation in sustainable energy generation, converting ambient environmental energy into usable electrical power. As global energy demands surge and renewable sources gain prominence, these systems are attracting widespread attention. They harness energy from diverse sources motion, vibration, heat, and light to fuel wearable technology, sensors, and compact electronic devices, making them indispensable in the push toward a more efficient and eco-friendly future [7].

Nanocomposites advanced materials that blend nanoparticles with other materials to increase their properties are among the most promising materials for energy harvesting. Nanocomposites are ideal for energy harvesting applications because of their special qualities, which include their high surface area, customized electrical conductivity, and flexibility. Because of their exceptional stability, broad availability, and tunable electronic and optical properties, metal oxides in particular have attracted a lot of interest in the field of nanocomposites. These qualities make them perfect candidates for a variety of energy conversion processes, such as photovoltaic, thermoelectric, piezoelectric, and triboelectric applications [7].

CHAPTER 17

Current Developments and Future Perspectives of Magnetic Nanocomposites for Advanced Applications

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Abstract: Magnetic nanocomposites have become increasingly important materials in distinct fields in terms of application and potential, such as biomedical engineering, environmental chemistry, energy storage, and the electronic industry. These materials incorporate characteristics of nanoparticles with the structural benefits of composite matrices, including high thermal stability, magnetic responsivity, and multi-functional properties. Recent advancements have been determined by improvements in synthesis methods, performance, and modified properties for various uses. Advancements in biomedical applications, such as drug targeting, magnetic hyperthermia, and biosensors, point towards a revolutionary future for healthcare. At the same time, they are becoming more involved in clean energy technologies such as supercapacitors and catalysts in the process of energy conversion. Machine learning for property prediction is another area that needs to be focused on, and the development of novel green synthesis methods is the major future research direction. This paper presents an analysis of magnetic nanocomposites and, additionally, future developments that suggest advancements in various fields with various challenges to combating world issues.

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INTRODUCTION

Magnetic nanocomposites are a group of novel materials that incorporate magnetic nanofillers into different matrix materials, offering a range of functionalities and stimuli-sensitivity for targetted applications. These magnetic nanoparticles mainly include Iron Oxide (Fe_3O_4), cobalt ferrite, or nickel /nickel-based materials, featuring superparamagnetism, high coercivity, or other stronger magnetic responses when the material is in nano-dimensions. These properties become even more desirable when incorporated into polymeric, ceramic, or metallic structures, thereby creating some of the most superior mechanical, thermal, and magnetic composites [1].

The high demand for smart materials with improved characteristics has led to a focus on research on magnetic nanocomposites [2]. These technologies have numerous uses in various industries, such as biomedical engineering for application in drug delivery, magnetic hyperthermia therapy, and biosensors. They act as good adsorbents for water treatment and as promoters of pollutant degradation in environmental science. Furthermore, these materials are increasingly being applied in batteries and supercapacitors, where the electrical conductivity and magnetic nature improve energy density and storage [3].

It is possible for molecules to be adsorbed on the surface or embedded in the coating [4]. Specific developments in synthesis processes, including sol-gel processes, hydrothermal methods, and green synthesis methodologies, enable researchers to control the size, shape, and composition of magnetic nanocomposites [5]. This development and use of artificial intelligence and computational modeling studies on material design help in predicting the best composition of nanoparticles and matrices for changes [6]. Furthermore, the development of new greener synthesis methods that apply bioinspired green chemistry for the formation of materials and devices fits perfectly into the contemporary global shift towards sustainable chemistry in materials science [7, 8].

However, there are some limitations regarding scalability, cost efficiency, and magnetic nanocomposite stability under operating conditions. The future work will be focused on these problems and further development of these prospects in new trends, including flexible electronics, wearable sensors, and advanced energy systems. The following paper presents current advancements in magnetic nanocomposites, focusing on their characteristics, synthesis techniques, and utilization. It also covers the difficulties and trends, emphasizing their indispensable function in sophisticated technologies and environmentally friendly initiatives.

Higher colloidal stability and potential surface modification by functional, reporter, and targeting molecules (such as vitamins, nucleic acids, and antibodies) are typically provided by polymer shells [9].

MAGNETIC NANOCOMPOSITES IN TARGETED DRUG DELIVERY

Target therapy is one of the radical prospects for increasing the efficiency of medications and decreasing unwanted effects, and magnetic nanocomposites are one of the most promising materials within this field [10]. These materials make use of the particle magnetic properties, for instance, iron oxide wrapped within biodegradable gels, to guide the release of the drug under the influence of an external magnetic field [11]. In this context, we are concerned with discussing the potential, mechanisms, and improvements of targeted drug delivery using magnetic nanocomposites, based on several studies.

Nanocomposites are characterized by an ability to target tissues or organs because of their magnetic features. In the presence of an outward magnetic field, the magnetic nanocomposites containing the required drugs can be guided to the desired location and, therefore, concentrate the required doses at the target tissue with minimal exposure to the rest of the organism [12]. It can respond to various stimuli such as pH, temperature, or enzymatic activity once the drug delivery has been localized and controlled [13].

Magnetic nanocomposites are prepared through the incorporation of magnetic nanoparticles, for example, Fe_3O_4, within biocompatible polymers, lipids, or silica matrices. The synthesis methods, such as co-precipitation, solvothermal techniques, and green synthesis, enable this composite to possess high magnetic saturation, stability, and biocompatibility [14]. Moreover, organic tailoring by ligands, antibodies, or peptides can be employed to produce selected interactions with required cells or tissues of the nanocomposites [15].

In oncology, particularly, magnetic nanocomposites have been revealed to hold a lot of potential where there is a need to deliver drugs to tumor regions accurately [16]. For instance, Fe_3O_4-based magnetic nanocomposite systems for the delivery of chemotherapeutic drugs like doxorubicin show enhanced anti-tumor effects with low side effects [17]. Also, magnetic nanocomposites enable magnetic hyperthermia, where a local temperature established by an alternating magnetic field increases the effectiveness of chemotherapy by affecting the cancer cell membrane. The last few years have been marked by the development of the versatile applicability of magnetic nanocomposites [18]. Such carriers of materials

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