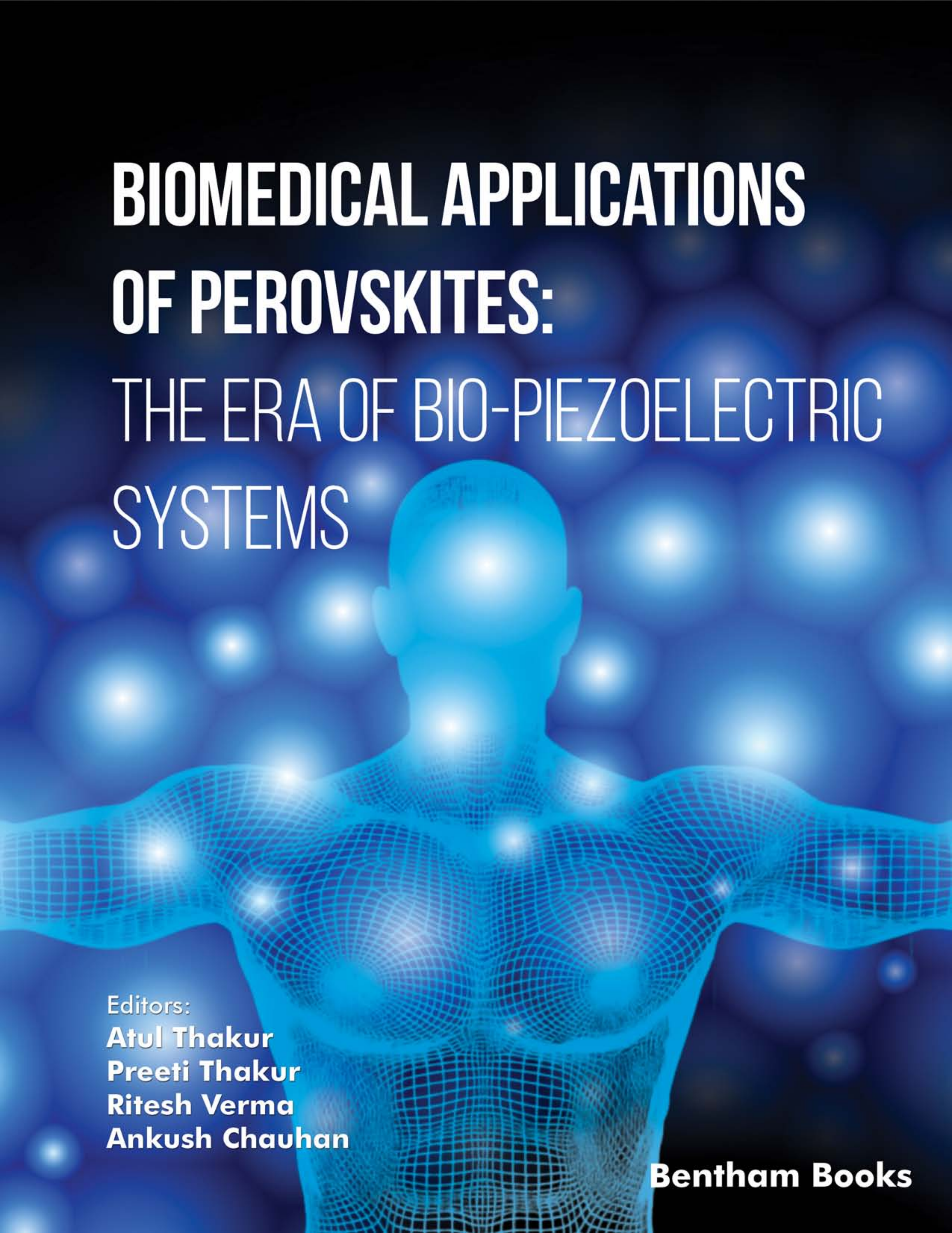

BIOMEDICAL APPLICATIONS OF PEROVSKITES:

THE ERA OF BIO-PIEZOELECTRIC SYSTEMS

Editors:

Atul Thakur
Preeti Thakur
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Biomedical Applications of Perovskites: The Era of Bio-Piezoelectric Systems

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ISBN (Online): 978-981-5256-38-3

ISBN (Print): 978-981-5256-39-0

ISBN (Paperback): 978-981-5256-40-6

Published by Bentham Science Publishers Pte. Ltd. Singapore.

First published in 2024.

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PREFACE

In the present era, self-powered technology and smart materials have paved the way for the design of several biomedical applications. Piezoelectric is a class of materials that could generate an electrical output on the application of strain or stress. Perovskite compositions are the best-known and the largest group of ferroelectric and piezoelectric materials. The book **“Biomedical Applications of Perovskites: The Era of Bio-Piezoelectric Systems”** focuses on the recent progress made in the area of piezoelectric systems and their applications. More specifically, this book focuses on various piezoelectric materials, device designs, and possible applications in the field of medical science. The future challenges and the roadmap for piezoelectric perovskite materials are discussed in this book. This book systematically explains the piezoelectric perovskite materials, starting from their introduction, their structure, synthesis techniques and their applications in the field of medical science, where the uses of piezoelectric perovskites have been discussed in different chapters.

This book explains the key devices, such as pacemakers, nanogenerators, *etc*, that are made up of perovskite materials. The biocompatibility of perovskite materials has also been discussed along with the cell response of these materials. This book also explains the applications of perovskite materials in bone regeneration and growth, bone replacement, tissue engineering, dental science, neurotrauma and neurodegenerative treatment and bionic prostheses in the form of various chapters. Herein, the issues that the biomedical industry is facing in terms of perovskite materials are also discussed. Thus, through this book, every possible application of the perovskite materials has been discussed.

This is a kind of unique book because in this book various experts of the related field have shared their expert opinion in the form of chapters. Each chapter is unique and provides insightful information so that researchers can innovate in a particular field and provide a better solution. Each chapter is a hot topic of research, and using the information in this book, one can pursue research for the development of new materials for the biomedical industry.

Editors would like to thank each of the authors for their valuable contributions to the book.

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CHAPTER 1

Introduction to Piezoelectric Perovskites

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Abstract: Perovskite (Calcium titanium oxide), which was discovered in 1839 by Perovski, a Russian mineralogist, has some favorable photophysical characteristics that enable perovskite and its nanocrystals to be used in the field of biomedical research. Presently, perovskites are being explored for various medical applications, including X-ray detection and imaging, cancer treatment, orthopedic implants and as antimicrobial agents. Advancements in nanocrystal research allowed the exploration of perovskites for their antibacterial, antifungal and antiviral activity against Severe Acute Respiratory Syndrome Corona Virus 2 (SARS-CoV-2). The antibacterial activity of several perovskite nanoparticles was explored, and to mention a few, Cesium lead bromide and zinc oxide perovskite nanoparticles showed activity against *Escherichia coli*, while Lanthanum potassium ferrate and silver-based perovskites against *Staphylococcus aureus* and *Pseudomonas aeruginosa*. This chapter will review the potential research studies that explored the anti-microbial activity of perovskites and their nanoparticles against bacteria, viruses, fungi and other microorganisms and provide insight into the mechanisms by which these particles exert antimicrobial action. Further, this chapter will discuss the potential biomedical applications of the antimicrobial activity of perovskites.

Keywords: Anti-microbial, Antiviral, Antibacterial, Antifungal, Air purification, Antimicrobial coatings, Biomedical applications, Nanomaterial, Nanocrystal, Perovskites, Water purification.

1. INTRODUCTION

1.1. Piezoelectricity

Piezoelectric materials have the capacity to produce a potential (electric) in reaction to a mechanical movement or piezoelectric effect (direct) in response to an inverse piezoelectric effect (Fig. **1**). Many applications have made use of this class of smart materials, mainly in the fields of communications and information,

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industrial automation, and medical diagnosis, *etc*. Transducers, sensors, actuators, imaging devices, ultrasonic motors, nano-positioners, and other similar devices are examples of typical uses. The brothers Pierre Curie and Jacques made the initial finding of the piezoelectric effect in 1880 [1, 2]. These creative forerunners discovered that certain crystals (inorganic), like quartz, tourmaline, Rochelle salt, topaz, and sugarcane, accumulated an electrical charge when mechanical stress was applied and that the voltage generated by the material was proportional to the mechanical stress. The direct piezoelectric effect (Fig. **1(a)**) is the phenomenon that connects strain (mechanical action) to an electrical reaction (displacement, polarization, or electric field). Afterward, the piezoelectric effect (inverse) was also verified experimentally through observations made of acentric symmetry in single crystals (Fig. **1(b)**), where an external field (electric) caused the crystal to mechanically respond by causing strain or stress in the sample.

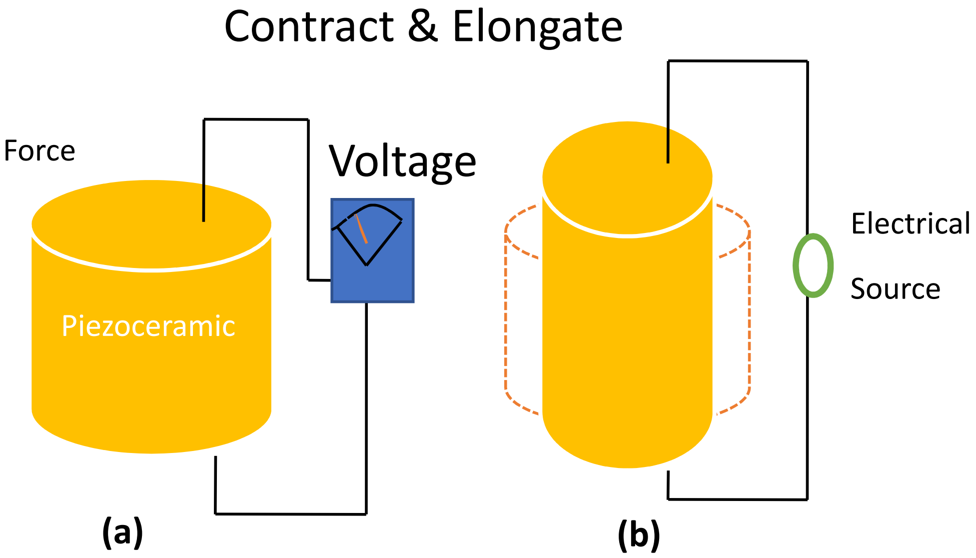

Fig. (1). (**a**) The direct piezoelectric effect, and (**b**)inverse piezoelectric effect.

2. PIEZOELECTRIC MATERIALS

The sonar detector, which was produced initially in the 1st World War, was the first significant piezoelectric device application. P. Langevin and his colleagues started developing a submarine detector (ultrasonic) in 1917. The hydrophone detector was used to listen for audio echoes, and a thin quartz transducer expertly bonded among two steel plates (whose resonance frequency was around 50 kHz). The gadget was housed in a casing made to withstand immersion in salt water [3]. After the war, they kept working toward their objective, which was to use a transducer to create a sound pulse of high-frequency and then how long it took for the pulse to bounce off a submerged item. With this knowledge, it was possible to determine how far away the submerged object was from the pulse's origin. Since the success of this effort had sparked broad interest in piezoelectric devices and materials, none of the industrial nations had ignored the strategic significance of their accomplishment. New piezoelectric components, tools, and applications were created and used during the ensuing decades. There are multiple applications of perovskites in the electronic industry, such as detectors, actuators, inkjet, Quantum dot Light Emitting Diodes, *etc.* [4 - 6].

It was discovered by inaccessible research teams in the USSR, Japan, and US during World War II that some ceramic materials made by sintering metallic oxide powders had dielectric constants (r) that were up to 100 times larger than those of ordinary quartz crystals. Ferroelectrics are a new class of artificial ceramic materials that have piezoelectric (d_{33}) constants that are significantly greater than those of natural materials [3]. Ferroelectrics show similar behavior as that of ferromagnetism in magnetic materials [7]. Due to this development, there is now a lot of research being done to create ceramics piezoelectric with certain qualities for multiple applications [8 - 10]. The ceramic (BT) $BaTiO_3$ was found to have a large ε_r of 1100, which is ten times greater than the maximum documented ε_r value for rutile TiO_2 at the time of its invention. A phonograph pickup that was created in 1947 was the first commercially available product made of BT. A historical turning point in piezoelectric research was thought to have been reached in the 1950s with the finding of $Pb(Zr_{1-x}Ti_x)O_3$ or $(1-x)PbTiO_{3-x}PbZrO_3$ ceramics, which are commonly exploited and utilized piezoelectric materials [1]. The ensuing research on the binary system established the significance of position-induced phase transitions on piezoelectric behavior, highlighting the significance of the MPB (morphotropic phase boundary) concept [11]. In $PbTiO_3$ (PT), ultrahigh piezoelectricity, single crystal piezoelectric and exceptional electromechanical coupling capabilities were found between the 1980s and 1990s [12]. When compared to traditional piezoelectric ceramics, these have a 3 to 10 times higher piezoelectric effect. Numerous studies have been conducted on relaxor-PT single crystals, which exhibit a large piezoelectric constant and high electro-mechanical coupling factors that are thought to be closely related to designed domain topologies [12, 13]. The study of relaxor-PT single crystal ferroelectrics has advanced significantly in recent years due to their exceptional features. Lead is a very poisonous substance that can harm a person's kidneys, brain, and nervous system, as is common knowledge. PZT use has increased, which has led to more harmful lead being released into the environment. As a result, international governments have passed legislation outlawing the utilization of lead-contained materials in the production of a variety of goods. PZT was classified as a hazardous material by the European Union in

CHAPTER 2

Techniques for the Synthesis of Piezoelectric Perovskites

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Abstract: Perovskite structures have strong piezoelectric properties, making them suitable for a wide range of applications such as sensors, energy harvesting devices and actuators. The chapter examines numerous synthesis procedures, including co-precipitation, hydrothermal, solid-state reaction, the Pechini process, sol-gel auto-combustion, low temperature, and pulsed-laser decomposition. Each technique's principles, benefits, limits, and special concerns are given, along with instances of successful perovskite synthesis. Furthermore, the chapter examines current advances and upcoming trends in the area, offering insights into the future direction of piezoelectric perovskite synthesis.

Keywords: Co-precipitation, Hydrothermal, Low temperature, Piezoelectric, Perovskite, Pechini, Pulsed- laser decomposition, Structure, Solid-State reaction, Sol-Gel auto-combustion.

1. INTRODUCTION

Piezoelectric materials have attracted significant attention from both academic and industries due to their interesting traits and broad applications, including some recent interesting advancements. A piezoelectric material exhibits electric polarization when subjected to mechanical stress along a specific direction. Similarly, whenever this material is subjected to an electric field, it undergoes mechanical distortion. Certain piezoelectric materials also possess pyroelectric properties, and some of these materials are additionally ferroelectric. Advanced materials have become essential in modern development, particularly in the sectors of information and communications, industrial automation, medical diagnostics, wastewater management, high-frequency devices, and so on [1 - 4]. Ceramics, polymers, and synthetic single crystals are among the materials utilized

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in piezoelectric technology. However, among these materials, perovskite-based compounds have appeared as extremely favorable contenders due to their exceptional piezoelectric performance.

Perovskite is a yellow, brown, or black mineral with the chemical formula $CaTiO_3$. It gets its name from the mineral calcium titanium oxide [5]. Perovskite compounds have a standard formula ABX_3. A and B are cations, while X is an anion that binds to both. X is usually oxygen, although other large ions such as halides, sulfides, and nitrides are also possible [6 - 9]. Perovskite oxides possess a cubic or near cubic structure in their ideal state, analogous with other transition metal oxides having a similar formula (ABO_3) [10, 11]. The perovskite structure is highly versatile and can accommodate a wide range of elements, providing tunability in terms of properties and functionalities. Perovskite-based piezoelectric materials exhibit superior piezoelectric coefficients, excellent electromechanical coupling, high Curie temperatures, and enhanced mechanical stability, making them ideal for a multitude of applications. The synthetic procedures utilized to create perovskite materials have a profound influence on their characteristics. Different synthesis procedures can alter the purity, crystallinity, morphology, grain size, and orientations of perovskite materials, which, in turn, affects their electrical, mechanical, thermal, and optical properties [12]. Also, the large-scale production of piezoelectric perovskite materials largely depends upon the scalability, ease of use and cost efficiency of the different synthesis approaches. In conclusion, studying different synthesis techniques for piezoelectric perovskite materials is vital for optimizing material properties, understanding structure-property relationships, ensuring scalability and reproducibility, exploring process flexibility, and discovering new materials. This knowledge is invaluable for advancing the field of piezoelectric materials and facilitating their integration into a wide range of technological applications.

In this book chapter, we will delve into various synthesis techniques, including sol-gel, co-precipitation, solid-state, hydrothermal, and pulse laser deposition, among others. Each technique possesses distinct advantages and limitations. By analyzing the synthesis techniques and their underlying mechanisms, we can gain valuable insights into optimizing the fabrication processes and ultimately enhancing the performance and production of piezoelectric materials. This book chapter aims to serve as a comprehensive guide for researchers, engineers, and material scientists interested in the synthesis of piezoelectric perovskite materials. Through a critical examination of the synthesis processes, we aim to shed light on the importance of synthesis techniques and emphasize the need to explore and compare various methods such as sol-gel, co-precipitation, solid state, hydrothermal, and pulse laser deposition in the context of fabricating piezoelectric perovskite materials.

2. SYNTHESIS TECHNIQUES

Various chemical and physical synthesis processes can be utilized for the fabrication of materials, in particular, nanosized materials [13, 14]. Traditional ceramic methods that utilize solid phase reactions at high temperatures are commonly used to make these materials. These types of methods have several difficulties due to the frequent grinding and heating of metal oxides or the equivalent salts prior to calcination [15]. These limitations include product inhomogeneity, the existence of flaws that interfere with luminescence, the presence of chemical particles *via* repeated grinding and heating methods, and particle coarseness that makes them unsuitable for coatings [16]. In order to obtain pure materials, several new techniques have been created to enhance existing synthesis procedures and get around these drawbacks. These techniques include solid-state reactions, co-precipitation, the Pechini method, hydrothermal synthesis, low-temperature solution combustion, sol-gel method, and PVD techniques [17, 18].

2.1. Co-precipitation Method

The co-precipitation method is a synthesis approach used to create materials, notably nanoparticles and nanocomposites, by precipitating numerous precursor chemicals from a solution at the same time [19 - 22]. Controlled mixing of aqueous solutions containing the necessary metal ions or compounds results in the production of solid particles. To begin the co-precipitation procedure, separate precursor solutions containing the appropriate metal ions or compounds are prepared [23]. These precursor solutions are often aqueous solutions of metal salts or metal-organic compounds that, upon dissolution, break into ions. The precursor solutions are then mixed, either by gently putting one solution into the other or by injecting them both into a reaction vessel at the same time [24]. To guarantee adequate homogeneity and the development of a homogenous precipitate, the mixing process should be carefully managed. Metal ions or compounds in the precursor solutions react and generate insoluble compounds or complexes when mixed.

This process results in the precipitation of solid particles, which are frequently colloidal suspensions or precipitates. Temperature, pH, and the concentration of the precursor solutions can all have an effect on the precipitation process. These parameters are changed to regulate precipitate nucleation and growth and to achieve the appropriate particle size and shape. Surfactants, stabilizers, or complexing agents can also be added to the precursor solutions as part of the co-precipitation technique. These additives serve to regulate particle size, reduce agglomeration, and increase the stability and dispersibility of the resultant

CHAPTER 3

Structural Analysis of Piezoelectric Perovskite Materials

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Abstract: Perovskite (Calcium titanium oxide)was discovered in 1839 by Alekseevich Perovski, a Russian mineralogist. Perovskites are materials with the same structure as calcium titanium oxide ($CaTiO_3$) mineral or you can say that all the materials with the same structure as $CaTiO_3$ are perovskites. The basic structure of perovskite is ABX_3, where the A-site is generally occupied by large twelve coordinated cations and B by smaller, octahedrally coordinated cations, and X is a common anion, for instance, Oxygen. A cation is divalent and B is tetravalent cation. Tilting of BO_6 octahedra through B-O-B linkage results in rhombohedral, orthorhombic and tetragonal structures. The structure of perovskites can be modified by doping and altering synthesis techniques, such as by changing pH value, calcination temperature, and calefactive velocity. Perovskite materials have a wide range of applications in different fields, such as solar cells, photodetectors, sensors, water purification, *etc*.

Keywords: Air purification, Anti-microbial, Antiviral, Antibacterial, Antifungal, Nanomaterial, Nanocrystal, Perovskites, Biomedical applications, Water purification, Antimicrobial coatings.

1. INTRODUCTION

In solid-state materials, oxides have several kinds of structures. Different kinds of oxides are mentioned in Table **1**.

The class of oxides known as “perovskites” has taken the spotlight amongst a variety of solid-state materials. The majority of the mass of planet Earth is made up of perovskite ($MgTiO_3$, a mineral composed primarily of the elements magne-

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sium, silicon, and oxygen [1]), making it the most easily accessible element in the universe. Nobody has yet extracted a sample from the Earth's mantle to demonstrate that it contains the many types of perovskite structures that are thought to make up the mantle.

Table 1. Representation of different kinds of known oxides.

Structure Type	Applications	Examples
Garnet	Water jet cutting	$Fe_3Al_2Si_3O_{12}$
Olivine	Refactory Material	$(Mg,Fe)_2SiO_4$
Fluorite	Camera Lens	CaF_2
Rutile	Aircraft Engine Parts	TiO_2
Perovskite	High-temperature thermal barrier coatings	$(Na,Ca)_2Nb_2O_6(OH.F)$
Spinel	Storage devices	$ZnFe_2O_4$
Ilmenite	Artificial human body parts	$(Fe,Ti)_2O_3$

The ringwoodite spinel structure of the silicate material olivine converts into a perovskite structure at extremely high pressures [1]. As shown in Fig. (**1**)., perovskite is a substance with the same crystal structure as calcium titanium oxide, which was the first perovskite crystal to be identified in 1839. The chemical formula for perovskite compounds is basically ABX_3, where 'A' and 'B' stand for cations, and 'X' is an anion that bonds to both of them. Perovskite structures can be created by combining a variety of various components. Physicists and chemists frequently refer to it as the “113 structure” because of the proportion of the components in its chemical formula (1:1:3). Perovskite crystals can be designed to have a wide range of electrical, physical, and optical properties using this compositional flexibility [2]. Due to their special characteristics and possible uses, perovskite materials have attracted a lot of interest in the field of piezoelectricity. A number of factors, such as crystal structure, symmetry, and piezoelectric coefficients, must be taken into account in order to undertake a structural study of piezoelectric perovskites [3 - 6]. Perovskites can be synthesized by a number of methods such as solid-state reaction technique, sol-gel auto combustion technique, hydrothermal technique, chemical or physical vapor deposition, and alkoxide-hydroxide sol precipitation method [7 - 10].

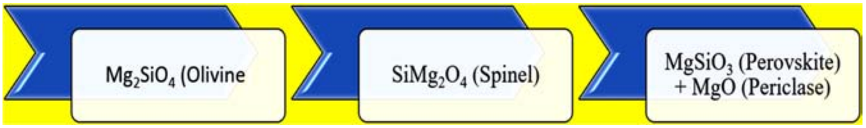

Fig. (1). Transformation of silicate material from olivine to perovskite structure.

2. PEROVSKITE MATERIALS

Calcium titanate ($CaTiO_3$), commonly referred to as perovskite, is a natural compound made up of magnesium, oxygen, and calcium [11]. Perovskites refer to the class of solid-state materials that have a calcium titanate structure. The mineral was discovered for the first time by Gustav Rose in the Ural Mountains and was given the name perovskite in honor of the renowned Russian mineralogist Count Lev Alekseevich Perovski (1792-1856). The advancement of perovskite structure and uses throughout its history is given in Table **2**. A material with a general formula ABX_3 and a similar crystallography structure as the original mineral calcium titanate is said to have a perovskite structure. The elements that typically occupy the A or B cationic positions are indicated in the periodic table in Fig. (**2**). It can be observed that practically all elements, with the exception of those that are typically either in a gaseous or liquid state, can occupy one of these two locations in the perovskite structure.

Table 2. Evolution of perovskite materials.

Year	Scientist/Institution	Discovery
1839	Gustav Rose (Berlin, Germany)	$CaTiO_3$ was discovered
1892	H.L. Wells, G.F. Campbell, P.T. Walden and A.P. Wheeler/ Sheffield Scientific School (New Haven, Conn.)	Prepared compounds made from halides in aqueous solutions with cesium, lead, and other elements.
1947	Philips (Eindhoven, the Netherlands)	Developed barium titanate for use in condenser production
1952	G. Parravano	Perovskite introduced into catalysis
1955	Western Electric (New York, N.Y.)	Described the production of electromechanical transducers using ferroelectric crystalline oxides with perovskite structures.
1957	C.K. Moller/ Chemical Laboratory at the Royal Veterinary and Agricultural College (Copenhagen, Denmark)	Examined the compounds created by H.L. Wells and his associates and discovered that they have a perovskite structure.
1957	Siemens (Munich, Germany)	Invented resistors made of barium titanate
1959	Clevite (Cleveland, Ohio)	Perovskite materials were added to the process of making piezoelectric resonators for electromechanical filters.
1962	A.E. Ringwood/ Australian National University (Canberra, Australia)	Proposed that the Earth's lower mantle is made primarily of $MgSiO_3$ perovskite.
1964	Compagni e Generale d'Electricité (Paris, France)	Solid electrolytes for fuel cells based on perovskite were produced.
1971	Corning Glass Works (Corning, N.Y.)	Perovskite oxides were reported to be used as frits for glass-ceramic products.

CHAPTER 4

Ferroelectric and Piezoelectric Response of Perovskites

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Abstract: Perovskite materials, with their unique properties and distinct crystal structure, have proven themselves as one of the most promising materials for various advanced technological applications. The exploration of ferroelectric and piezoelectric materials has gained significant attention in the field of condensed matter physics and materials science, and consequently, it is giving an edge to nanoengineered materials. This book chapter presents a comprehensive exploration of the ferroelectric and piezoelectric response exhibited by perovskite materials based on their crystal structure and other governing properties. The chapter begins with an introduction to perovskite structures, highlighting their crystallographic arrangement and the underlying principles governing their ferroelectric and piezoelectric behaviors. Finally, the chapter explores the diverse technological applications enabled by the unique ferroelectric and piezoelectric properties of perovskites. It discusses their utilization in sensors, actuators, energy harvesting devices, memory storage, and other emerging fields. The chapter concludes with an outlook on future directions and challenges in the field. The extensive study of the ferroelectric and piezoelectric response of perovskites will serve as a valuable resource for researchers, engineers, and students seeking to understand the underlying principles, characterization techniques, and potential applications of perovskite material.

Keywords: Bismuth ferrite, Dielectric, Energy harvesting, Ferroelectric, Ginzburg-Landau theory, Perovskite, Lead-free ceramics, Piezoelectric, Pyroelectric, Polarization, Titanates.

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1. INTRODUCTION

1.1. Overview of Perovskite Materials and their Structural Characteristics

A family of materials known as perovskite materials displays the characteristic perovskite crystal structure. Initially observed in the mineral calcium titanate ($CaTiO_3$), this structure was later shown to be displayed by a number of synthetic substances as well. Perovskite materials have drawn a lot of interest recently because of their extraordinary qualities and possible uses in a variety of industries, such as solar cells, LEDs, sensors, and catalysis. Perovskite compounds have the generic formula ABX_3, where 'A' and 'B' are cations and 'X' is an anion. The 'A' cation is usually a bigger, positively charged ion, such as an alkali metal (for example, Cs+, methylammonium, or formamidinium), whereas the 'B' cation is frequently a smaller, transition metal ion. The 'X' anion is often an oxygen ion (O_2) but can also be a halide ion (such Cl-, Br-, or I-) or a mixture of both [1 - 4]. The BX_6 octahedra that make up the perovskite crystal structure are arranged in three dimensions, with each 'B' cation surrounded by six 'X' anions in octahedral coordination. These octahedra connect to one another at their corners to create a three-dimensional network. The cavities between the octahedral network are where the 'A' cations are located.

Although distortions may happen as a result of events like the 'A' and 'B' cations' sizes not matching, this arrangement results in a cubic crystal structure. The capacity of perovskite materials to undergo numerous structural alterations by adding substitutions or doping is one noteworthy property. Due to their flexibility, perovskite derivatives with a variety of structures and functions have been found, allowing for fine-tuning of their properties. The additions of mixed cations or anions, as well as the substitution of various transition metals for 'B' cations, are a few frequent changes. High dielectric constants, ferroelectricity, semiconducting behavior, and superior light absorption are only a few of the many advantageous characteristics of perovskite materials [5]. These qualities make perovskite solar cells very appealing for photovoltaic applications, where they have demonstrated astounding power conversion efficiencies that challenge those of conventional silicon-based solar cells. Perovskites have also shown potential performance in a variety of electrical and optoelectronic applications, including light-emitting devices, catalytic reactions, and other electronic processes. Perovskite materials, despite their exceptional characteristics, also have limitations, such as stability issues, sensitivity to moisture and heat, and potential toxicity issues with some lead-containing perovskites [6]. To get beyond these restrictions and increase the stability, dependability, and scalability of perovskite-based systems, researchers are working hard [7]. In conclusion, perovskite materials are a group of substances that share a unique crystal structure called the perovskite structure.

They offer a variety of characteristics and hold a lot of potential for use in solar cells, LEDs, sensors, and catalysis. Perovskites have a lot of potential, but there are a lot of obstacles in the way of practical application. Ongoing research and development aim to overcome these obstacles.

1.2. Importance of Ferroelectric and Piezoelectric Properties in Perovskites

Ferroelectric and piezoelectric properties play crucial roles in perovskite materials and have significant implications for a wide range of applications. Ferroelectric materials exhibit a spontaneous electric polarization that can be reversed by applying an external electric field. Perovskites with ferroelectric properties have several key applications, such as in non-volatile memory devices, electro-optic devices, energy harvesting, *etc*. The ability of ferroelectric materials to retain polarization states even when the electric field is removed makes them suitable for non-volatile memory devices, such as ferroelectric random-access memory (FeRAM) devices [8]. FeRAMs offer fast access times, low power consumption, and high endurance compared to other memory technologies. Ferroelectric perovskites can be used in devices such as electro-optic modulators, where the polarization can be manipulated by an electric field to control the transmission of light. These devices find applications in telecommunications, data communications, and optical computing. These materials can convert mechanical energy into electrical energy through the piezoelectric effect, making them suitable for energy harvesting applications. They can be used to develop self-powered sensors, wearable devices, and systems that scavenge energy from vibrations or mechanical deformations in the environment.

On the other hand, piezoelectric materials generate an electric charge in response to applied mechanical stress and, conversely, undergo mechanical deformation when subjected to an electric field. Perovskites with piezoelectric properties have important applications in various fields, such as actuators and sensors, energy harvesting, biomedical applications, *etc*. Piezoelectric perovskite materials can be employed in actuators to convert electrical signals into mechanical motion or in sensors to convert mechanical stimuli into electrical signals. They are used in precision positioning systems, microelectromechanical systems (MEMS), ultrasound transducers, and pressure sensors [9 - 11]. Energy harvesting: The piezoelectric effect allows perovskite materials to harvest mechanical energy from vibrations, motions, or strain in the environment. This energy can be utilized to power small electronic devices, wireless sensors, or low-power systems in applications where conventional power sources may not be easily accessible. Biomedical applications: Piezoelectric perovskites find applications in the biomedical field, such as ultrasound imaging, drug delivery systems, and tissue engineering. They are used in medical imaging devices, therapeutic devices, and

CHAPTER 5

“Perovskite”: A Key Material for the Biomedical Industry

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Abstract: Perovskite materials are well-known for their remarkable thermal, optoelectronic, and magnetic capabilities. This chapter examines current advances in the study of biological applications involving perovskites. This chapter looks at how organic-inorganic hybrid perovskites can be used for X-ray detection and imaging. This can be achieved by switching to Cs^+-cations or MA+/Cs+ alloyed motifs, which not only widen the band gaps but also enhance the structural stability of perovskite materials. The future research direction should focus on fabricating large-area and thick 2D perovskite absorbers on thin-film transistor arrays through compatible printing (polycrystalline) and self-assembled (monocrystalline) methods to achieve X-ray detectors and imagers with high sensitivities and responsivities. The detailed material phases of $La_{0.7}Sr_{0.3}Mn_{0.98}Ti_{0.02}O_3$ perovskite nanoparticles have not been unambiguously elucidated due to inaccurate relative compositions of metal cations. Therefore, insightful structural analysis of the material is needed for confirmation of the magnetically thermally active phase. In the case of perovskite La_2NiMnO_6 nanoparticles, their ability to desorb BSA protein molecules has not been studied, which is required to fully comprehend the binding/detachment dynamics of enzyme reactions. Finally, the future research direction of $CaTiO_3$-based composites is to further understand their structure-property relationships under more complicated chemical environments with variations in temperature, pH, and pressure, given their promising biocompatibility and cytotoxicity.

Keywords: Anti-microbial, Antifungal, Antiviral, Antibacterial, Antimicrobial coatings, Biomedical applications, Nanomaterial, Nanocrystal, Perovskites.

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1. INTRODUCTION

Biosensors, cloning, artificial organs, tissue engineering, and regenerative medicine are all heavily reliant on complex bio-functional materials, such as porous silicon nanoparticles, hydrogel, and 3D graphene scaffolds [1 - 12]. However, tailoring their architectures, morphologies, sizes, and chemical and mechanical characteristics generally necessitates costly and technically demanding production processes [13 - 16]. Furthermore, because the majority of these materials are employed *in vivo*, significant study is necessary to understand their possible toxicological effects, biocompatibility, and biodegradability in biochemical, biophysical, and clinical contexts, complicating commercial viability [7, 16 - 18]. As a result, there is an urgent need to research novel, simple manufacturing procedures for high-performance *in vitro* biomedical applications in order to attain widespread availability at a cheap cost and with minimal health risks.

Perovskite materials are well-known for their remarkable thermal, optoelectronic, and magnetic capabilities, which have aided in their quick acceptance in a variety of sophisticated biological applications. This chapter examines current advances in the study of biological applications involving perovskites. Section 2 looks at how organic-inorganic hybrid perovskites can be used for X-ray detection and imaging, while Section 3 looks at how magnetic perovskite nanoparticles may be used to swiftly modulate magneto-temperature and adsorb bovine serum albumin. The fourth section highlights ongoing research on the biocompatibility and cytotoxicity of hydroxyapatite-$CaTiO_3$ composites. Section 5 concludes with a discussion of the promise and limits of biomedical perovskites in the realm of medicine.

1.1. X-Ray Detection and Imaging Using Perovskite Materials

X-ray has been known for its amazing capacity to pierce through things since its discovery [19]. This characteristic has substantially been used inmany medical procedures, including radiography, computed tomography (CT), and radiotherapy, which have proven useful in both diagnostic and therapeutic therapies [20 - 22].

Due to their favorable material properties, such as high charge carrier mobility-lifetime products, long carrier diffusion lengths, high material densities, and elements with high atomic numbers and X-ray absorption cross-sections, lead halide perovskites have demonstrated exceptional sensitivity, responsivity, and detectivity as X-ray photodetectors [23 - 29]. As illustrated in Fig. (**1a**), Yakunin *et al.* successfully created X-ray photodetectors utilizing a photovoltaic cell based on $MAPbI_3$ [25]. The photovoltaic cell is simply a photodiode that uses the p-i-n junction's built-in electrical potential upon photoinduced carrier generation, with p-type and n-type charge transport layers made of PEDOT:PSS and PCBM, respectively [25, 30 - 35].

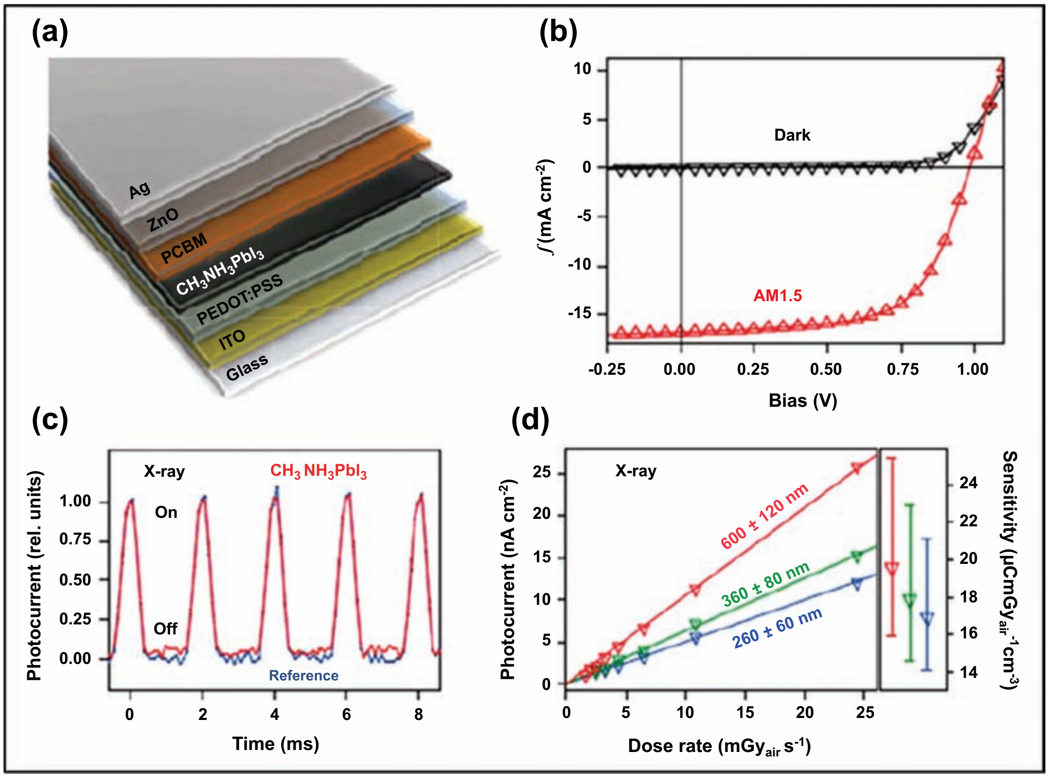

Fig. (1). (**a**) The photovoltaic cell with $MAPbI_3$ serving as the active layer for light harvesting. (**b**) The photocurrent-voltage curves under dark scan (black) and one-sun AM1.5 illumination (red). (**c**) Under pulsed X-ray illumination, the $MAPbI_3$ photovoltaic cell photocurrent response (red) and silicon/YAG:Ce photodetector (blue). (**d**) The photocurrent densities with different thicknesses of $MAPbI_3$ active layers (left) and the specific sensitivities of photovoltaic cells with corresponding $MAPbI_3$ thicknesses (right) [25].

The $MAPbI_3$ photodiode demonstrated a functional response to simulated one-sun AM1.5 illumination with a 10.4% power conversion efficiency (Fig. **1b**), and sensitive photocurrents were obtained when exposed to 50-Hz X-ray photons (peak energy of 75 keV and average energy of approximately 37 keV) (Fig. **1c**, red) compared to a reference silicon diode/YAG:Ce photodetector (Fig. The average photocurrent from the $MAPbI_3$ photodiode rose linearly with the dose rate of X-ray irradiation (measured in mGys-1 in the air) (Fig. **1d**), with enhanced sensitivity reaching a maximum of 25 lC mGyair-1 cm^{-3} at 480 nm (Fig. **1d** inset). This is due to the higher reception of X-ray photons, which have significantly

CHAPTER 6

Perovskites as Biocompatible Materials

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Abstract: Perovskite inorganic perovskite-type oxides are intriguing nanomaterials with numerous uses in electrochemical sensing, fuel cells, and catalysis. Because they are catalytic when employed as electrode modifiers, perovskites made at the nanoscale have recently attracted a lot of attention. These oxides have stronger catalytic activity than many compounds made of transition metals and even some oxides of precious metals. They display desirable physical and chemical properties like electronic conductivity, electrical activity, oxygen content variations, mobility of oxide ions through the crystal lattice, thermal and chemical stability, and super-magnetic, photocatalytic, thermoelectric, and dielectric properties. In oxygen reduction and hydrogen evolution events, nano-perovskites have been used as catalysts because they have strong electrocatalytic activity, low activation energy, and strong electron transfer kinetics. Additionally, some perovskites provide good prospects for the production of efficient anodic catalysts with high catalytic performance for direct fuel cells. They can improve the performance of the catalytic process in terms of selectivity, sensitivity, exceptional long-term stability, good repeatability, and interference-fighting capacity.

Keywords: Electron conductivity, Ferroelectric, Nano-perovskites, Piezoelectric, Photocatalytic, Perovskite.

1. INTRODUCTION

There is no doubt that materials with a perovskite-like structure are gaining popularity, particularly due to the possibility of employing them in solar cells. Since the photochemical properties of CH3NH3PbI3 perovskite were first observed in 2006 by Tsutomu Miyasaka's research group in Japan, the efficiency of these materials has increased so rapidly, and their potential to reach the markets appears so close, that we are currently in the midst of a new "perovskite boom" [1, 2]. The last time perovskites were so thoroughly studied was presumably in the

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1990s, during the “boom” associated with their magnetoresistance features. And we are, indeed, living in an exploding era of study, the excitement over which has spread to a much larger audience [3]. Cloning, biosensors, tissue engineering, and regenerative medicine are just a few of the important applications of biomedical technology in modern medicine [1 - 8]. The majority of these biomedical applications have so far been made possible by complex bio-functional materials (such as hydrogel, porous silicon nanoparticles, and 3D graphene scaffolds) [6, 9, 10]. The manufacture of these materials is often expensive and technically complex due to the need for specialist control over the materials' morphology, sizes, structures, and chemical and mechanical properties. Furthermore, the vast majority of these bio-functional materials are employed *in vivo*, where their biocompatibility, biodegradability, and potential toxicological effects are adequately elucidated by intensive research studies at the biophysical, biochemical, and clinical stages [11 - 17].

The goal of this chapter is to investigate novel materials with relatively simpler fabrication methods for high-performance biomedical applications *in vitro*, with the goal of achieving large-scale accessibility at low costs and with minimal health risks, as well as to demonstrate the historical development of perovskite research from the nineteenth-century mineralogical and crystallographic challenge to the wide range of possible and actual applications of these materials at present. This chapter has concentrated on the difficulties that this field has encountered as it has evolved over time [18, 19].

2. PEROVSKITE STRUCTURE AND PROPERTIES

2.1. Structure

The generic formula ABO_3 can be translated as follows: As shown in Fig. (**1**) are cations of different sizes, while O is the anion [20]. Despite the fact that the B atom has a 6-fold coordination number and the A atom has a 12-fold coordination number, the A site cation is marginally larger than the B site cation. While oxygen atoms are in face-centered positions, atom B is in the cube corner position, and atom A is in the body center, O is the oxygen ion with a 1:1:3 ratio [20]. The terms perovskite and perovskite-structure are used interchangeably. Everything with the generic form ABX_3 and the same crystallographic structure is referred to a perovskite. True perovskite is an oxygen, titanium, and calcium compound [21]. Additionally, it is referred to as a class of ceramic oxides with the formula ABX. These substances fall into three categories: organic metal halide perovskites, inorganic oxide perovskites, and alkaline metal halide perovskites [22]. The perovskite materials share a structure known as ABX_3, in which the cations A and B have different sizes, and the anion X is bound to both [23 - 26]. The 'A' atoms are larger than the 'B' atoms. Any metal or semimetal from the periodic table can be used in the A and B positions [27]. The anion is always oxygen, although any other ion may also be present at this place [22].

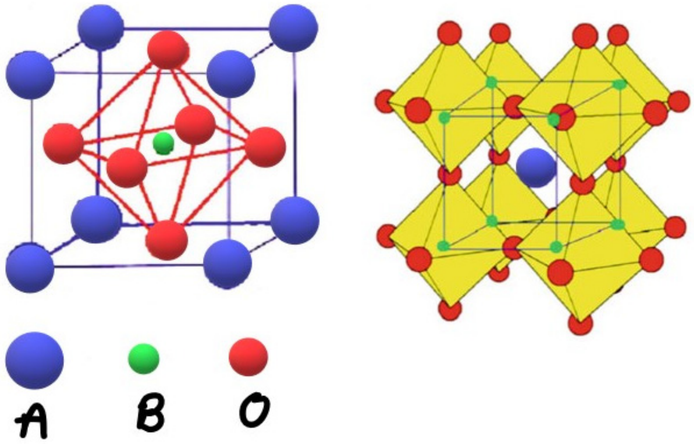

Fig. (1). Molecular arrangement in perovskites [19].

The introduction of organic-inorganic hybrid halide perovskite materials has led to significant interest in the field of solar research as shown in Fig. (**2**). The resources provide numerous advantages due to their electrical, magnetic, and optical properties. In the most recent years, due to the powerful electron-electron interaction, scientists have invested a lot of time and money into understanding the many physical benefits of the materials' magnetic characteristics, particularly those of B-site substituted perovskite and perovskite manganite. Perovskites with a B-site substitution are a perfect testing platform for magnetic characteristics because different combinations of all three cation positions can accommodate paramagnetic cations, opening a variety of possibilities. The magnetic properties of perovskite manganites are very diverse, such as massive multiferroic characteristics, the magnetocaloric effect, and magnetoresistance. Magnetism has a variety of uses, including magnetic uses for bioprocessing, miniaturized magnetic sensors, and refrigeration.

2.2. Magnetic Properties

The discovery of B-site substituted perovskite oxides $A_2B'B''X_6$ and nanoscale manganese-based perovskite oxides ($AMnO_3$) with extraordinary magnetoresistance has sparked a lot of interest in studies of the magnetic properties of perovskite materials. They are used to make fuel cells, sensors, catalysts, and magneto-optical materials.

CHAPTER 7

Impact of Perovskites on Cell Response

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Abstract: This chapter investigates how perovskite materials affect animal cell responsiveness and sheds light on possible biomedical uses. Perovskites are interesting prospects for a variety of biomedical applications because of their distinctive physical and chemical characteristics. The discussion of perovskites' interactions with cells includes their uptake and internalization by cells, as well as how cells react to scaffolds and substrates made of perovskites. The chapter also explores how the composition, structure, surface chemistry, and stability of perovskites affect cell behavior and response. Examining signaling cascades and intracellular destiny, mechanistic insights into perovskite-cell interactions are considered. The chapter concludes by examining existing and potential uses and risks involved with perovskite materials on tissues and regeneration of cells, identifying difficulties and pointing the way forward for further study. This chapter offers insightful information on how perovskites affect cell responsiveness, opening the door for the creation of ground-breaking perovskite-based biomedical solutions.

Keywords: Antimicrobial coatings, Anti-microbial, Antiviral, Antibacterial, Antifungal, Air purification, Biomedical applications, Nanomaterial, Nanocrystal, Perovskites, Water purification.

1. INTRODUCTION

Nanotechnology is one of the important areas of research which covers almost all the domains with a variety of applications, such as solar cells, electronic devices, water purification, biomedical devices, *etc.* [1 - 6]. However, in terms of nano-materials, Si-based (1st generation) technology accounts for 90% of the solar market, while thin film (2nd generation) technology accounts for 10% [7]. It is important to remember that the development of second-generation solar panels has been influenced by a variety of semiconducting materials, including CdTe, $CuInGaSe_2$ (CIGS), and GaAs [8]. Each of these substances has been designed to improve the efficiency of light conversion. Because silicon and thin films need to be of a very high purity grade, these technologies continue to be expensive. Per-

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ovskites, named after the mineralogist Lev Perovski, are natural minerals discovered in Russia's Ural Mountains. Their usual chemical formula is ABX_3 [9 - 12]. Perovskites are even synthetic substances with this composition that are not minerals [13, 14]. Calcium titanium oxide ($CaTiO_3$) was the first perovskite to be studied, and ironically, Edmond Becquerel made the photovoltaic effect discovery in the same year. However, perovskites did not reach the photovoltaics industry until 2009. D. Weber created this hybrid perovskite for the first time in 1978 using a few other sister compounds with various dimensionalities [15]. Over the last four years, the technique for processing the perovskite, the hole and electron conducting layers, and the connections have all been optimized in order to enhance perovskite-based solar cell technology. Its effectiveness has dramatically increased. No other solar cell technology has advanced as quickly as this one, going from 3.9% to 22.1% in just 7 years, a record for the industry. But there are problems associated with photovoltaic perovskites (Fig. **1**):

i. The material's long- and short-term stability is met with skepticism by the photovoltaic community. ii) The devices are vulnerable to quick deterioration due to the material's sensitivity to temperature fluctuations and water vapor. As a result, H. Snaith's group substituted single-walled carbon nanotubes (SWNTs) in an insulating polymer matrix for the organic hole transport medium [16]. They noticed a delay in device degradation with this arrangement. For perovskite solar cells, however, no extensive investigations or encapsulation methods have yet been shown. iii) Perovskite solar cells' heavy metal content gives rise to potential environmental and health risks.

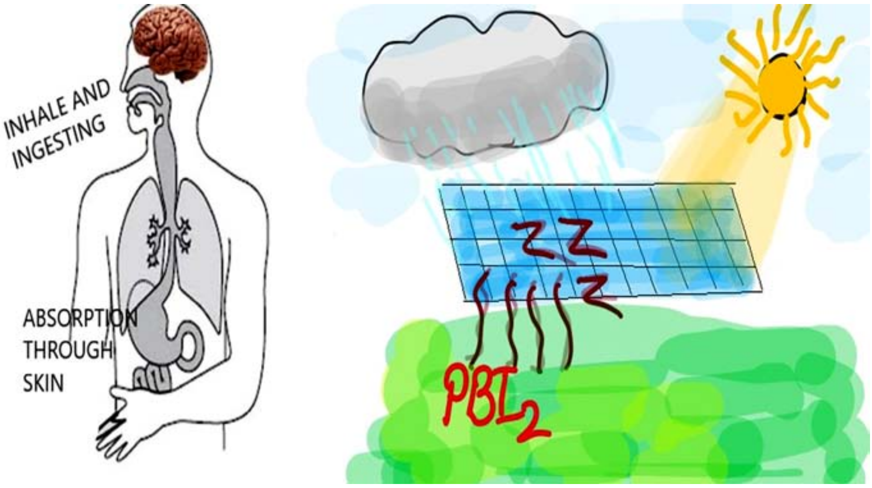

Fig. (1). Examples of health risks associated with photovoltaic perovskite, including interactions during production and manipulation, as well as its release into the environment following device failure [17, 18].

2. ROUTES OF EXPOSURE

The discharge of the material into the soil and rivers as a result of a failure of large-area solar cells poses major health and environmental risks, particularly due to severe thermal shock or failed encapsulation. Human exposure to the material during device production and handling is not the only issue but its impact on the cell and its growth is another issue as well [19]. Small particles from the initial powder-like substance may mistakenly be breathed, swallowed, or absorbed by the skin as the device is being made. Significant health and environmental concerns are likely to occur during device production, transit, and mounting due to the instabilities of the light harvester, which contains heavy metals. In this chapter, we will go over the various exposure pathways and any associated repercussions.

It is necessary to describe the numerous ways through which perovskites can be exposed to humans before talking about their potential toxicity. Direct interaction with humans during its synthesis and processing (occupational exposure), as well as its release into the environment (environmental exposure), are both potential routes of exposure. It is critical to recall that these characteristics apply to the vast majority of ENMs used in large-scale applications, regardless of their size or scientific relevance.

3. POLLUTION AND EXPOSURE SOURCES

Materials of any size can leak during industrial operations (waste discharge, storage, and transportation), resulting in additional transit and diffusion (Fig. **2**). Through farming and animal husbandry practices such as pesticide application or pollution cleanup, engineered elements may penetrate the soil and groundwater. If they reach a certain quantity in the air, drinking water, or food chain, they can have a harmful influence on the environment and human health. These substances, once released into the environment, have the potential to spread throughout numerous ecosystems and have negative effects. The designed materials have the potential to cause high levels of inhalation under specific job circumstances. Furthermore, smaller particles with a nanoscale may enter the body more readily than larger particles [20].

3.1. Endogenous Exposure Routes

The primary human exposure pathway to any airborne substance is through the respiratory system [18]. The lungs are constantly exposed to airborne particles; the total area of airways, including alveoli, is roughly 143m2 [20]. Aerosols enter the nose and, if they are soluble, can pass past the mucus that covers the olfactory system and into the brain.

CHAPTER 8

Anti-Microbial Activity of Perovskites

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Abstract: Perovskites can be used to develop new drugs and materials to combat antimicrobial resistance. These materials are useful in the field of biomedicine due to their chemical properties. They can also be used in the treatment of cancer and other diseases. Researchers are investigating the fate and behavior of perovskites in the environment to assess any potential risks and develop appropriate disposal and recycling methods. Perovskite materials have emerged as a new class of antimicrobial agents with potential applications in various fields. Their unique crystal structure, synthesis methods, and mechanisms of antimicrobial activity make them promising alternatives or add-on agents to conventional antimicrobial agents. The antimicrobial activity of perovskites presents new opportunities for addressing the challenges posed by antimicrobial resistance. Continued research and development efforts are necessary to optimize perovskite synthesis, enhance their stability, evaluate their toxicity, and explore their practical applications in healthcare, water purification, food preservation, textiles, and environmental remediation. In summary, the antimicrobial activity of perovskite materials holds great promise in combating infectious diseases and addressing the growing threat of antimicrobial resistance. Continued research and technological advancements in this field can contribute to the development of effective and sustainable antimicrobial strategies.

Keywords: Antimicrobial coatings, Anti-microbial, Air purification, Antiviral, Antibacterial, Antifungal, Biomedical applications, Nanomaterial, Nanocrystal, Perovskites, Water purification.

1. INTRODUCTION

Infectious diseases continue to pose a significant burden on global health despite advances in medical science and public health measures. These diseases are caused by pathogenic microorganisms such as bacteria, viruses, fungi, and

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parasites, and they can be transmitted from person to person through contaminated food or water or *via* vectors like mosquitoes and ticks. Infectious diseases are responsible for a substantial portion of the global disease burden. They affect people of all ages and socioeconomic backgrounds, but their impact is particularly severe in low- and middle-income countries with limited access to healthcare resources [1, 2]. They contribute to millions of deaths each year, particularly among vulnerable populations such as young children, the elderly, and individuals with weakened immune systems. Infectious diseases have a profound socioeconomic impact. They can lead to increased healthcare costs, decreased productivity, loss of income, and economic instability, particularly in resource-limited settings. The burden falls disproportionately on the most vulnerable populations, perpetuating health disparities [3]. New infectious diseases constantly emerge, and existing ones can re-emerge due to various factors, including changes in human behavior, environmental factors, microbial evolution, and globalization [4].

Overuse and misuse of antimicrobial drugs have led to the development of antimicrobial resistance, which is a major concern. Antimicrobial resistance (AMR) refers to the ability of microorganisms, such as bacteria, viruses, fungi, and parasites, to resist the effects of drugs that were originally effective in treating them. This resistance can occur naturally over time or be accelerated by factors such as the overuse and misuse of antimicrobial drugs in humans, animals, and agriculture. AMR reduces the effectiveness of antimicrobial drugs, making infections more difficult to treat and increasing the risk of complications, prolonged illness, and death [5]. Common infections, such as urinary tract infections, respiratory tract infections, and skin infections, can become untreatable. This poses a significant threat to public health and may lead to increased morbidity and mortality rates. AMR limits the treatment options available for infectious diseases. It can render commonly used antibiotics, antivirals, and antifungal drugs ineffective. As a result, healthcare providers may need to resort to more expensive, less effective, or potentially toxic drugs to combat infections. In some cases, there may be no suitable treatment options available. The development of new antimicrobial drugs and alternative treatment approaches is essential to combat AMR [6].

In order to prevent the spread of infectious diseases and/or to treat them, reduce microbial contamination, and address antimicrobial resistance, it is crucial to find novel materials or drugs with antimicrobial properties. In addition, these antimicrobial materials are useful in various other fields, such as water purification, food preservation and the textile industry. Perovskites with the chemical formula $CaTiO_3$, perovskite is a calcium titanate mineral that occurs naturally. The name of this mineral, which was given in honor of the Russian mineralogist Lev Perovski (1792–1856), was given by German mineralogist Gustav Rose in 1839. Perovskite minerals are typically described as having the same crystal structure as $CaTiO_3$. The usual crystal structure of these perovskite materials is cubic or tetragonal, with the formula AMX_3, where A, M, and X are all metal ions. A and M are cations, while X is an anion. The fundamental component of the perovskite structure is formed by each cation M being octahedrally coordinated with the anions X. With the cation A contained in the space created between neighboring MX_6 octahedra; these MX_6 octahedra are joined in a three-dimensional corner-sharing configuration, neutralizing the charge of the structure [4]. Several methods have been used to synthesize perovskite materials. Some of them are the co-precipitation method, solid-state reactions, hydrothermal synthesis, Pechini method, sol-gel method, low-temperature solution combustion method, microwave synthesis, laser ablation and wet chemical methods [7].

2. BIOMEDICAL APPLICATIONS OF PEROVSKITES

Perovskite materials have gained significant attention in the field of biomedicine due to their unique optical, electrical, and chemical properties. Biomedical applications of perovskites include bioimaging, photodynamic therapy in cancer treatment, drug delivery, biosensors, tissue engineering and bioelectronics. Perovskite nanocrystals, also known as quantum dots, have excellent optical properties such as high photoluminescence quantum yield, tunable emission wavelengths, and narrow emission spectra. These properties make them suitable for bioimaging applications. Perovskite quantum dots can be used as fluorescent labels for cellular imaging, tumor targeting, and tracking of biological processes [8].

Photodynamic therapy (PDT) is a non-invasive therapeutic approach for treating cancer and other diseases. Perovskite nanoparticles can serve as effective photosensitizers in PDT due to their strong light absorption and high quantum yield. They can generate reactive oxygen species upon exposure to light, which can selectively kill cancer cells or destroy pathogens. This property of perovskites could be used as a therapeutic approach in cancers [9].

Perovskite nanoparticles can be utilized as carriers for drug delivery systems. Their large surface area and versatile surface chemistry allow for efficient loading and controlled release of therapeutic drugs. Moreover, the photoluminescent properties of perovskite nanoparticles enable real-time tracking of drug delivery and distribution in the body [10]. Perovskite materials have been explored for the development of biosensors due to their excellent electrical properties and high surface-to-volume ratio. By integrating perovskite nanomaterials into sensor

CHAPTER 9

Bone Regeneration and Bone Growth Using Perovskites

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Abstract: Perovskite materials are becoming more popular in biomedical applications, notably bone tissue engineering and regenerative medicine. Their distinct physical features, such as high dielectric constant, ambipolar charge transfer, and ferroelectricity, make them ideal for bone regeneration. Perovskite-based scaffolds may replicate bone tissue's extracellular matrix and encourage cell behavior, hence aiding bone tissue regeneration. These materials have the potential to completely transform bone defect and injury therapy in regenerative medicine. However, issues like degradation, scalability, toxicity, device interaction, and cost must be solved before they can be widely used. To overcome these challenges, it is necessary to improve stability, scalability, and repeatability, reduce toxicity, achieve device compatibility, reduce manufacturing costs, and develop standardized testing and safety norms. To completely understand the biocompatibility and long-term effectiveness of perovskite materials in bone treatment, further studies and development are required. Despite these difficulties, perovskite materials offer promise in the treatment of bone abnormalities and fractures by acting as scaffolds for bone regeneration, medication delivery vehicles, and imaging agents. Overall, perovskite materials have the potential to improve bone regeneration and advance musculoskeletal disease therapies.

Keywords: Bone regeneration and growth, Biocompatibility, Cytotoxicity and immunological responses, Osseointegration, Perovskite materials, Strategies, Safety consideration.

1. INTRODUCTION

The discovery of perovskite materials has resulted in a dramatic revolution in the field of biomedical applications. In the year 1839, calcium titanate ($CaTiO_3$), which is also known as mineral perovskite, was discovered and named after the Russian mineralogist Lev Perovski. This extraordinary finding established the

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groundwork for further research and understanding of the distinguishing characteristics of perovskite structures [1]. Perovskites, which have traditionally been used in electronics and solar cells, are currently being explored as a potential route for enhancing regenerative medicine [2]. Regeneration and the growth of bones are important procedures employed by tissue engineering and regenerative medicine that strive to restore injured or missing bone tissue [3]. Current techniques encounter limited efficacy, donor site morbidity, and slow recovery. There is an urgent requirement to investigate novel techniques for overcoming these challenges and improving the effects of bone regeneration therapy.

Advanced materials are crucial for the regeneration and growth of bones. Conventional bone healing treatments, comprising autografts and allografts, possess limits and obstacles that can be overcome using modern materials [4]. Perovskite materials have been recognized as a potential category of advanced materials with distinctive features that make them ideal for bone tissue engineering and regenerative medicine. Perovskite materials have currently gained a lot of interest in the area of tissue regeneration due to their distinctive characteristics and versatility. Perovskite materials possess unique physical properties such as high dielectric constant, long-range ambipolar charge transport, ferroelectric properties, high absorption coefficient, low exciton-binding energy, *etc*. [1]. These materials also have remarkable electrical, optical, and structural properties, making them excellent for application in the biomedical field. The use of perovskite materials in bone tissue engineering has the potential to improve the regeneration of bone and stimulate bone development. One of the most difficult challenges associated with bone regeneration is the requirement for scaffolds that resemble bone tissue's native extracellular matrix (ECM) [5]. Sophisticated materials, such as perovskites, enables the design and fabrication of scaffolds with customized features like biocompatibility, porosity, and mechanical strength. Perovskite-based scaffolds are capable of providing structural support to cells while also regulating their behavior, enabling bone tissue regeneration [6].

Furthermore, perovskite nanoparticles exhibit great potential for improving osteogenic differentiation, which is essential for bone development and repair. These nanomaterials have the ability to trigger cellular responses while also modulating signaling pathways associated with bone repair [7]. They have the ability to stimulate the proliferation and differentiation of osteoblasts, which are the cells responsible for the process of bone production, resulting in the rapid formation of bones and better healing results. The use of these materials in bone regeneration and growth opens up the possibility of personalized therapy [8]. Advanced materials may be adjusted according to particular requirements, taking into account various factors, including age, general well-being, and the level of bone injury. This personalized method enables more efficient and specialized therapies, hence increasing treatment results and the quality of the patient's life. In general, the importance of these materials in bone regeneration and development emerges from their ability to go beyond the limitations of conventional procedures. These materials contain specific characteristics, adjustable properties, and the capacity to maintain drug delivery, enabling precise manipulation of cellular responses and improved bone tissue regeneration potential. As the field of regenerative medicine advances, complex materials such as perovskites hold immense potential for revolutionizing the treatment of bone defects and injuries, which has resulted in a new era of regenerative medicine.

2. BONE REGENERATION AND GROWTH

Bone plays a wide variety of roles, including structural support, attachment sites for muscles, ligaments, and tendons, protection of essential tissues, and facilitation of hematopoiesis and mineral storage. Osteoporosis, arthritis, and trauma-related injuries are common musculoskeletal disorders that cause severe pain and impairment. Inadequate bone regeneration can result in fractures of bone, which involves orthopedic treatment [9]. Autografts, allografts, and biomaterial replacements are all common bone grafting treatments, each with its own set of restrictions and possible consequences. In order to deal with these problems, researchers explored natural and synthetic biomaterials [10].

Living bone cells are integrated into a biomineral matrix to form bone. The organic part of the bone is made up mainly of collagen fibers, lipids, non-collagenous proteins, and other bone matrix proteins, whereas the inorganic region is made up of hydroxyapatite crystals. The interaction between bone cells and the matrix is essential for bone strength and tissue adhesion. Osteogenic cells, osteoblasts, osteocytes, and osteoclasts are important bone cells responsible for bone regeneration and structure [11] (Fig. **1**). Osteoblasts are in control of bone formation, collagen secretion, and mineralization of the bone matrix [12]. Osteocytes are the most numerous cell types in bone tissue, where they maintain communication and regulate calcium and phosphate balance. Bone-lining cells are inert osteoblasts that contribute to bone growth and resorption [13]. Osteoclasts are multiple nucleated cells of the hematopoietic lineage that are assigned for the resorption of bone [14].

Comprehending the intricate relationships between bone cells and biomaterials is critical for bone repair and regeneration to be effective. Biomaterials and tissue engineering advancements provide intriguing solutions for improving bone repair and treating musculoskeletal ailments [15].

CHAPTER 10

Perovskites for Bone Replacement

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Abstract: Similar to other transition metal oxides with the same formula, ABO_3, perovskite has a cubic or nearly cubic structure. According to where the electron and energy band gaps are located, perovskite materials can be divided into three categories, with the third combining the first two. The first type has localized electrons while the second type has delocalized energy-band states, and the third type is a transition between the abovementioned two types. There are several types of perovskites, including Layered Perovskite, Perovskite ABO_3, Double Perovskite, and Triple Perovskite. The important characteristics relevant to oxide and oxide-like perovskite crystals are insulator-metal transition, ionic conduction characteristics, dielectric, superconducting, alteration of solid-state phenomenon, and metallic properties. Recently, a number of perovskite applications, including those for random access memories, actuators, tunable microwave displays, piezoelectric devices, transducers, wireless communications, sensors, and capacitors, have been investigated. Electrochromic, photochromic, and filtering devices all demonstrate perovskite's great utility in surface acoustic wave signal processing.

Keywords: Biocompatible, Bone remodeling, Hydroxyapatite, Piezoelectric, Perovskite.

1. INTRODUCTION

Toxic-element-containing colors are prohibited from an ecological standpoint. These rigorous environmental requirements had an impact on many industrial branches. As a result, numerous workplaces started to conduct research to find

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new non-toxic materials that have the same or better properties than these prohibited substances. Particularly the anticorrosive pigments based on lead or chromates are part of the broad category of special inorganic pigments that are currently unsuitable. Perovskites with these cations, which can produce alkaline anticorrosive pigments, may be used as a form of compensation. As a result, the focus of our research is on perovskites that include Ba^{2+}, Ca^{2+}, and Sr^{2+}. It is essential to perform calcination at lower temperatures in the first step and then sintering at higher temperatures to create perovskite compounds as ceramic materials with outstanding electric and magnetic characteristics for usage [1]. The naturally occurring mineral calcium titanate, or $CaTiO_3$, is the source of perovskite molecules, which typically have the molecular formula ABX_3. It encompasses a broad spectrum of colors, including black, brown, grey, orange, and yellow. Perovskite crystals could look like cubes, however, this appearance is deceptive. Pseudocubic describes perovskite. Although its structure is very near to isometric, its symmetry is actually orthorhombic [2]. Most of the metallic ions in the periodic table can be constructed in a lattice in the ABX_3 form, where ion A is larger than ion B of perovskite [3]. Although oxyfluorides and oxides make up the majority of perovskite compounds, oxynitrides, halides, sulfides, hydrides, cyanides, and oxyfluorides are also known [4].

Perovskites are ceramic materials with exceptional electric and magnetic properties, and as a result of these qualities, they are used extensively in industry. Some perovskites are good conductors of oxygen ions because these materials can hold a significant amount of oxygen vacancies. First-row transition elements can be added to the lattice because of the small B-site in the perovskite formula ABO_3. These elements display multivalence under various circumstances, which could be the reason for their electric conductivity. Numerous perovskite oxides exhibit good mixed and ionic conductivity [5]. Barium titanate has a vast range of uses, such as in capacitors, positive temperature coefficient thermistors, piezoelectric devices, and optoelectronic components [6]. For upcoming pigment usage, it is important to understand the fundamental features of the pigments. Their physical and chemical characteristics can be used to describe them. The primary analysis, impurity content, crystal structure, particle size distribution, density, surface area, and optical characteristics of pigments are the most often measured pigment parameters [1]. Perovskite, or a crystallographic structure resembling it, is represented by the generic term ABX_3, which stands for perovskite.

Oxygen, calcium, and titanium combine to form $CaTiO_3$, which is the actual perovskite structure. It is also known as a specific type of ceramic oxide with the general formula ABX. The three different types of ceramic materials are alkaline metal halide perovskite, inorganic oxide perovskite, and organic metal halide perovskite. The A and B represent the cations of different sizes, whereas X is an anion in the common perovskite structure, ABX_3. Typically, elements A and B can be replaced by metal and semimetal from the periodic table. The perovskite is described as having a cubic structure. The structure at the center is surrounded by an octahedron of anions, which is occupied by an A atom, and the B atoms are located in the center of a 6-fold coordination as shown in Fig. (**1**). The oxygen atom is positioned in the face center and has 12-fold cubic-octahedral coordination with the A cation. The larger-radius lanthanides or alkali earth metals are the A cation in perovskite cubic unit cells. A and B are cations of different sizes while O is the anion in the general formula for perovskite, which is ABO_3. The A site cation is somewhat larger than the B cation, and the B atom has a 6-fold and a 12-fold coordination [7].

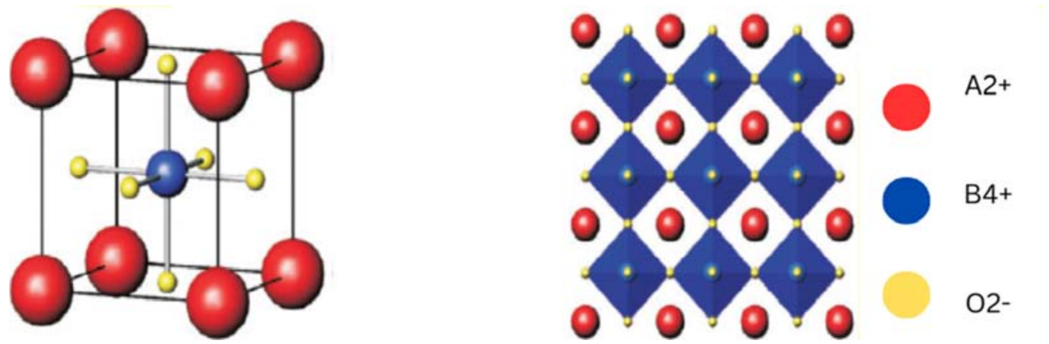

Fig. (1). Ideal cubic structure of ABO_3 perovskites.

2. LATTICE STRUCTURE

Perovskite is a highly stable structure where material optimization is accomplished by phase transition engineering and structure management. The material perovskite exhibits temperature-dependent phase transition. At room temperature, perovskite has a perfect cubic structure, but when the temperature drops to 100 K, a stable orthorhombic phase is attained, and when the temperature rises to 160 K, the phase changes. Variations in the ideal cubic structure of perovskite are responsible for the development of orthorhombic, rhombohedral, hexagonal, and tetragonal forms [8]. The criteria necessary for the production of perovskite are electroneutrality and ionic radii. When spontaneous polarization occurs in ferroelectric perovskite, it causes further deformations in the material Fig. (**2**). The Roddlesden-Popper phases, Aurivillus compounds, and oxygen-deficient brownmillerite compounds can all be assembled from the building blocks that the perovskite structure provides. The production of the perovskite halide is dependent on three factors: neutrality of charges between cations and anions; consistency of the BX6 octahedron predicted by the octahedral factor; and A, B and X, the ionic radii, in agreement with the requirement of the Goldschmidt

CHAPTER 11

Bone Tissue Engineering Using Perovskites in Regenerative Medicines

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Abstract: Regeneration of damaged bone tissue can be accomplished by mimicking the extracellular matrix (ECM) by generating porous topographic substrates. The process of bone tissue regeneration is supported by incorporating natural proteins and growth factors. The scaffolds developed for bone tissue regeneration support bone cell growth and induce bone-forming cells by using natural proteins and growth factors. Limitations associated with the referred approaches are improper scaffold stability, insufficient cell adhesion, proliferation, differentiation and mineralization with less expression of growth factor. Therefore, the use of engineered nanoparticles has been rapidly increasing in bone tissue engineering applications. The electrospray technique that produces nanomaterials has an advantage over other conventional methods as it generates particle sizes in the micro/nanoscale range. The size and charge of the particles are controlled by regulating the flow rate and electric voltage of the polymer solution. The unique properties of nanoparticles are the large surface area to volume ratio, small size and higher reactivity, making them a suitable substrate to be used in the field of biomedical engineering. These nanomaterials are extensively used for drug delivery as therapeutic agents, mimicking cellular components of extracellular matrix and restoring and improving the functions of damaged organs. The controlled and sustained release of encapsulated drugs, proteins, vaccines, growth factors, cells and nucleotides from nanoparticles has been well-established in nanomedicine. The present chapter provides insights into the preparation of nanoparticles by electrospraying and illustrates the use of nanoparticles in drug delivery for the purpose of bone tissue engineering.

Keywords: Biocompatible, Extracellular Matrix, Hydroxyapatite, Perovskite, Piezoelectric, Tissue Engineering.

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1. INTRODUCTION

From a green perspective, it is not allowed to use colors that include toxic elements. A wide range of industrial sectors felt the effects of these stringent environmental regulations. Consequently, a large number of companies are investing in studies to identify alternative, non-toxic materials with equivalent or superior characteristics to these banned compounds. One large class of specialized inorganic pigments that is not appropriate at the moment includes anticorrosive pigments made of lead or chromates. One possible remedy is to employ perovskites doped with these cations, which have the ability to generate alkaline anticorrosive pigments [1]. Ba^{2+}, Ca^{2+}, and Sr^{2+} perovskites are, therefore, the subject of our study. To produce perovskite compounds that are ceramic materials with exceptional electric and magnetic properties, it is necessary to use calcination at lower temperatures initially, followed by sintering at higher temperatures. Perovskite molecules, which usually have the chemical formula ABX3, are derived from the naturally occurring mineral calcium titanate, or $CaTiO_3$. It covers a wide variety of colors, from black and brown to gray, orange and yellow. Although cubes are one possible shape of perovskite crystals, other possible shapes include tetragonal, orthorhombic, rhombohedral, and pseudo-cubic [2 - 7]. Perovskites are characterized by pseudocubicity. Its symmetry is orthorhombic despite the fact that its structure is almost isometric [8]. The ABX3 lattice, in which perovskite ions A and B are bigger than one another, may accommodate the majority of the metallic ions found in the periodic table [9]. Most perovskites are oxides and oxyfluorides, but they are also oxynitrides, halides, sulfides, hydrides, cyanides, and oxyfluorides [10].

Perovskites are ceramics that have remarkable electric and magnetic capabilities; these features make them very useful in many industrial applications. Due to their high oxygen vacancy carrier capacity, some perovskites exhibit excellent oxygen ion conductivity. The small B-site in the perovskite formula ABO3 allows for the addition of first-row transition elements to the lattice. One possible explanation for these elements' electric conductivity is that they exhibit multivalence under different conditions. Ionic and mixed conductivity are well-exhibited by a large number of perovskite oxides [11]. The applications of barium titanate include piezoelectric devices, capacitors, thermistors with a positive temperature coefficient, optoelectronic components, and so on [12]. Having a solid grasp of the pigments' essential characteristics is crucial for their future use. They may be described by their physical and chemical properties. Most often measured parameters for pigments include primary analysis, impurity content, crystal structure, density, surface area, optical properties, and particle size distribution [1].

The general formula ABX3 represents perovskites or crystallographic structures that resemble them. The real perovskite structure, $CaTiO_3$, was formed by a combination of oxygen, calcium, and titanium. Its generic formula is ABX, and it is also known as a particular kind of ceramic oxide. Perovskites made of inorganic oxide, organic metal halide, and alkaline metal halide are the three main categories of ceramics. The common perovskite structure, ABX3, has cations of varying sizes represented by A and B and an anion X. Coordinated with the A cation in a 12-fold cub-octahedral pattern, the oxygen atoms are located in the face center. Perovskite cubic unit cells contain the A cation, which may be larger-radius lanthanides or alkali earth metals. As a whole, perovskites have the formula ABO3, where A and B are cations of varying sizes, and O is the anion. There is a small size difference between the A and B cations, and the B atom is coordinated in six and twelve folds [13].

2. LATTICE STRUCTURE

The phase transition of the perovskite material is temperature-dependant. The emergence of orthorhombic, rhombohedral, hexagonal, and tetragonal forms in perovskites is attributed to alterations in their ideal cubic structure [14]. The prodcution of perovskites relies on the presence of electroneutrality and ionic radii. Additional deformations in ferroelectric perovskite are caused by spontaneous polarization. The building blocks given by the perovskite structure may be used to construct Roddlesden-Popper phases, Aurivillus compounds, and oxygen-deficient brownmillerite compounds. All cations and anions must have a neutral charge, the octahedral factor must forecast that the BX6 octahedron will be consistent, and the ionic radii A, B, and X must be in accordance with the Goldschmidt tolerance factor's criteria in order to create the perovskite halide. A carbon cation, a halogen anion, and an organic cation are the components of the organometallic halide perovskite. Perovskite is classified according to the cation position substitutions and ion radii [15].

3. BONE REGENERATION

Bone remodeling and regeneration are coordinated, complicated processes. They involve normal fracture healing, cell types and intracellular and extracellular signaling pathways. Restoration and remodeling of bone structure follow a specific temporal and geographical route [16]. Osteoporosis, avascular necrosis, and atrophic nonunion may complicate bone tissue regeneration. Traditional autologous bone grafts, allograft implants, free fibula vascularized grafts, and growth factors to stimulate cell differentiation on osteoconductive scaffolds are used to overcome the above limitations [17]. Alternative bone-tissue regeneration methods include the two-step Masquelet procedure for big lesions. The two-step

CHAPTER 12

Perovskite as Tooth-Filling Material in Secondary Tooth

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Abstract: The incidence of dental problems is increasing owing to the modern lifestyle, sticky food and poor dental hygiene. Root canal treatment is one of the most common clinical practices in conservative dentistry. Despite the availability of various GIC materials, strength and durability remain the most common concerns. The mechanical properties of tooth filling material are compromised due to disturbances in glass and liquid composition or powder/liquid ratio, glass particle size, pretreatment, manual mixing. The intrinsic porosity is also influenced by reduced viscosity or compared with proportionate liquid ratio, resulting in increased porosity in the cement structure. The availability of nanoparticles, specifically that of perovskites, opens a new dimension. Since they are relatively smaller in size, they can offer stronger binding and cementing properties.

Keywords: Biocompatible, Bone remodeling, Hydroxyapatite, Perovskite, Piezoelectric.

1. INTRODUCTION

The demand for tooth color dental restorative material has drastically increased in recent decades. Among the different types of reparative materials, composite cement is the preferred material for direct restorative work, whereas gold and ceramics are the norm for indirect restorative work. Amalgam, glass ionomer

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cement, resin composites, and other materials are utilized as tooth fillings in standard dentistry procedures. Amalgam has a long history in the field of medicine owing to its ease of handling and lower cost, but the major drawbacks were its toxicity and subpar aesthetics. Due to their attractiveness and favorable physical characteristics as permanent filler materials, resin composites have grown in popularity. The downside, however, is that these materials are very expensive, time-consuming, and technique-sensitive [1]. Due to the flexibility to alter their physical properties by adjusting their formulations or the powder/liquid ratio, glass ionomer cement is another restorative material with a wide range of therapeutic applications. Comparatively speaking, metallic restorations are less aesthetically pleasing than glass ionomer cements. GIC's biocompatibility, anticariogenic potential, and adhesive ability to bond with mineralized dental tissues are the qualities that make it the most widely used filling material. The addition of fluorine enhances the anticariogenic property of glass ionomer cement, but its poor mechanical features, such as low fracture strength, toughness, and wear, restrict its use as a stress-bearing restorative material or forbid its use in the posterior dental region. In posterior teeth or teeth under stress, it is most frequently utilized as a temporary tooth-filling material [2].

During the early decades of the 19th century, when gold and amalgam were more commonly in use, the development of cement as a more aesthetic restorative material or as a luting and lining agent was supported. For the utility in inlays, crowns, posts, bridges, and orthodontic bands (labially or lingually), the tooth as well as cavity liners, three fundamental types of cement were established at the end of the 20th century: zinc oxide eugenol, zinc phosphate, and silicate cement [3]. As restorative materials evolved, it became clearly evident that hydrophilic materials may wet and react with the hydroxyapatite (HA) or collagenous/organic part of teeth or dentin, in particular. As a result, substances that chelate or complex with calcium seem to be attractive. In contrast to collagen, it has been discovered that polyacrylic acid, a crucial component in cement or cavity liners, has a greater capacity for building complexes with calcium and hydrogen bonds with organic polymers. In 1974, Wilson and Kent produced silicate cement by modifying the Al_2O_3/SiO_2 ratio in silicate glass [4]. The glass ionomer cement was first used in construction. The mineral perovskite is found in yellow, brown, or black minerals and has the chemical formula $CaTiO_3$. The material bears the name perovskite due to its original discoverer, Lev Perovski, who found this material in 1792. The earliest description of its crystal structure, which was published in 1945, was made in 1926. The primary equation for perovskite is ABX_3, where A and B are two cations that are very close in size, C is an octahedron ion that encircles the B ion, and X is an anion that bonds to both A and B. X can be a halide, a sulfide, or a nitride. Similar to other transition metal oxides with the same formula, ABO_3, perovskite has a cubic or nearly cubic structure. At low temperatures, some phase transitions might take place. Excellent ferroelectric and dielectric characteristics are seen in the simple oxide class of structures [5]. According to where the electron and energy band gaps are located, perovskite materials can be divided into three categories, with the third combining the first two. The first kind has localized electrons, the second type has delocalized energy-band states, and the third type is a transition between the first two. There are several types of perovskite, including Layered Perovskite, Perovskite ABO_3, Double Perovskite, and Triple Perovskite [6].

The important properties associated with oxide and oxide-like perovskite crystals are metal-insulator transition, ionic conduction characteristics, dielectric, solid-state variations phenomenon, metallic properties and superconducting characteristics. The oxides of perovskite possess one or both cationic sites that are susceptible to a wide range of replacement while keeping the original crystal structure. Recent research has also expanded into a number of other perovskite uses, which include random access memories, actuators, tunable microwave displays, piezoelectric devices, transducers, wireless communications, sensors, and capacitors. Surface acoustic wave signal processing devices, electrochromic and photochromic devices, and filtering devices all show that perovskite is quite useful in all of these applications [7].

1.1. Lattice Structure

Perovskite, or a crystallographic structure, is represented by the generic term ABX_3. Oxygen, calcium, and titanium combine to form $CaTiO_3$, which is the actual perovskite structure. It is also known as a specific type of ceramic oxide with the general formula ABX. Alkaline metal halide perovskite, inorganic oxide perovskite, and organic metal halide perovskite are three different types of ceramic materials. The A and B represent the cations of different sizes, whereas X is an anion in the common perovskite structure, ABX_3. Typically, A and B are replaced by metal or semimetal elements from the periodic table. The perovskite may be further illustrated as a cubic centric crystalline structure, wherein the corner position is occupied by A atoms while B atoms are located at the center of a 6-fold coordination, *i.e.*, surrounded by an octahedron. The oxygen atoms are positioned in the face center and in 12-fold cube-octahedral coordination with the A cation. Lanthanides with a greater radius or alkali earth metals serve as the A cation in perovskite cubic unit cells. A and B are cations of different sizes, while O is the anion in the general formula for perovskite, which is ABO_3. The A site cation is somewhat larger than the B site cation, and the B atom has sixfold coordination, while the A has twelve-fold coordination [8].

CHAPTER 13

Neurotrauma and Neurodegenerative Treatment Using Perovskites

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Abstract: Neurodegenerative disease (ND) is a progressive neurological condition that leads to damage to the neuronal connection essential for various sensory, motor and cognitive functions. Neurotrauma (NT) is an external injury to the brain or spinal cord. The incidence and prevalence of ND and NT are alarmingly increasing owing to several factors such as food intake, modern lifestyle, increased life expectancy and several other comorbid conditions. The identification of novel materials that can cross the BBB and delay or deny the onset and progress of neuropathophysiology of ND is essential. Perovskite, a nanomaterial with some specific characteristics such as semiconducting, photoemitting, photothermal, ferromagnetic and cations exchange properties, fosters the need for further exploration in the treatment of NDs and neurotrauma (NT). With subsequent research, the toxic side effects of perovskite are also minimized with the synthesis of lead-free perovskite. Various computational models, such as neuro-morphic networking, are used to explore the ability of perovskites to facilitate neural synapsis in NDs and NT. Potential identification of the novel pathway of ND directs in modifying the strategic intervention of ND. Initial findings regarding the application of perovskites in the treatment of NDs and NT have shown promising outcomes that need further exploration.

Keywords: Neurodegenerative Disorders, Neural Networks, Neurotrauma, Perovskites.

1. INTRODUCTION

The occurrence and onset of Neurotrauma (NT) and Neurodegenerative Disorders (NDs) are alarmingly increasing owing to several factors such as food intake, modern lifestyle, increased life expectancy and several other comorbid conditions. The NDs are characterized by structural and functional loss of the neurons. NT is any form of damage to the central nervous system; it could be external in the form of brain injury or internal, such as ischemic or hemorrhagic. Some of the common

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forms of NDs are Alzheimer's, Parkinson's, Huntington's, and Lewy body disease. According to the World Health Organization (WHO) report (2019), stroke is the second most fatal disease after AD and other forms of dementia [1]. Apart from cognitive and memory deficits, speech and language impairment, restricted movement, and breathing difficulty are the common symptoms of NDs. The complexity, vulnerability and dynamicity of CNS complicate the assessment and intervention of NDs and NT. Although significant progress has been documented in the assessment of NDs by understanding the histopathophysiology of NDs, limited success in the pharmacological intervention of NDs has been achieved. The major challenge in the intervention of NDs is the inability of pharmacological agents to reach the target neuronal cell as it must cross the BBB, which is the main gateway to access the brain [2]. The BBB allows only those lipophilic drugs that have a molecular weight of less than 500 Da to reach the neuronal level; this restricts the efficacy of many traditional drugs [3]. The BBB performs a strong gating action owing to its highly semi-permeability property; thus, it limits the entry of potential therapeutic drugs to the CNS. The property of strong selectivity of the BBB is the major challenge in the development of modern medicine [4]. Many pharmacological agents targeting to treat NDs are not able to cross the BBB to reach the target brain site in sufficient amounts to treat it effectively. This leads to the need for the identification of novel materials/molecules that can have optimal impact on the brain in NDs as well as cross the BBB.

Recently, the application of various types and shapes of nanomaterials in the treatment of NDs has been reported [5]. In nanotechnology, different types of nanomaterial and nanoparticles of size in the range of 1–100 nm in at least one dimension are engineered [6, 7]. Many nanomaterials, such as quantum dots (QDs), polymeric nanoparticles, micelles, metallic nanoparticles, *etc*., are already used in brain research owing to their small size. They can interact with biological systems at the molecular level [8]. The nanoparticles possess a high surface-t--volume ratio that enables surface modification and provides good stability [9 - 11]. Some other therapy approaches, such as photothermal, photodynamic and chemotherapy, are also used to treat NDs due to their ability to cross BBB; however, these therapies have numerous side effects. The identification of perovskites has opened a new horizon in the treatment of NDs.

2. APPLICATION OF PEROVSKITES

The identification and application of perovskites can address several existing NDs and NTs conditions that cannot be resolved using traditional methods. Semi-conductive nature of perovskites is used in molecular biology to access the target pathological neurons, and their potential pharmacological outcomes are investigated across various neurodegenerative disease conditions [12].

2.1. Role of Perovskites in Neural Networking

Decoding the neuroanatomical complexity of the brain is a complex task, as trillions of neurons perform various metabolic, cognitive, and motor activities. The human brain is comprised of 10^{11} neurons and 10^{15} synapses, and it processes a large amount of information with high efficiency under various environmental conditions [2, 13]. In neuroscience, synaptic plasticity is defined as the adjustable connection strength between neurons, which is the main principle of learning and memory. The synaptic transmission is regulated by the excitation and inhibition control by the cerebral cortex [14, 15].

2.2. Role of Perovskites in Neuroplasticity

There are at least four major forms of functional neuroplasticity observed in the human brain. These are homologous area adaptation, cross-modal reassignment, map expansion, and compensatory masquerade [16]. Homologous area adaptation is the functional representation of homologous regions in the opposite hemisphere to perform specific cognitive tasks. Cross-modal reassignment occurs when structures allocated previously to process information from a particular kind of sensory input are switched to accept input from a new sensory input. Map expansion is the enlargement of a functional brain region based on the performance for a specific behavioral, linguistic, or cognitive task. Compensatory masquerade is a novel allocation of a particular region of the brain to perform a particular cognitive task [17]. Perovskites have the potential to alter these four forms of functional neuroplasticity, which can enable the answer to several fundamental questions about how functional cooperation between brain regions is achieved and how, using various pharmacological agents, this neuroplasticity mechanism could be strengthened.

2.3. Impact of Perovskites on Neurotransmitters

Decoding the complexity of the functioning of neurons and their interconnection in the form of synapsis in the human brain is a herculean task. Tremendous efforts have been put forward to know how the brain mimics its role in the execution of day-to-day activities [18]. The role of synaptic plasticity is assumed to control the learning and memory in the human brain, which was experimentally supported by a synaptic map investigation using the green fluorescent protein reconstitution technique [19, 20].

CHAPTER 14

Perovskite for Antifouling Treatment

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Abstract: Fouling is a significant issue in wastewater treatment processes, leading to reduced efficiency and increased operational costs. Perovskite materials have emerged as a promising solution for antifouling treatment in wastewater systems due to their unique properties and versatile applications. This book chapter provides an overview of the recent advancements in perovskite-based antifouling strategies and highlights the challenges that need to be addressed for their practical implementation. Traditional antifouling strategies often involve the use of toxic chemicals that have detrimental effects on marine ecosystems. Therefore, there is a growing need for environmentally friendly and sustainable alternatives. In recent years, perovskite materials have emerged as a promising candidate for antifouling treatments due to their unique physicochemical properties. The use of perovskite materials in antifouling applications primarily relies on two approaches: photodynamic and photocatalytic mechanisms. Photodynamic antifouling involves the generation of reactive oxygen species (ROS) upon exposure to light, which can effectively disrupt and prevent the attachment and growth of fouling organisms. On the other hand, photocatalytic antifouling employs perovskite materials as catalysts to trigger chemical reactions that degrade fouling organisms or their adhesion mechanisms. By harnessing their unique properties, perovskite-based coatings have demonstrated significant antifouling capabilities. Continued research and development efforts are necessary to overcome technical challenges and evaluate the long-term effectiveness and environmental implications, ultimately paving the way for the practical application of perovskite-based antifouling treatments in diverse marine industries.

Keywords: Anti-Fouling Treatment, Perovskites, Photocatalytic antifouling, Reactive oxygen species.

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1. INTRODUCTION

Fouling, the unwanted accumulation of substances on surfaces, is a persistent challenge in various industries and applications. In the context of wastewater treatment, fouling poses significant problems, leading to reduced system performance, increased energy consumption, and higher operational costs. The accumulation of fouling agents, such as suspended solids, organic matter, and microorganisms, on equipment and surfaces interferes with the efficient treatment of wastewater, necessitating effective antifouling strategies [1 - 3]. In wastewater treatment processes, fouling can occur at various stages, including pre-treatment, filtration, membrane separation, and disinfection. It involves the adhesion and deposition of particles, colloids, and microorganisms on surfaces, leading to the formation of foulants and biofilms. Fouling not only reduces the efficiency of the treatment system but also promotes the growth of pathogenic microorganisms, posing risks to human health and the environment. To combat fouling and optimize wastewater treatment processes, researchers have been exploring innovative materials and technologies [4 - 7]. Perovskite materials have gained significant attention in recent years due to their unique properties and wide-ranging applications. Perovskites are a class of materials with a specific crystal structure characterized by a three-dimensional arrangement of metal cations and anions. This distinctive crystal structure gives rise to exceptional properties, including high electrical conductivity, catalytic activity, and optical absorption.

Perovskites can be tailored by adjusting their composition and structure, allowing for a wide range of applications in fields such as solar cells, LEDs, sensors, and catalysis [8 - 11]. Researchers and scientists have increasingly turned their attention to perovskite materials as a promising solution in the search for effective antifouling strategies in wastewater treatment. The unique properties of perovskites, such as high surface charge, hydrophilicity, and surface roughness, make them well-suited for inhibiting fouling agent adhesion, reducing biofilm formation, and facilitating fouling layer removal [12, 13]. These properties enable perovskites to act as effective antifouling agents, promoting the efficient operation of wastewater treatment systems [14, 15]. Moreover, perovskite materials can be synthesized using various techniques, allowing for the customization and optimization of their properties for specific antifouling applications. The synthesis methods enable control over the crystal structure, composition, morphology, and surface properties of perovskites, enhancing their antifouling performance and stability. Perovskite materials find versatile uses in antifouling treatment in wastewater systems. They can be incorporated into membranes, coatings, catalysts, and adsorbents to combat fouling at different stages of the treatment process. Perovskite membranes exhibit excellent fouling resistance, allowing for improved filtration efficiency and reduced membrane fouling. Perovskite catalysts can effectively degrade organic pollutants and prevent the formation of foulants [10, 16 - 18].

This book chapter aims to provide a comprehensive examination of the utilization of perovskite materials for antifouling treatment in wastewater systems. It covers the fundamental understanding of fouling in wastewater treatment, the properties and synthesis of perovskite materials, the antifouling mechanisms exhibited by perovskites, perovskite-based systems for antifouling treatment, challenges, and future perspectives. By addressing these key aspects, this work seeks to contribute to the development of innovative antifouling strategies.

2. UNDERSTANDING FOULING IN WASTEWATER TREATMENT

Fouling is a pervasive problem in wastewater treatment systems that significantly impacts their efficiency and operational costs. Understanding the underlying mechanisms of fouling is crucial for developing effective antifouling strategies. Fouling has severe consequences on the performance of wastewater treatment processes. It leads to reduced hydraulic capacity, increased energy consumption, elevated maintenance costs, and the need for more frequent system shutdowns for cleaning and maintenance. Moreover, fouling can compromise the removal efficiency of pollutants, such as suspended solids, dissolved organics, and nutrients. One common fouling mechanism in wastewater treatment is the deposition of suspended solids on surfaces. Particles present in the wastewater, such as sediment, organic matter, and inorganic compounds, can accumulate on equipment, membranes, or pipes, leading to reduced flow rates, increased pressure drops, and compromised treatment efficiency. The adhesion of organic matter, including proteins, lipids, and polysaccharides, is another significant fouling mechanism in wastewater treatment [4, 19, 20]. Organic compounds present in wastewater can adsorb onto surfaces and form biofilms, resulting in reduced hydraulic performance, increased energy consumption, and the potential for the growth of pathogenic microorganisms. Microbial growth and subsequent biofilm formation pose substantial challenges in wastewater treatment. Bacteria, algae, and other microorganisms present in the wastewater can colonize surfaces and form complex biofilm communities. These biofilms not only obstruct fluid flow and decrease treatment efficiency but also serve as a reservoir for pathogens. Fouling in wastewater treatment processes can significantly impede the overall efficiency and effectiveness of the treatment methods. It is crucial to consider fouling as a critical factor in any wastewater treatment approach, as it can negatively impact performance and give rise to various complications throughout the treatment processes [21 - 25].

CHAPTER 15

Perovskite Sensors to Monitor Physical Health

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Abstract: Due to its one-of-a-kind qualities, such as high sensitivity, cheap cost, and simplicity of manufacture, perovskite sensors have shown a lot of potential in the field of monitoring a person's physical health. This is especially true in light of recent research. This is due to the fact that producing perovskite sensors is a straightforward and low-cost process. In this chapter, an investigation is conducted into the potential uses of perovskite sensors in the realm of medical care. The application of perovskite sensors in the monitoring of vital signs, the detection of biomarkers, and the incorporation of such capabilities into wearable devices is receiving a lot of attention at the moment. This article delves further into the fundamentals of how perovskite sensors function, the many methods of their manufacture, as well as the difficulties and opportunities associated with using these sensors in medical settings. This chapter will throw light on the prospects that have surfaced in the area of perovskite sensors for monitoring physical health, as well as the improvements that have been achieved in the field of perovskite sensors. This chapter will shed light on the advances that have been made, which is the primary goal of the chapter.

Keywords: Biomarkers, Healthcare devices, Perovskite materials, Perovskite Sensors.

1. INTRODUCTION

Over the last decade, there has been a lot of interest in energy harvesting devices, which are devices that can convert the energy that is present in the environment, such as mechanical vibrations, heat, fluid flows, electromagnetic radiation, radio waves, and *in vivo* energies, into electrical energy that may then be used in low-

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power applications [1]. Energy harvesting is a renewable source of power that may be used in wireless sensor networks (WSNs), mobile electronics, and implantable and wearable Internet of Things devices. This eliminates the need for network-based energy, traditional batteries, and wires, and minimizes the expenses associated with maintenance and environmental damage [2]. In the field of energy harvesting, researchers have looked at a wide variety of energy conversion techniques, including piezoelectricity, pyroelectricity, photovoltaics, triboelectricity, and magneto-mechano-electricity [3 - 8]. Because piezoelectric materials can precisely convert tiny mechanical or biomechanical movements such as muscle contraction/relaxation and cardiac/lung movements into electricity due to their high electromechanical coupling factor and piezoelectric coefficient, piezoelectric energy harvesters have received a great deal of attention from the scientific community [9 - 11]. This is due to the fact that piezoelectric materials can be used to make piezoelectric energy harvesters. The use of piezoelectric energy harvesters in wireless sensor networks is one of their most significant applications. It is now feasible to gather ambient energy in order to provide sensor nodes with a sustainable power source. This is made possible by the continually increasing number of sensor nodes that have been deployed in a variety of domains, as well as the continuously decreasing node size and power need. For the purpose of monitoring the pressure in a car's tires, for instance, wireless communication of sensors that are powered by piezoelectric energy harvesters may be used [12].

In addition, piezoelectric harvesters have the ability to use *in vivo* energy, such as blood flow, heartbeat, and muscle stretching, in order to power biomedical equipment [13]. These devices include cardiac pacemakers and brain stimulators that are used to diagnose heart rate. In addition to *in vivo* energies, piezoelectric energy harvesters may be mounted on footwear, knees, elbows, wrists, and fingers to collect the biomechanical energy generated by physical activity such as footfalls, hand swings, finger tapping, and so on. These harvesters can also be used in conjunction with *in vivo* energies. A typical sensor mechanism is shown in Fig. (**1**), which may be found here. This energy is capable of powering a broad variety of electronic equipment, including implanted biomedical devices, LED lights, wristwatches, and mobile phones [14]. Through the use of the piezoelectric effect, ambient mechanical energy, which is the most pervasive kind of energy, may be used to self-power wireless sensor networks [15]. However, harvesters that are stiff and bulky have limited value as implantable or wearable energy sources within or outside the human body due to their incongruent interaction with the curved and corrugated surface of the human skin, muscles, and organs. This makes their use as energy sources inside or outside the body restricted. Piezoelectric-based flexible materials and lightweight and slender energy harvesting devices on thin plastic films have been extensively developed over the last decade to accomplish conformal settling and energy scavenging on the surfaces of human muscles and organs [16]. This was done with the intention of resolving the challenges that were discussed before. Particularly, numerous research organizations all over the world have investigated high-performance flexible piezoelectric energy harvesters by utilizing piezoelectric materials, which can generate electric energy by minute mechanical deformations and irregular vibrations, potentially enabling a variety of implantable and wearable self-powered Internet of Things devices [17]. The utilization of flexible piezoelectric devices is not limited to energy harvesting applications but also includes mechanical sensing applications.

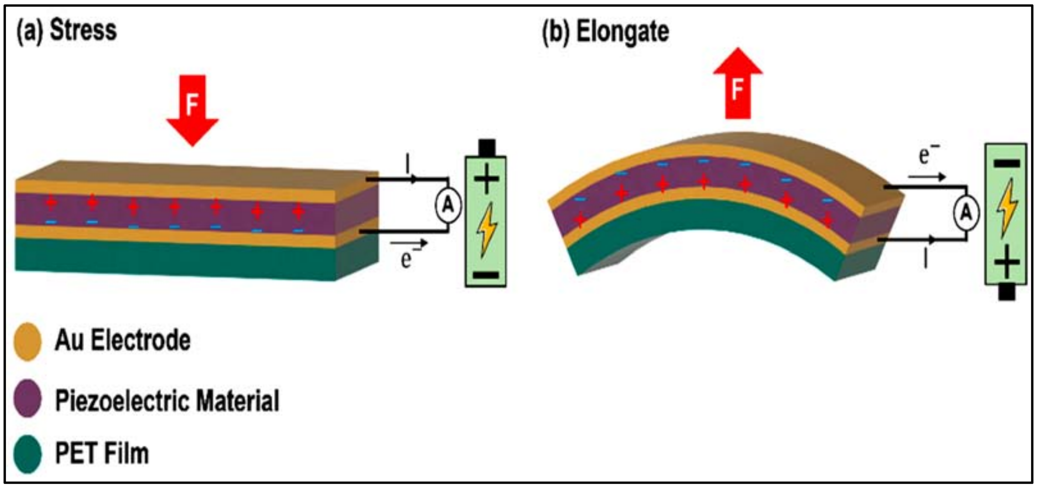

Fig. (1). Schematic illustration of the operation mechanism of piezoelectric energy harvester. Generation of electricity by (**a**) applying stress and (**b**) releasing stress [18].

In general, the strategy for scavenging energy from environmental or artificial sources is a function of the classification of the energy sources as well as the availability of the energy sources. In point of fact, various designs need to be put into place depending on the kind of power (alternating current or direct current) that is given by the source, the quantity of power that is delivered, and the availability of several sources. However, in its most basic form, the energy harvesting system needs a source of energy (heat, light energy, or mechanical energy) in addition to the following fundamental components, which are shown in Fig. (**2**).

CHAPTER 16

Bionic Prosthesis Using Perovskite Materials

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Abstract: Bionic prosthesis have revolutionized the field of medical science by providing individuals with limb loss the ability to regain functionality and independence. Traditional prosthetic materials, such as metals and plastics, have limitations in terms of weight, durability, and biocompatibility. The emergence of perovskite materials has opened up new possibilities for developing advanced bionic prosthesis. This chapter explores the application of perovskite materials in bionic prosthesis, highlighting their unique properties and potential advantages. It also discusses the challenges and future directions for utilizing perovskite materials in the development of next-generation bionic prosthesis.

Keywords: Air purification, Anti-microbial, Antimicrobial coatings, Antiviral, Antibacterial, Antifungal, Biomedical applications, Perovskites, Nanomaterial, Nanocrystal, Water purification.

1. INTRODUCTION

Bionic prosthesis, alternatively referred to as bioelectronic prosthesis or bionics, are sophisticated artificial devices designed to restore or augment the functionality of a body part that is absent or impaired. These prosthesis integrate state-of-the-art technologies, such as electronics, sensors, actuators, and advanced materials, in order to replicate the inherent movements and functionalities of the human

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body. Bionic prosthesis have significantly transformed the domain of medical technology by effectively integrating principles from human physiology and engineering. This integration has enabled individuals who have experienced limb loss or impairment to regain their mobility and independence. The advancement of bionic prosthesis has been motivated by the aspiration to enhance the overall well-being of individuals who have experienced limb loss or functional impairments. Conventional prosthetic devices, such as passive artificial limbs or mechanical prosthetics, exhibit certain constraints in relation to their functional capabilities, comfort levels, and ability to replicate natural movement. Bionic prosthesis strive to address these constraints through the integration of advanced technologies, facilitating a more seamless amalgamation of the user's physiological structure and neural network. The integration of myoelectric control systems represents a significant advancement in the field of bionic prosthesis. These systems employ electromyography (EMG) sensors to identify and interpret electrical signals produced by the user's muscles. Through the process of capturing and analyzing these signals, bionic prosthesis can be effectively controlled with enhanced precision, thereby facilitating the execution of more natural and intuitive movements. The activation and manipulation of prosthetic limbs can be achieved through the contraction of residual muscles by users, facilitating a heightened level of intuitive and responsive interaction. An additional crucial element pertaining to bionic prosthesis involves the utilization of sophisticated materials. Prosthetic limbs are constructed using lightweight and durable materials, including carbon fiber composites, titanium alloys, and high-performance plastics, in order to achieve a balance between strength and weight. These materials serve to improve both the overall functionality and durability of the prosthesis while also enhancing the user's comfort and achieving a more realistic fit. The capabilities of bionic prosthesis have been further expanded due to recent advancements in sensor technologies. Sensory feedback systems, such as pressure sensors and tactile sensors, have the capability to provide users with tactile and pressure perception, thereby enhancing their ability to comprehend and engage with their surrounding milieu. The aforementioned sensors possess the capability to perceive stimuli from the external environment and subsequently transform them into electrical signals. These signals are then conveyed to the nerves or muscles of the user, thereby facilitating a sensory encounter that is characterized by heightened immersion and realism.

Furthermore, the integration of advanced power systems has contributed to the improvement of bionic prosthesis, alongside the advancements in control systems and sensory feedback. The utilization of miniaturized batteries or energy harvesting mechanisms, such as kinetic energy or solar power, facilitates extended durability and enhanced self-sufficiency in the functioning of the prosthetic limb. This phenomenon mitigates the necessity for frequent battery replacements, thereby augmenting the user's mobility and convenience. Although there have been notable advancements in the field of bionic prosthesis, there remain various obstacles that need to be addressed. The financial implications associated with bionic prosthesis pose a significant obstacle for a considerable number of individuals, thereby restricting their ability to obtain and utilize such devices. Furthermore, the advancement of bionic prosthesis for intricate anatomical components, such as hands or eyes, presents supplementary technical and engineering obstacles. Conventional prosthetic materials, although fulfilling their intended function, frequently exhibit constraints that impede their efficacy and reception among users. The advent of perovskite materials, characterized by their exceptional properties in the realm of optoelectronics, has presented novel opportunities for the advancement of bionic prosthesis (Fig. **1**) [1].

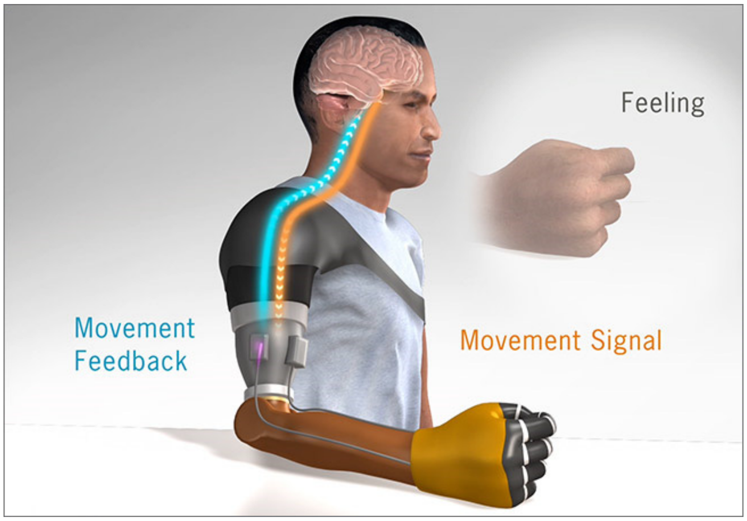

Fig. (1). Prosthetic function advances with first demonstration of illusory movement perception in amputees [1].

1.1. Biomedical Usages of Perovskites

The skin, being the largest organ in the human body, plays a crucial role in facilitating the interface between the human body and the surrounding external environment. Electronic skin, commonly referred to as e-skin, is a rapidly advancing technology that typically consists of thin, flexible, and stretchable materials [2, 3]. The material possesses the ability to replicate the functionality of human skin and convert external stimuli, such as pressure, deformation, vibration, or temperature, into electronic signals. This characteristic holds potential for the advancement of biomedical sensors, intelligent robots, and bionic prosthesis [4 - 12]. Over the past few decades, significant endeavors have been undertaken to advance the development of diverse electronic skin (e-skin) devices,

CHAPTER 17

Perovskite-Based Bio-Implantable Energy Harvesters

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Abstract: Energy harvesters based on perovskite nanomaterials have garnered significant attention in academia and industry because of their ability to transform mechanical and thermal energies into electric power. These materials have a great deal of promise for capturing body-induced and human activity-induced energy to power implantable and portable low-power devices. This book chapter builds upon previous works that have explored innovative materials and nanotechnologies for fabricating ferroelectric generators. We give a brief overview of flexible piezoelectric and pyroelectric energy harvesters' material selection procedure and reasonable microstructure design. We also stress the unique abilities of perovskite materials as energy collectors in biomedical applications, which include both conventional ferroelectrics and recently developed ferroelectric biomaterials. Additionally, we discuss the newest integration structures of hybrid generators with ferroelectric nanomaterials, which significantly enhance the functionalities of the energy harvesters, particularly for biological and implantable applications.

Keywords: Bio-applications, Bio-Implantable, Energy applications, Perovskite materials.

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1. INTRODUCTION

Energy harvesting remedies have drawn a lot of interest as a consequence of the advancement of Internet of Things (IoT) sensor-based wireless network technologies for addressing the sustainable power difficulties of wireless sensors. IoT wireless sensors are crucial components; they gather and communicate data on sound, electric current, light, motion, temperature, and added qualities [1]. Batteries are often utilized for sustaining a variety of sensors, but several hundred thousand future Internet of Things sensors might face maintenance and disposal issues. Energy harvesting technology that can convert ambient mental horsepower into electrical energy has been carefully explored to avoid the limitations of batteries [2, 3]. Using a variety of energy conversion techniques, this innovative technology derives electrical energy from environmental elements such as ambient vibration, light, and heat [4 - 9]. Mechanical energy, like vibration and pressure, may be transformed into electrical energy using piezoelectric and triboelectric phenomena [10 - 14]. Thermal energy may be transformed into electrical energy using their pyroelectric and moelectric actions. Solar energy may be converted into electrical energy through the photovoltaic effect. Solar energy harvesters and solar cells are significant energy sources with extraordinary energy conversion efficiencies, but they are restricted by time, space, and weather [15, 16].

On the other hand, mechanical energy harvesters are less constrained by the environment, such as weather, time, and location, than solar or thermal energy harvesters are. This is because mechanical energy sources are always available by means of oscillations and acoustic, hydraulic, and fluid energies. Due to this, piezoelectric energy harvesters are often used in many different applications, such as wireless sensors, actuators, and devices for biomedical [17]. In response to a change in the material's internal dipole moment caused by mechanical stress, the piezoelectric effect generates electrical energy, and vice versa; an applied voltage can physically deform the material. Examples of applications for piezoelectricity include inkjet printing, printer nozzles, injectors, actuators, ultrasonic wave detectors, speakers, ignitors, strain sensors, and energy harvesters [18, 19].

Implantable medical devices (IMDs) have grown tremendously in recent decades, becoming vital medical instruments for increasing patient quality of life and extending patient longevity. IMDs, such as implanted pacemakers, implantable cardioverter cardiac arrest devices, cochlear implants, deep brain, nerve, and bone stimulators, are presently placed in many parts of the human body as artificial treatments and diagnostic tools [20]. These surgically implanted electronic devices allow for both real-time therapy (such as muscle and nerve stimulation) and diagnostics (such as monitoring heart rate, blood pressure, and temperature) for a number of conditions affecting the heart, brain, and other essential organs. For instance, a cardiac pacemaker can help treat irregular heartbeats by electrically stimulating the patient's cardiac muscle to contract, therefore reducing heart blockage or sick sinus syndrome [21]. Furthermore, IMDs have significantly contributed to our understanding of the biological processes that exist in the human body, including the complicated mechanisms of neural communication, memory, and control, which significantly deepens our understanding of how these processes are affected by various diseases and treatments, in order to improve the quality of life and increase the survival rate of patients worldwide [22].

Despite tremendous advances in IMD development and deployment since the first *in vivo* cardiac pacemaker was created in 1958, today's IMDs face a number of challenges [23]. Recently, *in vivo* energy generation and internal charging using a physiological environment and normal physical activities have been documented. By using self-powered implanted devices that draw energy from the environment around the patient to directly power the device, further miniaturization is made feasible. Electric potentials from the inner ear, glucose oxidation, organ vibration, and muscle contraction are a few techniques for recovering energy from electrical, thermal, chemical, and mechanical processes *in vivo* [24]. In all of these biological power sources, mechanical energy is recognized as one of the most common and adequate abilities in a living organism. Biomechanical energy can be captured *in vitro* and *in vivo* to create self-powered medical gadgets.

Recently, the integration of energy harvesting devices has been investigated as an appealing strategy for self-powered biomedical systems. These devices can transform biomechanical energy from human body movements, including movement of the body, blood circulation, and the contraction and relaxation of cardiac, pulmonary, and muscle, into electricity [25]. This mechanical energy conversion process can make use of a variety of techniques, including the piezoelectric effect, triboelectric effect, magnetostrictive effect, and electromagnetic induction [26 - 31]. However, the unequal contact with the curved, corrugated, and irregularly shaped surfaces of organs, including the lung, brain, eye, and heart, limits the usage of another type of energy harvesters utilized for implanted energy sources [32]. Furthermore, turning the sensitive movements of inside muscles and organs into electrical power is not possible with energy harvesters based on hard and dense substrates. Energy harvesters that are lightweight and incredibly flexible are applied conformally to the surfaces of muscles and organs. These devices are manufactured using plastic thin films made of polyethylene terephthalate (PET), polyimide (PI), and polydimethylsiloxane (PDMS), which are frequently used in flexible electronics due to their adequate flexibility and resilience [33, 34].

CHAPTER 18

Issues Perovskites Encounter in the Biomedical Industry

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Abstract: Within the context of the medical field, this chapter explores the possible uses of perovskite materials, piezoelectric nanogenerators (PENGs), piezoelectric biomaterials, and metal halide nanocrystals. As a result of their one-of-a-kind qualities, perovskite materials have recently gained attention as possible candidates for use in medical diagnostics, treatments, and imaging methods. However, before their broad application in the biomedical sector, difficulties relating to biocompatibility, stability, biodegradability, integration with current technologies, and scalability need to be overcome. PENGs provide self-powered health monitoring devices and may be utilized as a power source for microdevices and bio-implants, bypassing the limits of current power sources. PENGs are also capable of being employed as a power source for other applications. Theranostic methods, tissue regeneration, and drug delivery systems are all potential uses for piezoelectric biomaterials like BT, ZnO, and nanoparticles based on BFO. Nanocrystals made of metal halides, such as CsPbX3, have extraordinary light-harvesting capabilities that make them ideal for use in photonic-based biomedical applications. These applications include multi-photon excitation for cellular imaging and photoactivated treatment. Additional study is required to fully investigate the capabilities of these materials and find solutions to the obstacles that stand in the way of their clinical use. Some of these obstacles include biocompatibility, biodegradability, and tissue accumulation.

Keywords: Biocompatibility , Biomedical industry, Metal halides, Perovskite materials, Piezoelectric nanogenerators.

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1. INTRODUCTION

The biomedical industry is continuously in search of cutting-edge raw materials that might usher in a new era of diagnostics, therapies, and imaging techniques in the medical field. Because of their one-of-a-kind properties and malleable character, perovskite materials have recently risen to the forefront as a potentially beneficial alternative for a broad variety of applications. This is due to the fact that perovskite substances are very adaptable. Crystalline substances known as perovskites have the formula ABX3 when written down in their universal chemical form [1 - 3]. Because of their outstanding optical, electrical, and chemical properties, these materials are suitable for use in a wide number of applications [4 - 7]. These properties make these materials desirable for use in a wide variety of applications. There are a few challenges that need to be overcome with regard to perovskite materials before they can be used in the field of biomedicine in an effective manner. Nevertheless, in spite of the great potential they provide, this is not an impediment that cannot be overcome. There are a variety of different advantages associated with the use of perovskite materials in biological applications. Fluorescence microscopy and other imaging techniques are able to make use of them because they have exceptional light-absorbing capacities and high photoluminescence quantum yields. These characteristics make it possible for the creation and detection of light to be carried out in an effective manner. In addition, the synthesis, modification, and engineering of perovskites to exhibit the features that are desired may be accomplished with relative ease. Because of this, it is now feasible to modify perovskites so that they better suit the needs of certain biological applications. Establishing the biocompatibility of perovskite materials is one of the primary challenges that must be addressed in order to begin the process of introducing perovskite materials in the biomedical industry. The term “biocompatibility” refers to a substance's capability to coexist with living tissues without causing any adverse effects, and it describes a substance's ability to interact with living things in a healthy manner. Perovskites have shown potential in electrical and optoelectronic applications; however, very little study has been done to determine whether or not they are biocompatible in biological systems. This is despite the fact that perovskites have proven to be promising in these areas. Before perovskite materials may be utilized in medical applications without risk, a substantial amount of research must first be carried out to get an understanding of the potential toxicity, degradation products, and long-term effects of perovskite materials on biological tissues and cells [8, 9]. This is necessary in order to provide assurance that perovskite materials can be used in medical applications without risk.

Perovskite materials have a number of major challenges in the area of biomedicine, one of which is related to their stability and endurance. Perovskites are notorious for their susceptibility to damage from environmental factors such as moisture, heat, and light, which, over time, may lead to a decline in their efficacy. In order for these materials to be used in implanted devices, biosensors, and other biomedical applications that call for longer lives, it is essential that they achieve long-term stability. To improve the perovskite materials' stability and endurance, researchers are constantly investigating various solutions, such as encapsulation approaches, surface passivation, and compositional engineering. Perovskite materials' biodegradability and biostability are significant characteristics in biomedical applications, in addition to their stability, which is an important consideration in this context. Certain applications, like medication delivery systems or temporary implants, need materials that can degrade over time and be removed from the body without leaving any toxic residues [8]. These materials must also be able to do so without causing any discomfort to the patient. Producing perovskite materials that are biodegradable or inventing suitable coatings to limit the pace at which they degrade is a major difficulty that has to be solved. The use of perovskite materials in already established biomedical devices presents a number of challenging logistical issues [9]. It is essential that careful consideration be given to compatibility with other components, including electrical interfaces, sensors, and biomolecules, in order to guarantee uninterrupted connection and operation. The development of strategies for integrating perovskite-based devices and systems with already existing biomedical technology is an area that requires attention. For perovskite materials to achieve broad usage in the biomedical sector, scalability and the development of production procedures that are both cost-effective and efficient are essential requirements. In spite of the fact that perovskites have shown exceptional performance in studies conducted on a smaller scale, increasing their production while preserving their quality and uniformity is still a difficult task. In order to allow the manufacture of perovskite-based biomedical devices and materials in large quantities, it is necessary to develop manufacturing procedures that are both efficient and compliant with regulatory norms [10].

In summary, perovskite materials have significant potential for use in biological applications; nevertheless, a number of obstacles need to be overcome before this potential can be fully realized. Critical aspects that need more study and development include biocompatibility, stability, biodegradability, integration with already existing technology, and scalability. In the biomedical sector, the effective utilization of perovskite materials will open the way for breakthroughs in medical diagnostics, treatments, and imaging methods. Overcoming these hurdles will pave the way for the utilization of perovskite materials in the biomedical business.

CHAPTER 19

Future Prospects of Piezoelectric Perovskite Materials

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Abstract: Piezoelectric perovskite materials have emerged as a promising class of materials due to their unique combination of piezoelectric properties, mechanical stability, and wide bandgap. This abstract presents an overview of the future prospects of piezoelectric perovskite materials, focusing on their potential applications and ongoing research efforts. The future prospects of piezoelectric perovskite materials lie in their application in various fields, including energy harvesting, sensors, actuators, and piezoelectric devices. These materials have the ability to convert mechanical energy into electrical energy and *vice versa*, offering opportunities for self-powered systems and wireless sensing applications. Additionally, their compatibility with flexible substrates opens up possibilities for the development of wearable and flexible electronics. One avenue of research focuses on lead-free perovskite materials, addressing the environmental concerns associated with lead-based perovskites. Extensive efforts have been made to explore alternative compositions, such as bismuth-based perovskites, which show promising piezoelectric properties. The development of lead-free perovskite materials will contribute to the sustainability and wider adoption of piezoelectric devices. Another area of interest is the integration of perovskite materials with other technologies, such as nanogenerators and energy storage systems. By combining piezoelectric perovskites with other functional materials, synergistic effects can be achieved, leading to enhanced performance and efficiency in energy conversion and storage. Furthermore, ongoing research is focused on improving the synthesis methods, understanding the fundamental mechanisms underlying the piezoelectric behavior, and optimizing the performance of piezoelectric perovskite materials. Advanced characterization techniques, including *in-situ* measurements and modeling approaches, are being employed to gain deeper insights into the material properties and enhance their performance.

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Keywords: Anti-microbial, Antiviral, Antibacterial, Antimicrobial coatings, Air purification, Antifungal, Biomedical applications, Nanomaterial, Nanocrystal, Perovskites, Water purification.

1. INTRODUCTION

In 1880, Pierre and Jacques developed piezoelectricity, which means "to press" [1]. They observed that if a material is exposed to mechanical pressure, it becomes electrically polarized, and the degree of polarization is directly proportional to the mechanical strain being applied [2 - 6]. Piezoelectricity is, hence, the outcome of applied mechanical stress and is represented in Fig. (**1a**) for the production of electricity. Cady describes piezoelectricity as the electric polarization of crystals belonging to specific classes, and polarization is related to strain [7]. The Curies discovered that the application of an external electric field to a given material results in the manifestation of structural anomalies within said material. This is described in Fig. (**1b**) as a piezoelectric reverse effect. Due to its outstanding piezoelectric constant (d_{33} ~ 200-750 pC/N), high curie temperature (T_c ~ 180ºC-320ºC), and now, its application for many electronic devices, high-efficiency lead-based piezoceramics, particularly PZT, have received great interest. However, the PZT section, which contains lead oxide, is extremely hazardous due to volatilization at high temperatures, particularly when it is calcinated and sintered. Lead can be easily accumulated in the human body due to its absorption through the lungs, cutaneous or digestive system. This accumulation results in lead storage in soft bone and tissue, including muscles and organs. The prompt consequence is profound blood, gastrointestinal, and cerebral system contamination due to lead, resulting in significant impairment [8]. Keeping these grave consequences in mind, various government rules in different nations, such as the European Union, USA, *etc.*, have effectively prohibited the use of such hazardous compounds.

Due to these implications of lead and lead-based ceramic materials, a global approach has evolved to reduce their disastrous effect on health and the environment. In this regard, lead-free piezoelectric ceramics have gained much attention in recent years [9]. Words like "lead-free", "piezoelectric", "ferroelectric", and "$BaTiO_3$" are now synonyms of each other and are considered a point of keen interest.

The discovery of piezoelectric materials began during World War II when secrecy was at its peak, and nations were looking for smart and effective materials. Through confidentiality, the nations were looking for such material. After the Second World War, publications and data relating to $BaTiO_3$'s piezoelectric action were published, and this substance was therefore obvious with a very high dielectric constant. Furthermore, the discovery of ferroelectricity in the ceramic industry in $BaTiO_3$ was a step forward [10]. This was the main finding since ceramics could not be piezoelectrically active due to high-temperature sintering that negates their net effective orientation.

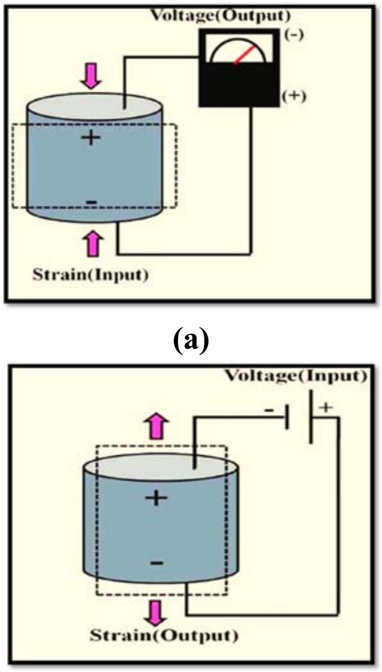

Fig. (1). (**a**) Piezoelectric Effect on Piezoelectric Materials and (**b**) Inverse Piezoelectric Effect.

Despite the extensive efforts to enhance the characteristics of $BaTiO_3$, there has been a lack of effective research on PZT substitution thus far. The tetragonal structure of $BaTiO_3$ is a highly efficient lead-free perovskite material, displaying a remarkably high dielectric constant of approximately 10,000 times. This material can be effectively employed as a dielectric material in the construction of multilayer capacitors [11]. This substance is highly intriguing owing to its favorable ferroelectric properties and uncomplicated crystallographic configuration [12]. At room temperature, $BaTiO_3$ exhibits favorable electrical properties, as well as chemical and mechanical stability, and can be easily prepared [13]. The incorporation of appropriate dopants has been observed to enhance the structural, morphological, optical, and electrical characteristics of $BaTiO_3$.

SUBJECT INDEX

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