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Nanostructured Materials and Their Physical Applications

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Abstract

People's perceptions about biodegradable materials have steadily changed as science and technology have advanced. Biodegradable materials often have a high percentage of polymers, many of which may be synthesised chemically. The manufacturing method is straightforward, and certain basic ingredients are inexpensive to get. The synthesis properties, applications, and perspectives of biodegradable polymers are the subject of this article, which reviews the related literature. This review highlights that biodegradable polymers such as PLA, PHA, PCL, PBS, and PBAT derived from renewable resources offer sustainable alternatives to petroleum-based plastics. Advances in synthesis techniques, including enzyme-catalyzed polycondensation, ring-opening polymerization, and copolymerization, have enhanced their thermal, mechanical, and degradation properties. Applications extend from packaging to biomedical fields, particularly in drug delivery and tissue engineering, where 3D bioprinting has shown great promise. Despite challenges in cost, scalability, and controlled degradation, biodegradable polymers demonstrate significant potential for reducing plastic pollution. Future research should focus on optimizing performance, standardizing processes, and developing multifunctional composites for broader industrial and medical applications.

Keywords; Nanostructured Materials; Nanomaterials; Healthcare; Biomedical Sector; Environment.

INTRODUCTION

Nanostructured materials have become a revolutionary type of materials, with dimensions that are frequently in the range of 1-100 nanometers in dimensions. Because to quantum confinement effects, huge surface-to-volume ratios, and size-dependent effects, materials at this scale exhibit unique mechanical, chemical, and physical properties that differ greatly from bulk materials. These unique properties have created new horizons of material science and engineering, making it possible to create more advanced technologies in a broad spectrum of physical applications [1]. The increased attention in nanostructured materials can be explained by the fact that they have the potential to transform the way electronics, energy, healthcare and environmental science are conducted. An example of this is in electronics where nanoscale materials have been used to achieve both the miniaturization of devices and facilitating better performance, resulting in faster and more efficient components [2], [3]. Nanomaterials are also important in the energy sector to improve the efficiency of solar cells, batteries, and fuel cells through the improvement of the process of charge transport and energy conversion. Because of their exceptional optical, magnetic, and thermal properties, they are also very useful in applications like as sensors, catalysis, and photonic devices. Based on their dimensionality, nanostructured materials may be roughly divided into four categories: "zero-dimensional (quantum dots), one-dimensional (nanowires, nanotubes), two-dimensional (thin films, graphene), and three-dimensional nanostructured systems" [4]. The physical behaviors of each of the classes are unique, and hence, each is suitable in a particular application. The capacity to precisely regulate size, form, and composition has been made possible by the development of techniques for making them, including as chemical vapour deposition, sol-gel procedures, and lithography, which has increased their utility [5].

Nanomaterials and its Classification

Materials having nanoscale dimensions, where surface or interface features predominate over bulk qualities, are known as nanomaterials. These nanoparticles' enormous surface area can lead to unique chemical and physical characteristics including enhanced solubility, enhanced catalytic activity, or altered optical behaviour. Nanostructured materials are those that have structural components like molecules, crystallites, or clusters with sizes ranging from 1 to 100 nm. Many consumer goods, including fabrics, paints, sunscreens, and other medical supplies, already include nanomaterials in the form of artificial nanoparticles. To just a few, extensive research is being conducted on the use of nanomaterials for solar cells, composite materials, medicines, life science applications, energy storage and conversion, and catalysis [6].

This classification divides nanomaterials into three groups: two-dimensional, one-dimensional, and zero-dimensional. A material is classified as having a 0-dimensional nanostructure if all three of its dimensions are inside the nanometre range. A material's nanostructure is one-dimensional if two of its dimensions fall within the nanoscale. A two-dimensional nanostructure is one that has one dimension in the nanometre range. Fig. 1 displays electron microscope pictures and schematics of zero-, one-, and two-dimensional nanomaterials. One of the most significant categories is the classification of nanomaterials according to their dimensions. These three kinds of nanostructures differ greatly from one another in terms of qualities and applications as well as synthesis and production methods. Each of these three nanomaterials has a unique set of applications due to the substantial differences in their electrical, optical, magnetic, surface, and other characteristics [7].

These nanomaterials can be composites made of dispersions of nanoparticles, nanowires, nanotubes, or nanolayers attached to a matrix core. They can be made wholly of multinanolayers, have crystalline or amorphous structures, and be metals, ceramics, or polymers. More sophisticated structures include "metal-organic frameworks and combinations of carbon-based, metal-based, or organic-based nanomaterials" with any kind of metal, ceramic, or polymer bulk materials. Coatings and thin films applied on structural bulk materials to increase wear resistance, friction resistance, or corrosion resistance are also classified as nanostructured materials, even if the bulk characteristics of the underlying material are the same [8].

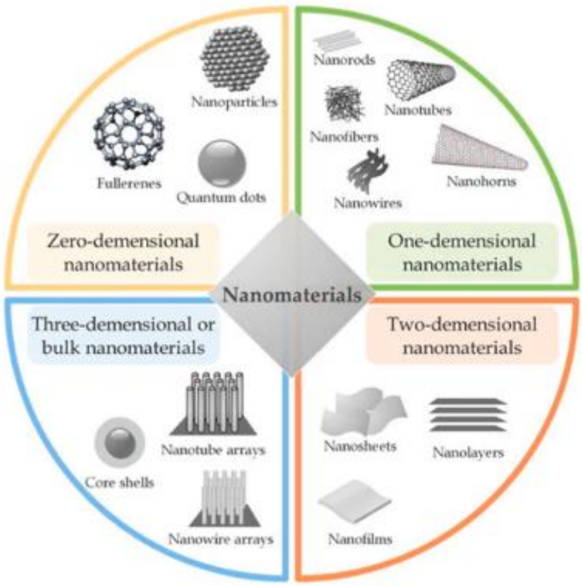

Figure 1: Schematic of types of zero, one and two- and three-dimensional nano- materials [7]**.**

Application of nanostructure material

In the chemical and cosmetic sectors, nanoscale chemicals and compounds, pigments, and coatings in materials science, as well as in nanomedicine disciplines such as "nano medicines, medical devices, and tissue engineering, nanostructures" are utilised in a diverse array of applications, as demonstrated in Table 1 [7], [9].

- **Medicine & Healthcare:** Nanoparticles based on gold and iron are also used in the diagnosis of cancer and delivery of drugs directly to tumor sites. Nanotubes are also applicable in the cardiovascular tissue engineering.
- **Electronics & Photonics:** Carbon nanotubes and silicon nanoclusters can be used to make smartphone displays flexible and capable of folding, as well as nanoceramics can be used to enhance memory chips and the reliability of circuit breakers.
- **Energy & Environment:** MnO2 nanorods find use as electrochemical capacitor and high temperature superconductors. Different nanomaterials such as graphene are employed to disinfect water by killing pathogenic bacteria.
- **Agriculture & Food Industry:** Nano-sensors control the environment of the soil and the development of crops, and the silver-silica nanoparticles are used as anti-fungal agents to

control the growth of crops. Food shelf life is made longer by use of nano-packaging.

- **Automotive & Industrial:** Nanomaterials develop more powerful and light materials to be used in the vehicle bodies. Nano-coatings are used to reduce engine erosion, and the so-called railplugs are used to increase engine fuel efficiency.
- **Consumer Goods:** Silver nanoparticles find extensive applications as antimicrobial agents in paints, cosmetics and textiles.

"Table 1: Summary of some applications of nanostructure [7]**.**

Field of application	Principles of application	Nanostructure
Solar cell	Transform photon energy into electrical energy	Ag NW, Cu NW ITO
OLED	To emit light	ITO electrodes
Super capacitor	High power storage and a very quick charger or discharger	Lithium, sodium, potassium
Transistor	For electrical power switching or amplification	Si & Ge
Lithium-ion batteries	Produce rechargeable batteries	Carbon nanotubes, nanosized transition metal oxide, nano-sized composite material
Imaging	Ability to enter cells, high-quality analytical signals	Ag and Cu bimetallic nanoparticles
Cancer diagnosis	Biomedical Imaging for the Identification of Tumours and Cancer	Gold and iron-based nanoparticles
Drug delivery and cancer therapy	Therapeutic effectiveness and precision targeting are among the goals of medication delivery.	Au nanoparticle, silicon nanoparticle, carbon nanotube, nano graphene
Biomedicine	Gene delivery	CNTs
Micro-electronics	To produce faster logic gates	Carbon nanotube, lead telluride, cadmium sulphide
Environmental	Increase growing rate of plants	CNTs
Energy	Media for alternating energy storage	CNTs
Car tires	Mechanical reinforcement	Carbon block

Current scenario of nanostructured materials in biomedical sector

The use of nanoparticles and nanostructures in several therapeutic and medical applications has been extensively studied by material scientists over the last fifty years. In order to expand its use in the biomedical area, the synthesis of nanostructures has recently been created at an advanced level with greater efficiency". Colloidal inorganic nanocrystals have attracted a lot of attention in the biomedical sector because to their fascinating size-subordinate properties, such as their restricted surface plasmonic influence and quantum control impact, which are not visible in their bulk form [10]. Recent research has focused on mesoporous nanostructures for therapeutic drug delivery to cancer cells with minimal drug leakage into active cells. Mesoporous nanostructured materials' increased porosity, surface functionality, and tiny pore diameters allow for effective medication loading at the target location and regulated drug release. In other areas, the ongoing advancements in image-guided treatments like magnetic resonance imaging (MRI) and CT scans have made magnetic nanoparticles even more significant [11]. Additionally, these nanoparticles are commonly employed in advanced cancer theranosis due to their beneficial properties, which include "X-ray absorption, high energy transfer efficiency", and the generation of reactive oxygen radicals. The increasing demand for molecular diagnostic devices is perfectly accommodated by nanostructured sensors, which possess a wide dynamic range, excellent sensitivity, discrimination, multiplexing, rapid reaction times, and the capacity for continuous analysis [12].

Sensors are needed in addition to diagnostic tools to study biological systems, predict the course of disease, and rationally develop better treatments for patients. One of the key factors restricting the use of nanoparticles is their safety, which is still a major concern. When these compounds are meant to enter the human body—whether intentionally or accidentally—the concern grows [13]. The prospective benefits of nanoparticles might be highly optimistic, which emphasises the risks associated with their use. Concerns about nanostructures' potential toxicity and harmful effects on human health are growing, as is the lack of a systematic method for evaluating their toxicology. Additionally, it was noted that bare and tiny nanostructures were more hazardous than bulk and modified nanostructures, respectively [14]. Nanomaterials are deployed extensively in drug delivery due to their extensive "surface area and nanoscale dimensions". The most extensively researched topic in drug delivery to the brain is currently nanoparticles, which are able to traverse the blood-brain barrier [15]. Fig. 2 shows the overall significance that nanoparticles have earned recently in several biological fields. Additionally, this image explains how nanoparticles are made, their special qualities, and how they may be used in a variety of biological and health-related fields [16].

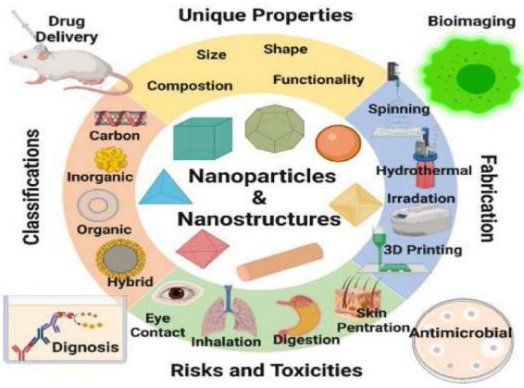

Figure 2: Recent subject on nanoparticles and nanostructured materials and their uses in numerous health and biomedical sectors [17]

LITERATURE REVIEW

(Anastasiou et al., 2024)[18] Cosmetic products are undergoing a rapid transformation in our society, as their utilisation is becoming more widely acknowledged as crucial to personal well-being. This emphasises how important it is to have a thorough grasp of nanoparticles (NPs) in cosmetics. The limits of conventional cosmetics are addressed by nanotechnology, which also adds advantageous aspects to formulations. For usage on skin, hair, nails, lips, and teeth, nano-cosmetics and nanocosmeceuticals have undergone significant research, showing improved effectiveness and increased consumer satisfaction. As a result, nanocosmeceuticals are gradually taking the place of conventional cosmeceuticals. The use of nanostructured materials in cosmetics raises questions over their immediate and long-term safety as well as their environmental impact, despite their growing popularity. This study aims to provide a critical and comprehensive review of the impact of nanostructured materials in advanced cosmetic formulations, highlighting their benefits for next-generation products, while acknowledging the ongoing concerns about nanotechnology in cosmetics. Nanocosmetics are a revolutionary advancement in personal and medical care, providing creative answers to a range of problems.

Table 2: List of various nanomaterials used in cosmetic industry

Nanomaterials	Application
Gold nanoparticles, silver nanoparticles, carbon black	Face care
Titanium dioxide, zinc oxide, Tris-biphenyl triazine	Skin care
Hydroxipatite	Oral care
Silicon dioxide Oral	Lip care

(Aydin, 2024) [19] Water contamination brought on by dangerous materials including metals, medications, insecticides, and pesticides has grown to be a major environmental and health issue in recent years that need immediate attention. The growing population's nutritional requirements also raise the demand for water and cause the pace of freshwater consumption to rise quickly. Nanostructured membranes are attractive as alternative water treatment options when it comes to the purification of various types of contaminants in environmental research. Recent studies provide an overview of nanostructured membranes that can be utilised for water treatment and filtration. In water treatment procedures, a variety of nanostructured membrane types are introduced and utilised to eliminate metallic ions and salts. These membrane systems' applications and representations are described. As a result, novel nanostructured membranes for water treatment are presented together with their efficient separation capabilities. The advantages of using nanostructured membranes to clean water and their advancements in purification are examined.

(Qin et al., 2024) [20] Magnetic, phase-change, and ferroelectric materials are thought to be viable options for cutting-edge memory systems. Ferroelectric materials' unique polarisation properties and range of manufacturing techniques make them stand out in the development challenge of traditional silicon-based memory devices. On the centennial of ferroelectricity, it was discovered that scandium-doped aluminium nitride, a unique wurtzite structure, was ferroelectric with "a higher coercive, remanent polarisation, curie temperature, and more stable ferroelectric phase". The inherent advantages have attracted a lot of interest because they promise superior performance when used as data storage materials and better meet the demands of the growth of the information age. In this study, we begin with the properties and development history of “ferroelectric materials”, with a particular emphasis on the properties, synthesis, and applications of ferroelectric wurtzite AlScN in memory devices. It assesses and compares the unique advantages of AlScN-based memory devices in an attempt to create a theoretical foundation for the future development of complex memory systems.

(Panigrahi et al., 2024) [21] Gas sensors are used in a wide range of sectors, including public safety, clinical diagnostics, pharmaceuticals, medical engineering, and food monitoring. Nanomaterials are outstanding candidates for application in gas sensing technologies because of their intrinsic properties, such as their ability to physically or chemically adsorb gas and their high surface to volume ratio. Furthermore, the nanomaterial-based gas sensors are very cost-effective, durable, repeatable, and selective. The study on gas sensor systems based on nanoparticles of different sizes is summarised in this review article. The many nanomaterial-based gas sensors, their production processes, sensing methods, and the latest developments are all thoroughly discussed. The main features of gas sensing devices constructed from different dimensions nanomaterials were also assessed and contrasted.

(Saud et al., 2024) [22] These days, desalination and water purification procedures heavily rely on nanotechnology. However, if nanoparticles (NPs) are released into the environment without the necessary precautions, they may cause chemical and physical harm. Water filtering has shown interest in the use of biobased nanomaterials (bio-NMs) generated from biomass due to its affordability, biocompatibility, and biodegradability. Numerous research have been conducted to efficiently produce NPs (both organic and inorganic) for use in wastewater treatment. Biosynthesised materials, including "zinc oxide nanoparticles, phytogenic magnetic nanoparticles, biopolymer-coated metal nanoparticles, cellulose nanocrystals, and silver nanoparticles", have been demonstrated to enhance water purification. Eliminating water pollution may be made more sustainable and effective by using eco-friendly NPs. This review explores biomass, its sources, and how it may be converted into NPs in an environmentally friendly manner. The use of greener NPs in modern wastewater and desalination systems will be investigated in this study.

(Shahid & Alam, 2024) [23] Due to their diminutive size, nanomaterials possess distinctive characteristics in the areas of optical, magnetic, electrical, and physical properties, including responsiveness, durability, surface area, sensitivity, and persistence. Nanoscale matter is different from matter in the liquid, gaseous, solid, and plasma phases due to its size and forms. Aim for materials with thicknesses between a few nanometres and several microns for producing thin films. Thin film technology is gaining a lot of interest worldwide because of its many applications. These characteristics provide the films remarkable qualities and functions when compared to conventional films manufactured of the same substance. For their adaptability, flexibility, affordability, and low weight, patterned polymer thin films are indispensable components of a wide range of devices. The future of nanostructured thin-film technology is really bright. The kinds, characteristics, production techniques, and applications of nanomaterials in a variety of sectors are all thoroughly examined in this paper.

"Table 3: Deposition techniques with advantage and disadvantage Deposition

Deposition Techniques	Advantages	Disadvantages
Electron beam Evaporation	Production rate high	% Yield is low
Chemical vapor deposition technique	Deposition rate high with thick coating	High temperature required
Sol gel method	High adhesive strength	Expensive
Hydrothermal deposition	Control size distribution	Expensive and some safety issue
Pulsed laser deposition	Porous coating	Expensive
Sputtering evaporation	High deposition rate	Difficult to control deposition
Chemical deposition	Throughput high	Reactive gas toxicity
Physical vapor deposition	Dense coating	Low coating rate

(Zhang et al., 2024) [24] provide a novel superparamagnetic metal oxide nanoparticle for imaging tumour xenografts in live mice that has a controlled chemical composition and magnetism". A simple one-pot co-precipitation process in water is used to create superparamagnetic Zn/Fe mixed metal oxide (ZnFe-MMO) nanoparticles, which are then thermally decomposed at different calcination temperatures and with adjustable Zn/Fe ratios. This work introduced metal oxides produced from LDH for an MPI application for the first time. An optimal MPI performance may be achieved by adjusting the metal composition. According to the analytical data, "ZnFe-MMO nanoparticles" at the intended molar ratio of Zn/Fe = 2:1 after calcination at 650 °C show an ideal MPI signal and a greater saturation magnetisation (MS) value than samples under other conditions. Both fibroblast cell cultures and breast cancer cells exhibit ZnFe-MMO's exceptional biocompatibility. In vivo imaging of 4T1 cancer xenografts in mice using ZnFe-MMO as a tracer highlighted ZnFe-MMO's promise for long-term MPI imaging applications.

The mean signal intensity was 1.27 times higher than that of the commercial tracer VivoTrax at 72 hours after injection.

(Das et al., 2020) [25] A flexible method for producing a range of nanomaterials with regulated size and form is the reverse microemulsion (ME) based synthesis. To achieve the required shape and size, the several elements involved in the production of a ME must be optimised. Data storage, biological imaging, therapies, catalysis, and sensor applications are just a few of the sectors where magnetic materials are extremely important. It is observed that the magnetic characteristics of the nanostructures produced using ME techniques differ from those produced using other techniques. Furthermore, the size and shape of the nanostructures, even those created via the ME approach, affect their magnetic characteristics. Therefore, a desirable goal of many research initiatives is to adjust the size and shape of the nanostructures to customise the magnetic characteristics. The nanostructures created using the ME approach whose magnetic properties were examined are thoroughly covered in this mini-review.

RESEARCH GAP

Although a lot of research has been conducted on nanostructured materials, there exists a number of gaps in understanding the full potential and the limitations of these materials. The current literature tends to be more application-specific than offering an integrated review of classification, applications, and biomedical innovations. Little comparative analysis of various dimensional nanomaterials (0D, 1D, 2D) in relation to performance and efficiency in applications have been made. Also, there has been a lack of focus on the toxicity, environmental impact, and long-term safety of nanomaterials, particularly in the biomedical field. There are also no standardized ways of assessing the properties and risks of nanomaterials. Moreover, the relation between synthesis methods and the functional performance is not thoroughly studied. It is necessary to fill these gaps in order to make the safe, efficient and sustainable use of nanostructured materials in different industries possible.

OBJECTIVE

1. To study the nanomaterials and its classification.
2. To study the application of nanostructure material.
3. To study the current scenario of nanostructured materials in biomedical sector.
4. To study the various literature on nanostructure material and their properties.

RESEARCH METHODOLOGY

This review paper is based on a systematic analysis of previously published research articles, review papers, and technical reports related to nanostructured materials. The literature is considered to be published during 2015-2024 to make sure that recent advances and developments are included. Peer-reviewed journals and conference papers were used to gather relevant data on nanomaterial classification, synthesis techniques, applications and biomedical applications. The gathered literature was critically examined and classified along required themes that included: dimensional classification, physical properties and area of application. The comparative analysis was done to determine the trends, challenges, and research gaps. They were also keen in analyzing reliability and relevance of sources to ensure accuracy and completeness in presenting the findings of nanostructured materials research.

DISCUSSION

The review indicates that nanostructured materials have outstanding properties which make them noticeable in their performance in various applications. The dimensionality in which they are classified is a very important factor in how they will act physically and also how suitable they will be in certain applications. As examples, 0D nanomaterials (quantum dots) are commonly used in imaging, with 1D and 2D materials (nanotubes and graphene) playing significant roles in electronics and energy applications. The biomedical field has been characterized by astonishing developments, especially in drug delivery, cancer diagnosis, and imaging technologies, owing to the special properties of the nanoparticles. Nonetheless, issues of toxicity, environmental effects, and non-standardized methods of testing are all critical issues. As the literature review shows, the research on nanotechnology is rapidly developing, particularly on sustainable and biocompatible materials. Comprehensively, although nanostructured materials have tremendous potential, concerns about safety and scalability must be met to allow nanostructured materials to be used widely and responsibly.

CONCLUSION

Nanostructured materials are an area of rapid development with a great potential to revolutionise the modern technology and industry. Their size-dependent properties allow new applications in electronics, energy systems, healthcare, environmental protection, and so on. The review has articulated the classification of nanomaterials, their various applications and the increasing role of nanomaterials in the biomedical sector. It also reviewed recent literature to bring out the new trends in synthesis methods, functional properties, and new trends. Although they have benefits, they have some challenges which include toxicity, environmental risks and lack of standardization which must be addressed so as to achieve safe use and sustainable use. The future studies are supposed to be devoted to the development of eco-friendly nanomaterials, the enhancement of the synthesis process, and the establishment of regulation frameworks. Nanostructured materials can be useful in improving the quality of life and sustainable development of any industry by overcoming these limitations.

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