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REVIEW OF NANOSTRUCTURED NANOMATERIALS IN BIOMEDICAL, ENVIRONMENTAL, AND ENERGY SECTORS

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Abstract

Nanostructured nanomaterials have emerged as a transformative force across multiple sectors, including biomedical, environmental, and energy fields, due to their unique properties and versatile applications. In the biomedical sector, these materials enhance drug delivery systems, enabling targeted and controlled release, and improve diagnostic techniques through advanced imaging technologies. Their small size, high surface area, and biocompatibility make them ideal for use in tissue engineering and regenerative medicine. In the environmental sector, nanostructured materials are pivotal in water purification, pollutant removal, and air filtration, owing to their high reactivity and adsorption capacity. Additionally, they play a significant role in developing sustainable energy solutions. Nanomaterials are crucial in creating high-efficiency photovoltaic cells, advanced batteries, and fuel cells, enhancing energy storage and conversion technologies. This review highlights recent advancements in nanostructured nanomaterials and discusses their potential to revolutionize these sectors. It also addresses the challenges associated with their synthesis, scalability, and potential environmental and health risks. Future research should focus on optimizing the properties of these materials, understanding their long-term impacts, and developing safer and more sustainable applications to fully harness their potential in advancing biomedical, environmental, and energy technologies.

Introduction

Nanostructured nanomaterials have gained substantial attention in recent years due to their exceptional properties and wide-ranging applications across various fields, including biomedical, environmental, and energy sectors. These materials, characterized by their nanoscale dimensions and high surface area-to-volume ratios, exhibit unique physical, chemical, and biological properties that differ significantly from their bulk counterparts. This distinct behavior arises from the quantum effects and surface phenomena that become prominent at the nanoscale, making them ideal for applications that require high reactivity, enhanced strength, or tailored electronic and optical properties.

In the biomedical sector, nanostructured nanomaterials have revolutionized drug delivery systems, enabling more precise targeting of therapeutic agents to specific cells or tissues, thereby minimizing side effects and improving treatment efficacy. They are also integral to the development of advanced imaging techniques and biosensors, providing enhanced sensitivity and specificity for early disease detection. Furthermore, their biocompatibility and ability to mimic the extracellular matrix make them promising candidates for tissue engineering and regenerative medicine. Environmentally, nanomaterials play a crucial role in addressing some of the most pressing ecological challenges. They are used in water purification processes, where their high surface area and reactivity enable efficient removal of contaminants, and in air filtration systems, where they help in capturing harmful pollutants. Additionally, they are being explored for their potential to break down hazardous substances in soil remediation efforts. In the energy sector, nanostructured materials are driving significant advancements in renewable energy technologies. They are central to the development of next-generation solar cells, which promise higher conversion efficiencies and lower production costs. Moreover, their application in batteries and fuel cells is crucial for enhancing energy storage capabilities, a key requirement for the widespread adoption of renewable energy sources. This review aims to provide a comprehensive overview of the recent advancements in nanostructured nanomaterials and their applications in these critical sectors. It will explore their potential benefits, the challenges in their development and deployment, and future research directions needed to fully exploit their capabilities.

Overview of Nanostructured Nanomaterials

Nanostructured nanomaterials, a cornerstone of nanotechnology, are materials engineered at an atomic or molecular scale, typically within the range of 1 to 100 nanometers. This size range is crucial as it endows the materials with unique properties that differ significantly from their bulk counterparts. These materials exhibit extraordinary mechanical, electrical, thermal, and optical characteristics, which arise from the quantum effects and increased surface-to-volume ratio at the nanoscale. The manipulation of materials at this scale allows for the design of structures with specific functions, making nanostructured materials versatile and highly valuable across various fields of science and technology.

At the heart of nanostructured materials lies the ability to tailor their properties to suit specific applications. For instance, carbon-based nanomaterials like carbon nanotubes and graphene have remarkable strength and conductivity, making them ideal for applications in electronics, composite materials, and energy storage devices. Similarly, metal-based nanomaterials, such as gold and silver nanoparticles, are widely used in medical diagnostics, drug delivery, and catalysis due to their biocompatibility and unique chemical reactivity. Polymer-based nanomaterials and composite nanomaterials, which combine organic and inorganic components, further expand the functionality and application potential of nanomaterials in areas such as biotechnology, environmental remediation, and sustainable energy solutions.

The application of nanostructured nanomaterials extends across numerous industries, including biomedicine, where they are used in targeted drug delivery systems, advanced imaging techniques, and regenerative medicine. In the environmental sector, these materials contribute to pollution control, water purification, and the development of sensors for monitoring environmental changes. The energy sector, too, benefits from nanomaterials in the form of more efficient solar cells, batteries, and fuel cells, driving advancements in renewable energy technologies. Despite their potential, the rapid development of nanostructured nanomaterials also necessitates a thorough understanding of their environmental and health impacts, as well as the establishment of regulatory frameworks to ensure their safe and sustainable use. nanostructured nanomaterials represent a significant leap forward in material science, offering innovative solutions to many of today's technological challenges.

Importance and Relevance of Research

The research into nanostructured nanomaterials holds critical importance and relevance in today's rapidly evolving scientific and technological landscape. As global challenges such as healthcare crises, environmental degradation, and energy shortages intensify, there is an urgent need for innovative solutions that can address these issues efficiently and sustainably. Nanostructured nanomaterials, with their unique properties and vast potential applications, represent a frontier in this quest for innovation. Their ability to enhance the performance of existing technologies and enable the development of new ones makes them indispensable in various sectors, including biomedicine, environmental protection, and energy.

In biomedicine, the application of nanostructured materials can revolutionize disease diagnosis and treatment. The precision with which these materials can be engineered allows for the creation of highly targeted drug delivery systems, minimizing side effects and improving patient outcomes. Their use in medical imaging and regenerative medicine opens new avenues for early detection of diseases and the repair of damaged tissues, contributing to the advancement of personalized medicine. This research is not only relevant for improving individual health outcomes but also has the potential to significantly reduce healthcare costs by making treatments more effective and efficient.

From an environmental perspective, the ability of nanostructured materials to purify water, clean the air, and remediate polluted sites is of paramount importance as the world grapples with the consequences of industrialization and urbanization. These materials offer innovative approaches to managing and mitigating environmental impacts, making them central to efforts aimed at achieving sustainability. In the energy sector, the role of nanomaterials in enhancing the efficiency of renewable energy technologies and storage systems is crucial for the transition to a low-carbon economy. By improving the performance of solar cells, batteries, and fuel cells, nanostructured materials contribute directly to the global push for clean energy solutions.

The research into nanostructured nanomaterials is not only a scientific imperative but also a societal one, offering the potential to address some of the most pressing challenges of our time and paving the way for a more sustainable and technologically advanced future.

Literature Review

Ramos, Ana & Cruz, Marcos & Tovani (2021) With the ability to dissect molecules down to their molecular structure, the search for remarkable materials with medical applications has accelerated. Nanobiotechnology, the study of how these novel materials are used to detect disease, create new medicines, and implant prosthetics, is a relatively young but critically important field of study. Carbon nanotubes, liposomes, metallic and metal oxide nanoparticles, and nanopatterned flat surfaces are just a few of the materials and techniques discussed, all of which find use in various biological applications. Diagnostics, biosensing and bioimaging instruments, drug delivery systems, and bone replacement implants are all possible uses for these materials because of their chemical and physical properties on their surfaces. Nanotoxicology, a new field that studies how nanostructured materials affect their surroundings, including investigations into nanoparticle toxicity.

Nikalje, Anna (2015) The study of very tiny structures, ranging in size from 0.1 to 100 nm, is known as nanotechnology. A relatively recent area of science and technology is nanomedicine. The several kinds of pharmaceutical nanosystems are briefly explained. Nanomaterials are categorised according to their dimensions. In-depth discussion is given on the use of nanotechnology in a number of industries, including electronics, energy, and the environment. Nanoparticle applications in cancer, protein and peptide delivery, and medication delivery are described. Cancer therapy using various nanosystems, including carbon nanotubes, dendrimers, nanocrystals, nanowires, and nanoshells, is described. Improvements in nanotechnology have facilitated the treatment of neurodegenerative disorders like Parkinson's and Alzheimer's. Clinical applications of nanotechnology are discussed, including their use in the treatment of tuberculosis (TB), as well as in operational dentistry, ophthalmology, surgery, visualization, tissue engineering, antibiotic resistance, and the immune response. Nanomaterials in pharmaceuticals could significantly improve early disease diagnosis.

Bhattacharya, Priyanka & Du, Dan & Lin, Yuehe (2014) Scientists working in several disciplines have been inspired by nature to create materials with special qualities including miniaturisation, hierarchical structure, and flexibility. This is because there is a growing need for eco-friendly, reasonably priced, and ecologically sustainable materials. The subject of bioinspired nanomaterials has advanced significantly during the last century, along with the extraordinary features of nanoparticles. Synthetic control over the development of nanomaterials enables the construction of materials with specialized functions, just as complex hierarchical structures give biological systems the ability to perform a wide range of tasks. The purpose of this article is to provide readers with an up-to-date, comprehensive understanding of bioinspired nanomaterials, which we will broadly classify as either biotemplates or biomimics. Using examples from catalysis, nanomedicine, immunoassays, and energy, we highlight cutting-edge materials like protein cages that have been inspired by nature. Application of bioinspired materials in tissue engineering and biomineralization is also discussed.

Choe, Han-Cheol & Yeung, Kelvin (2010) The use of modified and functionalized nanostructures into diverse biological applications has recently attracted a great deal of scientific attention. Nanotechnology has a wide range of uses in biomedical engineering and medicine, including the development of implants and tissues as well as diagnostic and therapeutic procedures. The current environment necessitates the construction of nanotools that can address biological issue requirements and provide more effective biomedical strategies. This article examines recent advances in nanobiotechnology with a focus on innovative tissue-engineered scaffolds and load-bearing implants. Additionally addressed are cutting-edge nanomedicine research methodologies and significant obstacles to real-world applications.

Bueno, P. R., & Gabrielli, C. (2009) In this study, we discuss the synthesis and design of functional electrodes and electrolytes, two key components of electrochemical cells, and how these components can be used to create more efficient electrochemical cells whose sole purpose is the conversion and storage of energy. This chapter covers the fundamentals of electrochemistry dictating the impacts of nanoscale design on electrodes and electrolytes, as well as introducing unique tactics that use nanoscale structures to improve the efficiency of alternative energy conversion and storage devices. Additionally, the chapter summarizes the most important ideas concerning electron transfer that are important to understand while working with electrochemistry and renewable energy devices.

Mabrouk, M., Das, D. B. et al,(2016) The development of novel biomedical applications has pushed the design of nanomaterials to the forefront of scientific inquiry. It has been increasingly clear in recent publications that comprehensive studies focusing on the design and manufacture of nanomaterials are lacking. Because of their impact on nanoparticle performance, size, shape, surface charge, and microstructure are all essential considerations (NPs). The procedures used in their creation have been discovered to have an effect on these parameters as well. Characterization methods used to study these nanomaterials vary widely in their underlying principles, sample preparation procedures, and final findings. Therefore, the goal of this review article is to have an in-depth discussion on the latest advancements in nanomaterials for biomedical engineering, with a special emphasis on the selection of nanomaterials, preparation methods/instruments, and characterization techniques used in the design of nanomaterials. We also briefly discuss the significant roles that these nanomaterials play in a variety of fields, such as tissue regeneration, drug delivery, and wound healing. Filling in this information void will improve our comprehension of the promise and challenges inherent in nanomaterial creation and eventual large-scale applications.

Sarfraz, N., & Khan, I. (2016) Controlling the particle size and shape of standard AuNPs can induce plasmonic features, particularly localized surface plasmon resonance (LSPR), which can significantly improve electrical, electrochemical, and optical properties. Plasmonic gold nanoparticles (AuNPs) can be used in a wide variety of energy, environmental, and biological settings, and their production relies heavily on synthetic processes and adaptable fabrication methods. This review aims to help readers get familiar with the experimental procedure for each of the many synthetic strategies for creating highly plasmonic AuNPs. In the review's final section, we focus on cutting-edge, recently developed uses of solar-induced energy, environmental, and biological technologies. The methods of synthesis are examined in order to determine the most appropriate synthetic route that may be followed when using plasmonic AuNPs for a certain application. The review's instructional format is useful not only for seasoned professionals in the field of nanomaterial synthesis and applications, but also for those new to the field.

Mughal, B., Zaidi, S. Z. J. et al,(2016) Nanotechnology is increasingly important in many areas of modern life, from the biomedical to the energy. Nanoparticles can be synthesized for a wide variety of uses using a wide variety of physicochemical and biological techniques. The use of microorganisms for the biogenic synthesis of nanoparticles has many advantages over traditional methods and is thus receiving growing attention. Nanoparticles can be biogenically synthesized by microorganisms like bacteria, fungi, and algae, and this review looks at how they can be used. Nanoparticles can be synthesized in a variety of microorganisms, each of which provides a unique environment for the process. However, there are a number of challenges that must be overcome in order to achieve optimal production and minimal time to obtain the desired size and shape, to increase the stability of nanoparticles, and to optimise particular microorganisms for particular applications. Numerous medical, environmental, pharmaceutical, and biochemical sensor uses for biogenic nanoparticles are discussed.

Almatroudi, A. (2021) Nanotechnology is a rapidly growing field because of its novel properties and wide range of possible applications. Nanomedicine is the study of how insights and methods from nanotechnology can be applied to healthcare, specifically to improve and ensure the health and safety of individual patients. Silver nanoparticles with diameters between 1 and 100 nm are highly prized due to their wide range of beneficial properties, including their ability to kill bacteria and cancer cells, speed up the healing process after an injury, and treat other medical conditions at a low cost. In this study, we investigate the physical, chemical, and biological techniques used to produce silver nanoparticles. In addition to their antitumor properties, silver nanoparticles have been put to use in dentistry and dental implants, in the treatment of wounds, in the repair of bone and cardiovascular implants, and in the acceleration of wound healing. The paper also delves into the mechanism of action, synthesis techniques, and morphological characterization of silver nanoparticles to determine their role in medicine and disease management.

Pokropivny, V. V., & Skorokhod, V. V. (2007) Materials used in nanotechnology are called nanostructured materials (NSMs), and they are defined as two- or three-dimensional (2D) materials with size effects due to the use of building units on the nano- or sub-micron scale. Any area of research requires structure before making any headway. The need for categorizing these materials has become more critical since the last decade has seen the discovery of hundreds of new NSMs and an abundance of unique nanostructures (NSs). Intercrystalline grain boundaries that run parallel to crystallites are treated as building blocks in Gleiter's scheme for classifying NSMs, which in turn is based on crystalline morphologies and chemical composition. Unfortunately, this plan was flawed since it ignored 0D and 1D structures like fullerenes and nanotubes. This means that instead of the standard 12 categories, there are only 3 with 4 subcategories under this system.

Nasrollahzadeh, M., Issaabadi, Z. et al,(2021) The unusual physicochemical and plasmonic features of nanostructured materials, as well as their prospective applications, have garnered a significant deal of scholarly attention in recent years. Because of their unique physicochemical and biological qualities, nanoscale materials can be used in a wide variety of innovative ways, from improving energy efficiency to bolstering the durability of structures to fighting germs and even cleaning themselves. Opportunities for the production and improvement of hitherto undiscovered nanomaterials may come as a result of the discovery of novel nanoscale materials and structures, as well as the development of novel theoretical and experimental research approaches. Nanostructures have risen to prominence in technological advances due to the fact that their physicochemical properties, such as melting points, electrical and thermal conductivities, light absorption and scattering properties, optical sensitivity, (photo)catalytic activity, and wettability, can be adjusted, resulting in vastly improved performance over bulk counterparts. Businesses in the building and infrastructure industries are looking into the possibilities of using both man-made and naturally occurring nanomaterials. There are and will be further advancements in areas such as nanoelectronics, nanomedicine, sensor technologies, energy storage devices, and catalysts.

Pokropivny, V. V., & Skorokhod, V. V. (2008) Subject to nanotechnology, nanostructured materials (NSMs) are one- or two-dimensional materials with size effects due to their nano- or sub-micron-sized building components. The development of any branch of science relies heavily on systematic categorization. The past decade has seen the discovery of hundreds of new NSMs and a wealth of novel nanostructures (NSs), making it imperative that they be categorized. Gleiter suggested a classification scheme for NSMs based on crystalline morphologies and chemical content, in which low-dimensional nanocrystallites were viewed as building blocks on par with intercrystalline grain boundaries. As a result of the scheme's apparent lack of depth, however, we can only rate it as "not full" in the 0D and 1D dimensions (0D, 1D). In this case, nanoscale structures (NSs) like fullerenes and nanotubes (NTs) were ignored. His system only allows for three broad categories of NSMs, each of which contains four subtypes. There must be a reliable system for categorizing NSs, and one of the most important aspects of this is their dimensionality, which unifies their size and shape under a single umbrella. There is no limit to the variety of shapes that can be made from macroworld's 3D materials. Due to the lack of distinction between similarly sized and shaped NSs in the nanoworld, they can be treated as interchangeable. Therefore, it may be argued that several NS classes eventually become finite. The research aims to tackle the problem this poses for classifying contemporary NSs.

Belenkov, E. A., & Greshnyakov, V. A. (2013) Different phases and nanostructures made of carbon atoms have different properties despite sharing the same chemical make-up. Carbon materials can be organized in a variety of ways, making it easier to solve practical problems and identify materials with the needed qualities. Despite this, there are times when a carbon material is needed with characteristics that cannot be replicated by using any of the currently known carbon materials. So, it's important to figure out how to create new materials with the appropriate characteristics. New materials' potential for synthesis and their properties must be evaluated before any work can begin on their creation. It is intriguing to develop carbon phases and nanostructures based on classification schemes that can predict all the possible structural carbon types and the range of properties they can exhibit, given that different structural modifications at a fixed chemical composition can result in vastly different properties for carbon materials. Hybridized carbon atoms in distinct compounds can exist in a broad variety of states, each of which determines a unique set of attributes for the resulting substance. Using this classification system, the three most common valence states can be distinguished by their characteristic allotropic shapes: diamond with an sp3 hybridization structure (3D structure).

Stoner, B. R., & Glass, J. T. (2012) The high surface area and area specific capacitance of nanostructured carbons offer great promise for use in a range of electrode applications. As the importance of energy applications grows, so does the need to assess activated and nanostructured carbons in terms of their electrochemical charge-storage capacity. Gravimetric or area specific capacitance may be uninformative or even deceptive due to the importance of exposed linear edge density on charge transfer processes; edges exhibit roughly 20 higher specific capacitance than basal planes. Therefore, a stricter normalization is needed for materials with such high levels of severe anisotropy. By grouping nanostructures together according to their linear edge density, we can learn more about the properties of individual nanostructures and make more informed comparisons. The paper states that different types of carbon nanostructures can be distinguished by the degree of dimensional organization present in their edge structures. Here, we use the novel graphenated CNT hybrid as a morphological standard since it increases the linear edge density of nanostructured carbons by an order of magnitude. By considering the edge organization's dimensions, geometry allows us to calculate the edge density per unit nominal area.

Research Problem

Nanostructured nanomaterials represent a burgeoning field with transformative potential across biomedical, environmental, and energy sectors. This research endeavors to delve deeply into these materials, focusing on their synthesis, characterization, and practical applications. The significance lies in their unique properties at the nanoscale, including enhanced surface area, quantum effects, and versatile chemical reactivity, which make them exceptionally suited for targeted applications. By elucidating synthesis methodologies such as sol-gel and chemical vapor deposition, alongside advanced characterization techniques like TEM and XRD, this study seeks to uncover their structural, morphological, and chemical attributes. Practical applications will be explored, evaluating their efficacy in biomedical arenas such as drug delivery and bioimaging, environmental realms like water purification and pollutant degradation, and energy domains encompassing photovoltaics and energy storage. Through a systematic approach integrating literature review, experimental synthesis, characterization studies, and case analyses, this research aims to advance understanding of nanostructured nanomaterials. Ultimately, it seeks to foster innovations that address pressing societal needs and propel sustainable advancements across multiple sectors.

Conclusion

Nanostructured nanomaterials have demonstrated immense potential across biomedical, environmental, and energy sectors due to their unique properties and versatility. In biomedicine, these materials offer innovative solutions for drug delivery, diagnostics, and regenerative medicine, significantly improving therapeutic outcomes and disease management. Environmentally, they provide effective means for water purification, pollutant removal, and air quality enhancement, contributing to sustainable development goals. In the energy sector, nanomaterials are at the forefront of advancing renewable energy technologies, including high-efficiency solar cells, batteries, and fuel cells, which are crucial for transitioning to a low-carbon future. challenges remain in terms of scalability, cost-effectiveness, and understanding their long-term environmental and health impacts. Addressing these challenges requires continued research and development focused on optimizing their properties, enhancing their safety profiles, and developing sustainable manufacturing processes. Future advancements in nanotechnology should also consider ethical and regulatory aspects to ensure responsible development and application. the strategic integration of nanostructured nanomaterials across these sectors holds the promise of addressing some of the most pressing global challenges. By harnessing their full potential, we can drive innovation and sustainability, ultimately contributing to improved health outcomes, environmental preservation, and energy security worldwide.

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