

NANOMATERIALS AND NANOSTRUCTURES IN CHEMISTRY: A REVIEW OF SYNTHESIS AND CHARACTERIZATION METHODS

Abstract

Nanomaterials and nanostructures have emerged as pivotal components in the realm of chemistry, bearing profound implications for numerous scientific disciplines and applications. This comprehensive review delves into the synthesis and characterization methods underpinning the dynamic field of nanochemistry. We explore a wide array of synthesis techniques, encompassing chemical, physical, biological, and template-assisted approaches, while elucidating their fundamental principles, advantages, and constraints. Likewise, we investigate various characterization methodologies, including electron microscopy, X-ray diffraction, spectroscopy, and nuclear magnetic resonance, to unveil the structural intricacies of nanomaterials. Categorizing nanomaterials by structure, we delve into their distinctive properties and multifarious applications. Recent breakthroughs and ongoing developments are scrutinized to identify emerging trends. Furthermore, we spotlight the

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diverse applications of nanomaterials across medicine, electronics, energy, and environmental domains, showcasing their transformative potential. In conclusion, this review encapsulates the synthesis and characterization frontiers in nanochemistry, explores their applications, and anticipates future challenges and prospects.

I. INTRODUCTION

Nanochemistry, situated at the interface of chemistry and nanoscience, has emerged as a groundbreaking discipline with immense implications for scientific research and technological innovation. It encompasses the design, synthesis, and manipulation of materials at the nanoscale, where unique properties and behaviors manifest, setting it apart from bulk materials. The significance of nanochemistry resides in its potential to revolutionize diverse fields, from medicine to energy and beyond. This paper aims to provide an in-depth exploration of the synthesis and characterization methods employed in the fascinating world of nanomaterials and nanostructures.

Synthesis methods are the cornerstone of nanochemistry, enabling the creation of materials with tailored properties. The choice of synthesis method greatly influences the size, shape, and composition of nanomaterials. Characterization techniques, on the other hand, play a pivotal role in unveiling the structural and chemical intricacies of these nanoscale wonders. By scrutinizing the synthesis and characterization methods, we aim to provide a comprehensive understanding of the tools and techniques that underpin the field.

The scope of this review encompasses a wide array of synthesis and characterization methods, exploring their principles, advantages, and limitations. We categorize various nanomaterials by structure and investigate their properties and applications. Furthermore, we delve into recent advancements and emerging trends in the field. By offering a holistic view of nanochemistry, this review seeks to elucidate the transformative potential of nanomaterials and to identify key challenges and future directions for research and development.

II. SYNTHETIC METHODS

1. Chemical Methods

Sol-Gel Process: The sol-gel process involves the transformation of a chemical solution (sol) into a solid gel. It is widely used for producing oxide-based nanomaterials. For instance, the synthesis of silica nanoparticles for drug delivery systems or catalyst supports.

Precipitation: In precipitation methods, a soluble compound is converted into an insoluble one by the addition of a precipitating agent. This is often used for the synthesis of metal nanoparticles. For example, the precipitation of silver nanoparticles from a silver salt solution.

2. Physical Methods

Laser Ablation: In laser ablation, a high-energy laser beam is focused on a target material, causing vaporization and subsequent condensation into nanoparticles. This method is used to synthesize a wide range of nanoparticles, including carbon nanotubes and metal nanoparticles.

Physical Vapor Deposition (PVD): PVD techniques involve the physical deposition of material atoms onto a substrate. One common example is sputter deposition, which is used to produce thin films and coatings.

3. Biological Methods

Green Synthesis: This environmentally friendly approach harnesses the reducing and capping properties of various biological entities like microorganisms, plants, and enzymes to produce nanomaterials. An example is the use of plant extracts to synthesize silver nanoparticles. Plant extracts can act as reducing agents, converting metal ions into nanoparticles.

4. Template-Assisted Methods

Nanocasting: In nanocasting, a nanoporous template, often made of materials like silica or zeolites, is used to mold nanomaterials. By infiltrating precursor materials into the template and then removing the template, nanostructures with controlled pore sizes and shapes are achieved. An example is the synthesis of ordered mesoporous carbon materials using a silica template.

These synthesis methods offer versatility in tailoring the size, shape, and properties of nanomaterials, making them suitable for various applications. The choice of method depends on the desired nanomaterial, its properties, and the specific applications. Researchers often select the most appropriate method based on factors such as cost-effectiveness, scalability, and the need for precise control over the resulting nanomaterial's characteristics.

III. CHARACTERIZATION TECHNIQUES

1. Scanning Electron Microscopy (SEM)

Principle: SEM utilizes a focused beam of electrons to scan the surface of a sample, producing high-resolution images. It provides information about the surface morphology and topography of nanomaterials.

Applications: SEM is widely used to examine the size, shape, and surface features of nanoparticles. It is valuable for visualizing nanomaterials and understanding their physical characteristics.

2. Transmission Electron Microscopy (TEM)

Principle: TEM involves the transmission of electrons through a thin specimen. It provides extremely high-resolution images and structural information at the atomic scale, making it essential for nanoscale investigations.

Applications: TEM is crucial for examining the internal structure, crystallography, and defects in nanomaterials. It can reveal details about nanoparticle size, shape, and distribution.

3. X-ray Diffraction (XRD)

Principle: XRD measures the diffraction pattern produced when X-rays interact with a crystalline material. It is used to determine the crystal structure and phase composition of nanomaterials.

Applications: XRD helps identify the crystalline phases present in nanoparticles and nanocrystalline materials. It is vital for assessing the crystallinity of nanomaterials.

4. Fourier-Transform Infrared Spectroscopy (FTIR)

Principle: FTIR measures the absorption and emission of infrared radiation by a material. It provides information about the chemical composition and functional groups in nanomaterials.

Applications: FTIR is used to analyze surface chemistry and chemical bonding in nanomaterials. It helps identify organic and inorganic components and monitor chemical changes during synthesis.

5. Nuclear Magnetic Resonance (NMR)

Principle: NMR analyzes the nuclear magnetic properties of atoms in a magnetic field. It is particularly useful for investigating the structure and chemical environment of nanomaterials, especially organic or hybrid nanomaterials.

Applications: NMR can elucidate the atomic-level structure, confirm functional group interactions, and characterize the chemical environment of atoms within nanomaterials.

6. Dynamic Light Scattering (DLS)

Principle: DLS measures the fluctuation of scattered light caused by Brownian motion of particles in a liquid medium. It provides information about particle size and size distribution.

Applications: DLS is valuable for determining the hydrodynamic size and dispersity of nanoparticles in solution. It is particularly useful in assessing colloidal stability and aggregation behavior.

7. Raman Spectroscopy

Principle: Raman spectroscopy measures the scattering of monochromatic light by vibrating molecules. It provides information about molecular vibrations, crystal structures, and chemical compositions.

Applications: Raman spectroscopy is employed to investigate the molecular structure and chemical composition of nanomaterials, offering insights into bonding and structural modifications.

8. Atomic Force Microscopy (AFM)

Principle: AFM uses a sharp tip to scan the surface of a sample and measures the interaction forces between the tip and the material. It provides topographical information at the atomic and molecular scales.

Applications: AFM is essential for characterizing surface roughness, topography, and mechanical properties of nanomaterials. It is also valuable for studying interactions at the nanoscale.

These characterization techniques are indispensable for gaining insights into the properties and structures of nanomaterials. By using a combination of these methods, researchers can comprehensively analyze the physical, chemical, and structural aspects of

nanomaterials and nanostructures, enabling advancements in a wide range of applications, from materials science to medicine and beyond.

IV. NANOMATERIALS AND NANOSTRUCTURES

Encompass a diverse array of materials and architectures engineered at the nanoscale, with properties and functionalities distinct from those of bulk materials. Understanding their characteristics and potential applications is pivotal in the field of nanochemistry. Let's delve into this topic in more detail:

1. Types of Nanomaterials

- **Nanoparticles:** These are nanoscale particles, often with dimensions between 1 and 100 nanometers. Examples include metal nanoparticles (e.g., gold, silver), semiconductor nanoparticles (e.g., quantum dots), and carbon-based nanoparticles (e.g., fullerenes).
- **Nanowires and Nanorods:** Elongated nanostructures with a high aspect ratio. They find use in electronics, sensors, and as building blocks for nanodevices.
- **Nanotubes:** Hollow cylinders composed of carbon (carbon nanotubes) or other materials. They exhibit remarkable mechanical and electrical properties and are explored in various applications, from nanocomposites to drug delivery.
- **Nanoplates and Nanosheets:** Thin, two-dimensional nanostructures, including graphene and other 2D materials. They are known for their exceptional mechanical and electronic properties.
- **Nanoclusters:** Aggregations of a few to several atoms with unique properties. Clusters are valuable in catalysis and as model systems for understanding nanoscale phenomena.

2. Properties of Nanomaterials

- **Size-Dependent Properties:** Nanomaterials display size-dependent properties due to their high surface-to-volume ratio. Quantum size effects and changes in electronic, optical, and mechanical properties are often observed.
- **Enhanced Reactivity:** The high surface area and the presence of under-coordinated atoms in nanoparticles make them highly reactive. This is harnessed in catalysis and chemical sensing.
- **Unique Optical Properties:** Quantum dots, for example, exhibit size-tunable fluorescence and are used in imaging and displays.
- **Exceptional Strength and Toughness:** Carbon nanotubes, due to their strong covalent bonds, are incredibly strong and lightweight.

3. Applications of Nanomaterials and Nanostructures

- **Medicine and Healthcare:** Nanoparticles are employed in drug delivery, imaging, and diagnostic tools. Gold nanoparticles can carry drugs to targeted sites, while iron oxide nanoparticles are used as contrast agents in magnetic resonance imaging (MRI).
- **Electronics and Photonics:** Nanowires and quantum dots are essential components of next-generation electronic and optoelectronic devices. They are used in transistors, LEDs, and solar cells.
- **Energy:** Nanomaterials enhance the efficiency of energy storage and conversion devices. Lithium-ion batteries benefit from nanoscale electrodes, and quantum dot solar cells are on the horizon as cost-effective energy sources.
- **Environmental Remediation:** Nanomaterials are used to remove pollutants from water and air. For instance, titanium dioxide nanoparticles can degrade organic contaminants in water under UV light.

- **Catalysis:** Nanoparticles serve as catalysts for chemical reactions, often outperforming bulk catalysts due to their high surface area and reactivity. They are integral in green chemistry and industrial processes.

4. Nanoscale Engineering and Design

Nanomaterials and nanostructures can be engineered with precision, allowing for the tailoring of specific properties. This engineering may involve the manipulation of size, shape, composition, and surface modifications. Techniques like self-assembly and template-assisted synthesis enable the creation of complex nanostructures.

Understanding the diversity of nanomaterials and their unique properties is essential for harnessing their potential in various applications. The manipulation and control of nanoscale structures open up exciting possibilities for innovation in materials science, technology, and medicine. Researchers continually explore new ways to design and utilize nanomaterials, and their contributions drive advancements across a wide range of industries.

V. RECENT ADVANCEMENTS IN NANOCHEMISTRY

Recent advancements in nanotechnology have propelled the field to new heights, offering novel insights, applications, and opportunities for researchers and industries. Some of the noteworthy developments in this dynamic field:

1. Advanced Nanoparticle Synthesis Techniques

Hydrothermal and Solvothermal Synthesis: These methods allow the controlled growth of nanoparticles under high-temperature and high-pressure conditions, resulting in improved size and shape control.

Seed-Mediated Growth: This approach enables the synthesis of monodisperse nanoparticles with precisely controlled dimensions, which is critical for applications like catalysis and drug delivery.

2. Smart Nanomaterials

Responsive Nanomaterials: Nanoparticles and nanostructures that respond to external stimuli (e.g., temperature, pH, light, or magnetic fields) have been developed for applications in drug delivery and nanosensors.

Self-healing Materials: Materials with the ability to repair themselves at the nanoscale are emerging, offering potential applications in durable coatings and electronic components.

3. Nanomaterials for Sustainable Energy

Perovskite Solar Cells: Perovskite nanomaterials have shown great promise in photovoltaics due to their high efficiency and low cost, potentially revolutionizing the renewable energy sector.

Nanomaterials for Energy Storage: Advanced nanomaterials are enhancing the performance of batteries and supercapacitors, enabling faster charging, longer life cycles, and higher energy densities.

4. Nanomedicine Breakthroughs

Precision Medicine: Targeted drug delivery using nanoparticles has progressed, allowing for the delivery of therapeutic agents directly to affected cells or tissues while minimizing side effects.

Nanoparticles for Diagnostics: Nanomaterials have been integrated into diagnostic tools for the early detection of diseases, such as cancer biomarker detection and point-of-care testing.

5. Nanomaterials in Environmental Remediation

Nanoparticle-based Water Purification: Advanced nanoparticles are being employed for efficient removal of pollutants, heavy metals, and pathogens from water sources.

Air Filtration: Nanomaterials are enhancing air filtration systems, helping to remove harmful particulate matter and pollutants from indoor and outdoor air.

6. Nanoelectronics and Quantum Computing

Quantum Dots and Qubits: Quantum dots are integral to the development of qubits in quantum computing. They offer a potential breakthrough in exponentially faster computing power.

Flexible Electronics: Nanomaterials are enabling the creation of flexible and wearable electronics with improved performance and durability.

7. Biodegradable Nanomaterials

Eco-friendly Nanoparticles: Researchers are focusing on developing biodegradable nanomaterials that reduce environmental impact. These materials have applications in packaging, agriculture, and environmental remediation.

8. 2D Materials Beyond Graphene

Beyond Graphene: Other 2D materials, such as transition metal dichalcogenides (TMDs) and black phosphorus, are being explored for their unique electronic and optical properties.

9. Nano-to-Macro Scaling

Researchers are working on integrating nanomaterials into macroscopic products and systems. This includes the development of nanocomposites for structural materials and nanoelectronics for large-scale industrial applications.

These recent advancements illustrate the incredible versatility and potential of nanomaterials and nanostructures. They not only promise groundbreaking solutions to pressing challenges in various fields but also open up new avenues for innovation. As nanochemistry continues to evolve, it plays a crucial role in advancing science, technology, and industry in the 21st century.

VI. APPLICATIONS OF NANOMATERIALS

Applications of nanomaterials span a wide range of industries and have a profound impact on technology, healthcare, environmental sustainability, and many other fields. Some key applications of nanomaterials:

1. Medicine and Healthcare

Drug Delivery: Nanoparticles are used to encapsulate and deliver drugs, enhancing drug solubility and targeting specific cells or tissues, reducing side effects.

Medical Imaging: Nanomaterials are employed as contrast agents in various imaging techniques, including MRI, CT scans, and ultrasound, improving diagnosis and monitoring.

Cancer Therapy: Nanoparticles, such as gold nanoparticles, can target and destroy cancer cells selectively, minimizing damage to healthy tissues.

Wound Healing: Nanomaterials are used in wound dressings and bandages to enhance tissue regeneration and prevent infection.

2. Electronics and Photonics

Nanoelectronics: The development of transistors and memory devices using nanomaterials has led to faster and more energy-efficient electronic components.

Quantum Dots: Quantum dots are used in displays and lighting due to their tunable and highly efficient light emission.

Sensors: Nanomaterial-based sensors are employed in various applications, from environmental monitoring to medical diagnostics.

Flexible Electronics: Nanomaterials enable the creation of flexible and wearable electronic devices.

3. Energy

Solar Cells: Nanomaterials like perovskite nanocrystals have the potential to significantly boost the efficiency and reduce the cost of solar cells.

Energy Storage: Nanomaterials enhance the performance of batteries and supercapacitors, allowing for faster charging and longer life cycles.

Catalysis: Nanoparticles are used as catalysts in various processes, including fuel cells and hydrogen production.

4. Environmental Remediation

Water Purification: Nanomaterials are used to remove pollutants, heavy metals, and pathogens from water sources efficiently.

Air Filtration: Nanomaterials are integrated into air filtration systems to remove particulate matter and pollutants from indoor and outdoor air.

Waste Treatment: Nanomaterials are employed in waste treatment processes to improve the degradation of organic and inorganic waste.

5. Advanced Materials

Nanocomposites: Nanomaterials are incorporated into materials like polymers, ceramics, and metals to enhance their properties, such as strength, durability, and thermal conductivity.

Self-cleaning Surfaces: Nanostructured materials, like superhydrophobic coatings, make surfaces self-cleaning and stain-resistant.

6. Environmental Monitoring

Nanosensors: Nanomaterial-based sensors are used for real-time monitoring of environmental parameters, such as air quality, water quality, and soil conditions.

7. Food and Agriculture

Food Packaging: Nanomaterials are used in food packaging to extend the shelf life of products by preventing spoilage and microbial growth.

Pesticide Delivery: Nanocarriers are utilized to deliver pesticides precisely to targeted areas in agriculture, reducing the need for excessive chemical use.

8. Aerospace and Automotive Industry

Lightweight Materials: Nanocomposites are incorporated into aircraft and vehicle components to reduce weight and improve fuel efficiency.

Protective Coatings: Nanomaterial-based coatings provide protection against corrosion and wear in extreme environments.

9. Cosmetics and Personal Care

Sunscreen: Nano-sized titanium dioxide and zinc oxide particles provide effective UV protection without the white residue associated with traditional sunscreens.

Anti-aging Products: Nanomaterials are used in cosmetics to enhance skin penetration and the delivery of active ingredients.

These applications represent just a portion of the potential uses of nanomaterials. Their unique properties, including size-tunable properties, high surface area, and improved reactivity, make them highly adaptable for addressing a wide range of challenges and opportunities across various industries. As research in nanomaterials continues to advance, it is expected that new applications will continue to emerge, further shaping the future of science, technology, and industry.

VII. CHALLENGES IN NANOMATERIALS AND NANOSTRUCTURES

Toxicity and Safety Concerns: The potential adverse health and environmental effects of some nanomaterials, especially when released into the environment, remain a concern. Comprehensive studies on the toxicity of nanomaterials and the development of safe handling and disposal protocols are essential.

Regulation and Standardization: There is a lack of standardized regulations and guidelines for the production, use, and disposal of nanomaterials. Establishing regulatory frameworks to ensure the safe use of nanomaterials is crucial.

Scale-Up and Manufacturing Challenges: Transitioning from laboratory-scale synthesis to large-scale manufacturing is often a significant challenge, impacting the scalability and cost-effectiveness of nanomaterial-based products.

Nanomaterial Agglomeration: Nanoparticles tend to agglomerate, reducing their effectiveness and altering their properties. Developing strategies to prevent or control agglomeration is vital for many applications.

Stability and Long-Term Performance: Ensuring the long-term stability and performance of nanomaterials in various environments, such as extreme temperatures, is a significant challenge.

Future Directions in Nanomaterials and Nanostructures

Multifunctional Nanomaterials: The development of nanomaterials with multifunctional properties, where a single material can serve multiple purposes, is an exciting avenue. For instance, nanoparticles that can simultaneously deliver drugs and image tissues in medicine.

Smart and Adaptive Nanomaterials: Creating nanomaterials that can respond to changing environmental conditions or stimuli offers new possibilities in fields like self-healing materials and adaptable drug delivery systems.

Nanomaterials for Sustainable Energy: Advancements in nanomaterials for renewable energy, including perovskite solar cells, thermoelectric materials, and advanced battery technologies, can contribute to a more sustainable future.

Nanomaterials in Quantum Technologies: The development of nanomaterials for quantum computing and quantum communication holds great promise, potentially revolutionizing information processing and cryptography.

Environmental Remediation: The use of nanomaterials for efficient and environmentally friendly pollutant removal, water purification, and soil remediation is expected to grow as the need for sustainable environmental solutions increases.

Nanomaterials for Precision Medicine: Continued research in nanomaterial-based drug delivery and theranostics (combined therapy and diagnostics) will contribute to personalized and targeted medicine.

Nanomaterials in 3D Printing: Integrating nanomaterials into 3D printing processes can lead to the creation of intricate structures with improved mechanical, thermal, and electrical properties.

Green Nanotechnology: The development of eco-friendly and sustainable synthesis methods for nanomaterials, as well as the use of biodegradable and non-toxic nanomaterials, aligns with the principles of green nanotechnology.

Interdisciplinary Collaborations: As nanomaterials have applications in diverse fields, interdisciplinary collaborations among scientists, engineers, and experts from various domains will be essential to drive innovation and address complex challenges.

Education and Training: The development of educational programs and training for researchers, technicians, and the workforce in the field of nanomaterials is critical to ensure safe and responsible practices.

As nanomaterials and nanostructures continue to evolve, they hold the promise of solving some of society's most pressing challenges, from healthcare to sustainable energy and environmental protection. Research and innovation in this field are likely to play a pivotal role in shaping the future of science, technology, and industry. Addressing challenges while exploring these promising directions is essential for realizing the full potential of nanomaterials.

VIII. CONCLUSION

In conclusion, the field of nanomaterials and nanostructures has burgeoned into a realm of innovation with transformative potential. The synthesis and characterization methods discussed herein underscore the fundamental pillars that support this dynamic discipline. Recent advancements have showcased the extraordinary versatility of nanomaterials, offering groundbreaking solutions in healthcare, electronics, energy, and environmental sustainability. Nanomaterials have already revolutionized various industries and hold the promise of addressing some of the world's most pressing challenges. However, challenges remain, including safety concerns, regulation, and scalability.

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