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Nanomaterials: Synthesis, Characterization, and Applications in Drug Delivery, Soft Robotics, and Self-Healing Materials

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Abstract

From clothes, sunglasses we wear to computer hard drives and even cleaning products, nanotechnology plays a vital role manufacturing many materials. We have been using LEDs, DVDs, CD players, Lasers for a long time which contain nano size components and this is studied in nanoscience. Nanoscience is the study of phenomenon and manipulation of materials at atomic, molecular and macromolecular scales where properties differ significantly from those materials at a large scale. Basically, 'Nano' is a Greek word which means dwarf but in actually case nano is even smaller than dwarf. Conventionally, the nanometre scale is defined as 1 to 100 nm and one nanometre is one billionth of a metre that is 10^{-9} m. The materials we see all around us are bulk materials that possess macroscopic physical properties. Grains of sand that is micron sized material but also possess same bult properties. But materials which are synthesized at nanoscale (10^{-9} m) possess unique properties. The potential of nanomaterials to transform a variety of industries, including material sciences, biotechnology, and medicine, has pulled more and more attention of ours. There are some of their unique characteristics like large surface area, enhanced chemical reactivity, thermal, magnetic, catalytic, size dependent optical and electrical effects, and the ability to modify the surface, allow them to do tasks that conventional materials are unable to.

Top to down approach, bottom up approach, and integrated techniques are among the various synthesis paths that have been developed as a result of the great and rapid advancements in nanotechnology. These approaches allow for exact control over particle's size, shape, and surface characteristic features. To better tailor those to specific uses, it is essential to comprehend their structural, chemical, and functional behaviour, which is completely supported by many advanced characterisation technologies. In this study, important uses of nanomaterials are highlighted, with a focus on technological and biomedical developments. Nanocarriers greatly increase therapeutic efficacy in medication delivery by facilitating focused and controlled transport, controlled and precise release, specific target, and fewer adverse effects. Their coordination into soft robotics has brought up new avenues for the development of lightweight, flexible, specific, and adaptive systems that can react to external stimuli, advancing industries like Bioinspired devices and minimally invasive medical procedures. The design of self-healing materials, which are being investigated more and more in order to extend the life of biomedical implants, coatings, and infrastructure, also heavily relies on nanomaterials.

Keywords: *Nanomaterials, Drug Delivery, Self-healing NPs, Soft Robotics, Liposomes and Polymeric NPs, TEM, SEM, FTIR, ZPM, DLS, XRD etc.*

Introduction

Nanotechnology is an interdisciplinary science that deals with the designing, synthesis, and application of materials at the nanoscale (1–100 nm i.e. 10^{-9}). Nanomaterials have become more relevant in a variety of scientific areas due to their special qualities, which include their capacity, very high surface to volume ratio, and small size to interact with biological systems at the molecular (very small) level. Recent research highlights their potential in revolutionizing fields such as medicinal science (medicines), materials sciences, and robotics. According to their dimensions, nanomaterials are divided into four categories: zero- (0D), one- (1D), two- (2D), and three-dimensional (3D). The most widely studied nanomaterials include nanoparticles (NPs), nanofibers, nanotubes, and nanocomposites.

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These materials are utilized in a variety of applications, which ranges from drug delivery systems & Drug Designing (Molecular Docking) to sensors and advanced materials in electronics and constructions. This review aims to study deeply by diving into the synthesis, characterization, and applications of nanomaterials, with particular emphasis on their role in drug delivery, soft robotics, and self-healing materials.

Synthesis of Nanoparticles (NPs):

The two main techniques for synthesizing nanoparticles are top to down and bottom up approaches.

1. **Top down Approaches:**

Using these techniques, larger materials are broken down into nanoscale structures. Top down approaches include processes like lithography, laser ablation, and milling. These approaches are advantageous for producing nanoparticles from bulk materials but can result in broader size distributions.

2. **Bottom up Approaches:**

These processes use chemical reactions to bring atoms or molecules together to form nanoscale structures. Simply, the particles which are even smaller than nanoparticles (< 10-9m) are used to synthesize nanomaterials.

Methods like Chemical Vapour Deposition (CVD), Sol Gel processes, and electrochemical deposition are prominent bottom up techniques. These methods provide more control over the size, shape, and composition of the nanoparticles. Recent advances in nanoparticle synthesis have also incorporated the twelve principles of green chemistry, focusing on environmentally friendly methods that minimize toxic by-products, lower energy emissions, and use of safe solvents. For instance, biological entities such as bacteria, fungi, and plant extracts have been used to synthesize nanoparticles with distinct properties for various applications, including biomedical uses.

Evaluation of Nanoparticle Properties:

Characterizing nanoparticles is very crucial to understand their characteristics and capabilities. The most commonly used techniques include:

1. Transmission Electron Microscopy (TEM): It offers high resolution pictures of the morphology and internal structure of nanoparticles.
2. Scanning Electron Microscopy (SEM): This technique gives surface imaging and details the size, shape, and texture of various nanoparticles.
3. X-ray Diffraction (XRD): A technique for examining the phase composition and crystalline structure of nanoparticles.
4. Dynamic Light Scattering (DLS): This technique uses light scattering to determine the size distribution of nanoparticles in solution.
5. Fourier Transform Infrared Spectroscopy (FTIR): This technique is essential for figuring out how reactive and how well nanoparticles interact with biological systems since it can identify functional groups on their surface.
6. Zeta Potential Measurement: This technique assists in figuring out the stability and surface charge of nanoparticles in suspension.

Applications of Nanomaterials:

Nanomaterials have found widespread applications in various fields. Here, we focus on three major areas where their impact is most significant: drug delivery, soft robotics, and self-healing materials.

1. Nanomaterials in Drug Delivery

Nanomaterials have revolutionized drug delivery systems by improving the bioavailability, targeting efficiency, and controlled release of therapeutic agents. Nanoparticles, due to their small size, can easily interact with biological systems and cross biological barriers such as the blood-brain barrier.

1. Liposomes and Polymeric Nanoparticles: Liposomes, which are lipid based nanoparticles, and polymeric nanoparticles are widely used in drug delivery. These nanoparticles can encapsulate hydrophilic and hydrophobic drugs, enabling the controlled and sustained release of drugs at the targeted site. The pH-sensitive properties of these nanoparticles, such as those found in halochromic materials, enable targeted drug release in specific environments, such as acidic tumour microenvironments.
2. Quantum Dots in Imaging and Therapy: Quantum dots are semiconductor nanocrystals that exhibit unique optical properties. Their high surface area and ability to conjugate with biomolecules make them ideal candidates for both drug delivery and diagnostic imaging. Quantum dots can be functionalized with therapeutic agents, enabling precise delivery to cancer cells or other targeted tissues.

2. Nanomaterials in Soft Robotics

Nanomaterials' Application in Soft Robots The developing area of soft robotics aims to create robots with pliable, malleable bodies. Nanomaterials, especially carbon-based nanomaterials, have played a crucial role in this field by enhancing the mechanical properties of soft robots.

1. Graphene and Carbon Nanotubes (CNTs): Graphene and CNTs are widely used in soft robotics due to their excellent electrical conductivity, mechanical strength, and flexibility. These materials enable the creation of flexible actuators and sensors that mimic biological systems, providing robots with enhanced dexterity and adaptability.
2. Conductive Polymers: Conductive polymers like polypyrrole and polyaniline are integrated into soft robotic systems to provide electrical stimuli for movement and actuation. These materials enable robots to respond to external signals, making them highly versatile in applications like prosthetics and human-machine interfaces.

3. Nanomaterials in Self-Healing Materials

1. Materials having self-healing properties are made to fix damage on their own without seeking help from other materials. Nanomaterials have wonderfully advanced the development of these materials, offering a significant way to enhance their durability and longevity.
2. Nanoparticle Embedded Polymers: Nanoparticles are incorporated into polymers to create self-healing materials that respond to mechanical damage by initiating repair mechanisms. For example, the incorporation of microcapsules filled with healing agents can release these agents when cracks or damage occur, thereby enabling the material to heal itself.
3. Nano Structured Coatings: Nano coatings applied to surfaces can prevent damage and wear over time. When the coating is damaged, embedded nanoparticles can release healing agents to repair the damage, maintaining the integrity of the material.

New Discoveries and Inventions in Nanotechnology

Recent research in nanotechnology has unveiled new opportunities for the application of nanomaterials in various fields.
Some notable discoveries include:

1. Quantum-Based Drug Delivery: Researchers are exploring the use of quantum mechanics to design drug delivery systems that can operate at the molecular level. By utilizing quantum dots and nanoparticles, drugs can be delivered with unprecedented precision and efficiency.
2. Bio Inspired Nanomaterials: Nanomaterials inspired by natural biological systems, such as the self-healing properties of skin or the light-harvesting mechanisms in plants, are being developed for a wide range of applications, from environmental remediation to advanced medical therapies.
3. Nanomaterials for Environmental Remediation: Air, water, and soil pollutants are being removed using nanoparticles. They are useful for cleaning up the environment because of their high surface area and reactivity, especially when dealing with problems like heavy metal contamination.

Conclusion:

Nanomaterials are at the forefront of scientific research and innovation, offering novel solutions across various sectors. Their unique properties, such as size dependent behaviour, surface reactivity, and tenability, make them ideal candidates for applications in drug delivery, robotics, and self-healing materials. As research progresses, new discoveries in the synthesis, characterization, and functionalization of nanomaterials will continue to push the boundaries of what is possible in fields ranging from medicine to environmental science.

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Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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