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Nanomaterials and Nanotechnology: An Overview on Synthesis, Characterization and Application

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Abstract

Nanomaterials have significant large surface area relative to their volume which makes them unique regarding the physical and chemical characteristics. They have notable optical, electrical, magnetic, mechanical, and catalytic properties and these brings the new scientific era- nanotechnology. Ball milling, lithography, sputtering, and laser ablation are commonly used 'Top-down' method where larger materials are broken down to the nanoscale. However, 'Bottom-up' methods, such as chemical vapor deposition (CVD), sol-gel processes and hydrothermal processes build nanoparticles from atoms or molecules with controlled modulation of shape and composition. Researchers of late have focused on green nanotechnology by producing the metal nanoparticles from plants, algae, and microorganisms. This could be a potential era for biotechnologists to explore more to find the environmental friendly and less expensive biological approach. X-ray diffraction (XRD), scanning and transmission electron microscopy (SEM, TEM), atomic force microscopy (AFM), and X-ray photoelectron spectroscopy (XPS) are widely used surface characterization of nanomaterials. From environmental remediation to modern electronic devices, nanotechnology has kept his impactful footprint along with food and medicine disciplines. This review summarizes the synthesis, characterization, and application of nanotechnology in recent research fields, guiding future contributors in the innovation of nanotechnology.

Keywords Nanomaterial, Nanotechnology, Nanocomposite, Nanotube

1. Introduction

Nanotechnology is the new advancing research field that contributes to the innovation of tiny particles from about 1 to 100 nanometers scale (one billionth of a meter). These nanomaterials have one, two and three-dimensional structures. Combining it with other materials, nanomaterials can form nanocomposites. According to quantum theory, particles at nanoscale can act more like waves than the particles. They have large surface area with high particles number per mass unit and fewer direct neighbors. As a result, their physical, chemical, and biological properties differ significantly at nanoscale (1, 2). Nanotechnology is considering as a modern science although people are unknowingly utilizing nanomaterials since decades. Dyeing hair in ancient Egypt, Lycurgus Cup of fourth century CE etc. are evidence of using nanoparticles of Au, Ag and nanocomposite of PbS (3).

Nanomaterials are unique significantly than the bulk materials due to their surface effects and quantum effects (3). They can exist as individual particles or as aggregates, agglomerates, or fused clusters. Based on dimensionality, they can be zero, one, or two-dimensional. Morphologically they can be spherical, tubular, or irregular shapes. Common examples include nanotubes, quantum dots, and fullerenes, which are extensively utilized in nanotechnology. Classification of nanomaterials is based on dimensionality, phase composition, and manufacturing process (1,4,5) are shown in figure 1.

Nanomaterials are produced by top-down and bottom-up methods. Both methods have several advantages and disadvantages. Top-down techniques break down large

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materials to the nanoscale, for example- mechanical milling and lithography techniques. It is advantageous for large-scale production though often results in uneven particle sizes and structural defects (6). However, bottom-up methods have precise control over size, morphology and shape (6). Chemical vapor deposition, sol-gel methods are commonly used bottom-up methods. They compile nanomaterials from atomic or molecular precursors. Still these methods are challenging and complicated for large-scale production (5). Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), Raman, Fourier Transform Infrared (FTIR) spectroscopy are widely used analytical techniques for nanomaterials. They provide detailed images of nanostructures along with their chemical composition and molecular interactions (6-12). Purity is very vital for energy and electronics applications. To check the purity of nanocrystal structure, X-ray Diffraction (XRD) method is utilized (7,13,14).

From the energy sector to environmental remediation, nanotechnology has numerous blessings for mankind. They have contributed to revolutionary impacts in electronics by creating high-performance devices. The technological breakthrough has advanced medical science in targeted drug delivery and cancer therapy. Despite all the positive aspects, there are many obstacles to widespread adoption of nanotechnological advancements. High production cost, potential toxicity, and lack of regulatory framework have made the implementation challenging (15). Integrating proper regulations and transdisciplinary scientific research collaboration must be brought into practice. A comprehensive knowledge of synthesis, characterization and application is important to achieve scientific progress in nanotechnology.

2. Synthesis techniques of nanomaterials

Top-down and bottom-up approaches (Figure 2) are generally used techniques for the preparation of nanomaterials (16). Top-down approaches break down large particles into nanoparticles physically or mechanically. Ball milling, lithography, sputtering, laser ablation, and arc discharge are mostly used top-down procedures. Milling and etching are generally used in electronic device fabrication. It is particularly important for producing thin films and nanomaterials larger than 100 nm. Despite being cost-effective, top-down techniques often produce particles with less uniformity and more defects (15,16). On the other hand, bottom-up approaches comprise making nanomaterials out of atoms, molecules, or nanoparticles. Such techniques include chemical vapor deposition, hydrothermal synthesis, sol-gel processing and co-precipitation methods. Bottom-up methods can produce nanomaterials with higher uniformity and less defects. However, it's more complicated and expensive approach (15). Hybrid methods can be used to assemble the strengths of both approaches (16).

Mechanical synthesis methods produce nanomaterials by reducing solid materials to smaller particles through grinding, refining, high-energy ball milling, or cutting. These processes use various carbide tools to convert bulk materials into nanoparticles (16). Mechanical alloying and reactive milling are less complicated, and they require minimal equipment with zero environmental waste generation. However, these methods require high energy input and can introduce contamination from tool wear. They also have limited control over particle size and morphology (16).

Physical synthesis methods include evaporation and condensation, laser ablation, physical vapor deposition (PVD) and spray techniques. These methods produce uniform nanoparticles with high-purity thin films and are commonly used in optical, electronic, and coating applications (15,16). Nevertheless, they require significant energy, expensive equipment, and have slow production rates. Chemical vapor deposition, electrochemical synthesis, and polymerization are some common physicochemical methods. They provide higher control over nanomaterial formation. However, they involve toxic reagents and higher expenditure (16). Table 1 shows various methods used to manufacture nanoparticles and their diverse applications (16-21).

3. Characterization of nanomaterials

Study of morphology, size, surface charge, structure, and chemical composition is very important for characterization of nanomaterials. Analytical techniques such as microscopy, spectroscopy, light scattering, and diffraction are used for this purpose. Electron microscopy, including SEM and TEM, is widely used to examine nanoparticle morphology and structure. SEM provides detailed images of surface features and particle size, while TEM delivers higher-resolution images of internal structure, crystallinity, and atomic arrangement

(6-10). Atomic force microscopy (AFM) scans surfaces at the nanoscale to evaluate particle size, shape, dispersion, and aggregation (6).

X-ray diffraction (XRD) is a non-destructive method for analyzing nanocrystal structure, lattice parameters, and phase composition (7). However, sometimes it is less effective for very small or amorphous nanoparticles (22). Dynamic light scattering (DLS) measures particle size distributions in liquid suspensions using laser light (6). Spectroscopic techniques can be used to detect the chemical composition and bonding nature in nanoparticles. Fourier transform infrared (FTIR) spectroscopy can detect functional groups through infrared absorption in nanomaterials and Raman spectroscopy examines vibrational energy shifts to examine molecular structure (11,12). X-ray photoelectron spectroscopy (XPS) evaluates electron binding energies and chemical bonding in nanostructures (6). Combining these methods provides comprehensive characterization of nanomaterials for biomedicine, electronics, and environmental remediation (22). Figure 3 shows the characterization methods of nanomaterials (15,22).

4. Carbon nanotube and nanocomposites

Carbon nanotubes (CNTs) are cylindrical nanostructures formed by rolling one or more layers of graphene. Their diameters are typically only a few nanometers with a larger length (1). Sumio Iijima first discovered CNTs in 1991. Since then, CNTs have been recognized for their exceptional mechanical, electrical, and thermal properties due to the strong and diverse carbon-carbon bonds (15). Their electrical conductivity is related to their atomic arrangement and chirality. Due to their high strength, low density, and superior conductivity, CNTs are widely employed to reinforce advanced composite materials (23). In polymer matrices, CNTs serve as effective fillers because of their high aspect ratio and large surface area. Combining CNTs into polymer chains improves mechanical properties compared to unmodified polymers by enhancing chain alignment and packing (23).

Nanocomposites are materials that assimilate at least one nanoscale component into a matrix. Thus, it enhances properties such as mechanical strength, thermal stability, electrical conductivity, and barrier performance (24). Nanocomposites include metal matrix, ceramic matrix, and polymer matrix composites. Among them, polymer-CNT nanocomposites are mostly important for producing high-strength fibers and structural components (1). They can improve barrier properties and durability without significantly increasing weight. Current research focus on optimizing CNT within polymers to expand applications in aerospace, electronics, energy, and high-performance plastics (24).

5. Applications of Nanotechnology Energy

The use of nanotechnology in the realm of energy greatly influences the efficiency, sustainability, and capacity of energy systems. As we know, the high surface area and some specific features like electrical properties and catalytic action make nanomaterials useful in energy applications. Carbon nanotubes, graphene and nanoparticles of metal oxides may be used in producing batteries and supercapacitors due to the high ability of charge accumulation and enhanced conductivity. Therefore, the efficiency and stability of energy systems increase (1).

Regarding the development of solar energy technologies, nanotechnology has been used to improve solar energy collection and performance of solar cells. Pyroelectric zinc oxide (ZnO) nanowires can spontaneously change their polarization in case of changes in temperature and produce electricity. Such nano-generators can convert small temperature variations and wasted heat into energy and thus provide electricity production for micro devices and sensors (1). Moreover, the use of quantum dots and semiconductors on a nanoscale level facilitates greater energy capture and efficiency of energy conversion and makes it possible to create flexible and thinner solar panels. Also, catalytic nanoparticles are applied to enhance the reaction rates and minimize energy losses. Thus, the efficiency and economic viability of renewable energy sources are greatly improved (25).

With the advent of nanotechnology, energy storage systems are considerably upgraded. Application of modern nanomaterials allows increasing energy density and fast charging ability, decreasing their weight, and lifetime (15,20,21). In simple words, due to nanotechnology, we have an opportunity to design lightweight and efficient energy storage systems with high lifetime (1). To sum up, nanotechnology has been successfully used in the development of energy systems by providing sustainable solutions to energy production.

6. Environment, Food, and Agriculture

The environment is undoubtedly one of the world's most complicated topics in terms of monitoring and protection (5,26). Nanosized particles contribute significantly to environmental contamination detection, control, and elimination (1). They are exceptionally sensitive and allow tracking even low concentrations of pollutants. Nanosensors are employed to monitor threats and prevent them in advance regarding ecosystem and human health. It is due to the implementation of nanotechnologies that the correct outcomes are ensured as well as prompt response to negative conditions.

Global challenges related to water pollution and its scarcity have existed for decades. Nanotechnology provides an opportunity to solve problems associated with purification and processing of water sources. Nanoparticles and nanocomposites can effectively remove organic and inorganic contaminants (24). For example, the materials like titanium dioxide (TiO_2), zinc oxide (ZnO), and silver show photocatalytic and antimicrobial effects, thus contributing to the breakdown of hazardous compounds (27). Nanofibers serve as excellent filters and membranes. Their application allows for removing heavy metals, bacteria, and other impurities. The implementation of nanotechnology enhances desalination procedures and promotes the production of freshwater from saltwater (28).

Nanoparticles are used to clean contaminated soil and water bodies by oxidizing dangerous compounds, including trichloroethylene (29). Agriculture benefits from nanomaterials and products because they allow increasing efficiency and reducing negative impacts on the environment. Nanopesticides and fertilizers release components gradually and target the exact plant parts (1). It leads to higher yields and less wastefulness. Nanotechnology can be helpful in enhancing food security by creating appropriate packaging and sensors. Nanocomposites improve packaging materials' characteristics by preventing oxygen, moisture, and microorganism penetration (30). As a result, food products preserve their properties longer. Nanosensors can detect spoiled food or its contamination during transportation or storage. These measures guarantee food quality assurance, lower post-harvest losses, and promote sustainable agricultural practices (4,26).

7. Medicinal and Pharmaceutical

Nanotechnology offers an improvement to medicine and pharmaceutical sciences through precise diagnosis and innovative treatments as well as drug delivery approaches. Targeted drug delivery is one of the advantages offered by nanotechnology. With conventional drug delivery systems, the whole body is exposed to medication. This results in low efficacy of medications and adverse reactions (31). Nanocarriers such as liposomes, polymeric nanoparticles, dendrimers, and nanocapsules allow for drug targeting to tissues or diseased cells (31). Drug targeting results in higher concentration at the target site, high efficacy, and reduced risks of damage to other sites.

Regarding disease diagnosis and visualization, nanotechnology has proven a blessing. Nanomaterials increase the sensitivity of MRI, CT, and fluorescence imaging and enable early diagnoses of diseases including cancer and other complicated disorders (32). Photothermics or photodynamic therapy uses nanomaterials that produce heat or reactive oxygen species which destroy cancer cells (31).

Nanomaterials such as silver and zinc oxide are used in wound dressings and other medical devices because of their strong antibacterial properties. They can cause disintegration of the cell membranes and metabolism of microorganisms. Nanotechnology can assist in tissue engineering through provision of matrices that support cells to grow. Toxicity should be considered to ensure safe use of these technologies in hospitals.

8. Textiles

The introduction of nanotechnology in textile engineering has witnessed numerous innovations in the industry. The technique enables ways of designing fabrics with enhanced durability, apart from having several other applications (1,5,22). Nanomaterials may be included in fibers and coatings without impacting on the appearance and comfort levels of the textiles. Examples of such nanomaterials that are included in producing healthcare, sports and technical clothes include metallic nanoparticles, metal oxides, carbon nanotubes, and polymer nanocomposites (15,23,24).

There are various innovations created using nanotechnology, among which is the production of textiles with antifungal properties. Metallic silver and zinc oxide nanoparticles eliminate microorganisms by damaging their cellular membranes and thus causing oxidative stress. Therefore, they prove to be effective in the creation of medical and hygienic fabrics (1). Titanium dioxide and zinc oxide help increase the capability of fabrics in absorbing and reflecting ultraviolet rays, thereby providing stability and safety for the consumers. Surface modification at nanoscale level enhances the water-repellent characteristics and makes the fabrics resistant to any kind of adherence by reducing surface energy.

With the inclusion of conductive nanomaterials, it has become possible to develop intelligent fabrics that can monitor environmental and physiological factors. It has resulted in major achievements especially in the healthcare industry. Sustainability has also improved significantly because of nanotechnology owing to the reduced use of chemicals and greener processes involved (16,22,26). However, the possibility of release of nanoparticles during washing and continual dermal exposure should not be overlooked. Environmental pollution and economics must be considered. The current trends in nanomaterial fabrication, nanocomposites design and green production technologies give hope to further improvement of textile technologies (1,4,12,16).

9. Green Nanotechnology

Utilizing microorganisms, biomolecules, and plant extracts to produce metal and metal-oxide nanoparticles is the green synthesis or bio-assisted synthesis. It is environmentally friendly and cost effective (26). Microorganisms like bacteria, fungi, algae, yeast, and actinomycetes convert metal ions into nanoparticles using enzymes (33). Thus, nanoparticles can be formed inside a cell when enzymes reduce metal ions, or outside the cell through enzyme activity on the cell surface. Microorganisms have functional groups, proteins, and enzymes that help bind and reduce metal ions. Candida glabrata and Rhodosporidium diobovatum yeast can produce cadmium (Cd) and lead sulfide (PbS) nanoparticles and actinomycetes like Thermomonospora sp. can make gold nanoparticles (34,35). Another method is biomolecule-templated synthesis, which uses nucleic acids, viruses, membranes, and diatoms as templates to build nanoparticles. DNA molecules can attract metal ions and help form gold nanoparticles or conductive nanowires made from gold, palladium, or cadmium sulfide (36).

Plant-based synthesis is popular for their phytochemicals, such as phenolics, flavonoids, tannins, and saponins. They help to reduce and stabilize nanoparticles (37). Plant bark, leaves, fruits, seeds, and peels, are used to make nanoparticles. Euphorbia nivulia, Annona squamosa, and Chenopodium album can produce silver nanoparticles, gold nanoparticles come from Magnolia kobus and Diospyros kaki, while copper nanoparticles are made from Garcinia mangostana and other nanoformulations use Silybum marianum (36). These plant-based methods help create sustainable nanotechnology for cleaning the environment, medicine, and fighting microbes.

10. Conclusion

In this review, an introduction to nanomaterials has been discussed with respect to synthesis, characterization techniques, and applications in science and technology. Nowadays sustainable and environmentally friendly green synthesis using biomaterials is employed in addition to conventional synthesis procedures. Several different microscopic and spectroscopic techniques are applied to investigate structural, surface characteristics of nanomaterials as well as their interactions.

Relation between the synthesis method and resulting structure/properties are important for improvement of the efficiency of the nanomaterial utilization. Rational synthesis allows obtaining unique optical, electrical, magnetic, or catalytic properties of nanomaterials. Proper characterization enables accurate determination of all important parameters that affect performance of nanomaterials. Combination of innovative synthesis methods with cutting-edge characterization techniques plays a decisive role in the development of nanotechnology to address its existing issues and create novel breakthroughs.

Despite the inclusion of the most relevant information about nanomaterial synthesis, analysis, and application in this review, there still exist several limitations. This review provides a general picture of the most common synthesis and analysis techniques but does not touch upon the process itself or ways to improve nanomaterials synthesis and analysis. Some issues such as scalability, affordability, sustainability, longevity, environmental and health hazards remain topical for nanotechnology. For the future, further research direction might be related to addressing problems mentioned above.

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Author Contributions

1. Halima-E-Sadia

o Conceptualization, study planning, execution of research work, data curation, software, formal analysis, and manuscript writing.

2. Md. Mirja Sarwar

o Software, validation, formal analysis, and manuscript writing.

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o Conceptualization, supervision, project administration, funding acquisition, investigation, resources, data curation, manuscript review and editing, and visualization.

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