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An Energetic Materials for Sustainable Solutions

R. M. Aadarsh Vel[1], S. Ravichandran[2,*]

Abstract

Nanomaterials are typically described as engineered substances possessing at least one dimension between 1 and 100 nm. Materials at the nanoscale display distinctive or enhanced characteristics, such as increased chemical reactivity, superior sensing performance, and improved mechanical properties. Nanotechnology provides a straightforward, rapid, clean, and cost-effective approach for synthesizing a wide range of organic compounds, encouraging many researchers to transition from conventional synthetic techniques. This article aims to highlight the fundamental concept of nanomaterials, their methods of preparation, and their overall significance. The synthesis of nanomaterials can generally be categorized into two major strategies: top-down and bottom-up approaches. In the top-down method, bulk materials are reduced to nanoscale dimensions through processes such as milling, lithography, and etching. Conversely, the bottom-up approach involves assembling nanostructures from atoms or molecules using techniques like chemical vapor deposition, sol-gel methods, and green synthesis. Among these, green synthesis has attracted considerable interest due to its environmentally benign nature, employing plant extracts, microorganisms, or other biological agents to fabricate nanoparticles without harmful chemicals. The exceptional properties of nanomaterials are largely attributed to their high surface area-to-volume ratio along with quantum mechanical effects. These factors strongly affect their optical, electrical, magnetic, and catalytic properties. Consequently, nanomaterials have wide-ranging applications across fields such as healthcare, electronics, environmental management, and energy systems. For example, in medicine, nanoparticles are widely utilized in targeted drug delivery, imaging, and diagnostic applications. Similarly, in environmental applications, they are effectively used in water treatment and pollution control by facilitating the removal of contaminants. Furthermore, nanotechnology has revolutionized catalysis by providing highly active and selective catalysts, thereby improving reaction efficiency and reducing waste generation. Despite these advantages, concerns regarding toxicity, environmental impact, and safe handling of nanomaterials must be carefully addressed. Therefore, ongoing research is essential to ensure the sustainable development and responsible use of nanotechnology in the future

Keyword: Nanomaterials, synthesis, properties, applications, nan

INTRODUCTION

The concept of "nanotechnology" was first introduced by Norio Taniguchi of Tokyo Science University in 1974. Often abbreviated as "nanotech, " nanotechnology refers to the study and manipulation of matter at the atomic and molecular levels. It generally focuses on structures with dimensions ranging from 1 to 100 nm and involves the design and development of materials or devices within this scale. The term "nano" is derived from the Greek word nanos, meaning "dwarf" [1–6].

Nanotechnology is a multidisciplinary domain that investigates the physical, chemical, and biological characteristics of materials at the nanoscale and explores their potential applications. Particles with sizes between 1 and 100 nm are known as nanoparticles. In this context, a particle is

***Author for Correspondence**
S. Ravichandran
E-mail: drravichandran.chemistry@spiher.ac.in

[1]BBA Student, Department of Airlines & Airport Management, Lovely Professional University, Jalandhar, Punjab, India
[2]Professor and Head, Department of in Chemistry, St. Peter's Institute of Higher Education and Research, Chennai, Tamil Nadu, India

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considered a complete unit exhibiting distinct properties. However, individual molecules are not classified as nanoparticles; instead, nanoparticles are those entities that display size-dependent behavior [7–10].

The properties of nanoparticles differ significantly from those of their bulk counterparts. Due to their extremely small size, electrons are confined within these particles, leading to quantum effects. As a result, nanoparticles often exhibit unusual optical characteristics. For example, gold nanoparticles can appear in colors ranging from deep red to black depending on their size (Figure 1).

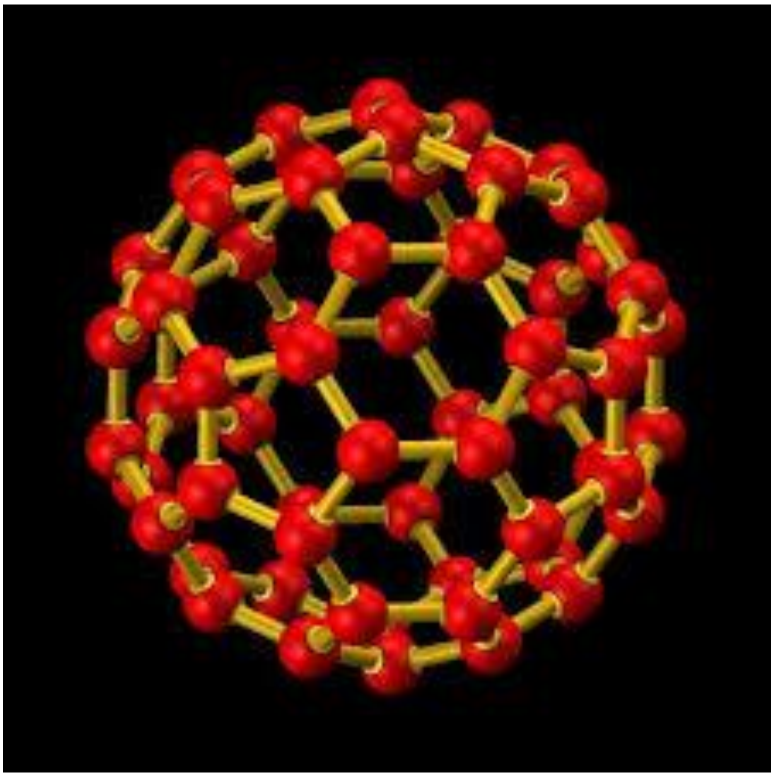

Figure 1. The appearance of nanoparticles in red colors.

In general, nanomaterials show markedly different chemical and physical properties compared to bulk materials [11]. These include variations in optical absorption, fluorescence, melting point, catalytic activity, magnetism, and electrical and thermal conductivity. By controlling structures at the nanoscale, a wide array of material properties can be finely tuned and optimized for specific applications (Table 1)

Table 1. Nanomaterials properties.

Properties	Examples
Catalytic	Better catalytic efficiency through higher surface-to-volume ratio.
Electrical	Increased electrical conductivity in ceramics and magnetic nanocomposites, increased electric resistance in metals.
Magnetic	Increased magnetic coercivity up to a critical grain size, superparamagnetic behavior.
Mechanical	Improved hardness and toughness of metals and alloys, ductility and superplasticity of ceramics.
Optical	Spectral shift of optical absorption and fluorescence properties, increased quantum efficiency of semiconductor crystals.
Sterical	Increased selectivity, hollow spheres for specific drug transportation and controlled release.
Biological	Increased permeability through biological barriers, improved biocompatibility.

Synthesis of Nanomaterials

Nanoparticles can be synthesized from a wide range of materials, including metals, dielectrics, and semiconductors. In addition, more complex architectures such as core-shell nanostructures have also been developed. Semiconductor nanoparticles are commonly referred to as quantum dots (QDs) when their size is sufficiently small (typically below 10 nm), allowing discrete energy levels to emerge due to quantum confinement [12, 13]. These nanostructures are widely utilized in biomedical fields, particularly as drug delivery carriers and imaging probes. Nanomaterials can be produced using several established techniques, some of which are outlined below:

Pyrolysis

This method involves the thermal decomposition of hydrocarbons such as acetylene at approximately 700 °C in the presence of catalysts like iron supported on silica or graphite under an inert atmosphere [14].

Carbon Arc Method

In this technique, a direct-current arc (typically 60–100 A and 20–25 V) is generated between graphite electrodes with diameters of 10–20 μm, leading to the formation of nanostructured materials [15].

Laser Evaporation Method

This process includes the vaporization of graphite containing trace amounts of cobalt and nickel using a high-temperature laser (~1200°C) in a quartz tube reactor. An inert gas such as argon carries the vaporized carbon atoms to a copper collector, where they condense into nanomaterials.

Chemical Vapor Deposition (CVD)

CVD involves the decomposition of hydrocarbon vapors like methane, ethylene, or acetylene at around 1100°C in the presence of catalysts such as nickel, cobalt, or iron supported on magnesium oxide [16, 17].

Applications of Nanomaterials

Nanomaterials have found extensive applications across various fields, many of which represent advancements of existing technologies, such as the miniaturization of electronic devices [18–24].

Sunscreens and Cosmetics

Conventional UV-protective formulations often suffer from limited stability over time. In contrast, mineral-based nanoparticles like titanium dioxide provide effective UV protection while remaining transparent to visible light, enhancing consumer appeal. Zinc oxide nanoparticles are also widely used in sunscreens for their UV absorption and reflection properties. Additionally, nanoscale iron oxide is employed as a pigment in certain cosmetic products. However, concerns regarding the long-term safety of nanoparticles in cosmetics persist [25].

Paints

The incorporation of nanoparticles into paints enhances their performance by improving properties such as durability and reducing weight. Lightweight coatings, particularly in aerospace applications, contribute to reduced fuel consumption and environmental benefits [26].

Batteries

The increasing demand for portable electronic devices has driven the need for lightweight, high-energy-density batteries. Nanocrystalline materials produced via sol–gel methods are promising for battery separators due to their porous, aerogel-like structure, which enables higher energy storage. Batteries made with nanostructured nickel and metal hydrides exhibit improved longevity and reduced charging frequency owing to their high surface area [27].

Catalysis

Nanoparticles exhibit enhanced catalytic efficiency due to their large surface-to-volume ratio. They play a crucial role in chemical manufacturing and industrial reactions. For instance, platinum nanoparticles are being explored for use in advanced automotive catalytic converters, potentially reducing the required amount of precious metal. Nanomaterials are also applied in reactions such as the reduction of nickel oxide to metallic nickel [28].

Food Industry

Nanotechnology is increasingly being applied in food production, processing, and packaging. Nanocomposite coatings with antimicrobial properties can improve food safety and shelf life. Emerging nano-enabled food products incorporate additives designed to enhance nutrient delivery within the body [29].

Energy Sector

Nanotechnology contributes to advancements in energy storage, conversion, and efficiency. It plays a role in improving solar cell performance by enabling better light absorption through nanostructured materials, potentially increasing energy conversion efficiency beyond current commercial limits

Health and Safety

There are ongoing concerns regarding the potential toxicity and environmental impact of nanoparticles. Due to their high reactivity and small size, nanoparticles can penetrate biological membranes and interact with cellular components. While some studies suggest that certain nanoparticles, such as zinc oxide, may not readily enter the bloodstream, further research is required to fully assess their safety.

Nanomedicine

Nanomedicine involves the use of nanotechnology in medical applications, including diagnostic tools, biosensors, and therapeutic systems. It enables advancements in both in vivo and in vitro research. The development of nanoscale devices for biological applications holds significant promise, although concerns regarding toxicity and environmental effects remain.

Drug Delivery

One of the most significant applications of nanotechnology is targeted drug delivery. Nanocarriers enable drugs to be delivered directly to affected tissues, reducing overall dosage and minimizing side effects. These systems enhance bioavailability and allow controlled release over time. Nanoengineered devices offer advantages such as reduced invasiveness, rapid response, and improved therapeutic efficiency compared to conventional methods.

Cancer Treatment

Nanoparticles are particularly valuable in cancer therapy due to their high surface area, which allows the attachment of multiple targeting molecules. They can selectively accumulate in tumor tissues because of the enhanced permeability and retention (EPR) effect, overcoming limitations of traditional chemotherapy such as poor selectivity, drug resistance, and solubility issues

Environment

Nanosensor technologies capable of continuous monitoring, along with providing alerts and alarms when values exceed predefined limits, are increasingly being adopted for tracking pollution in air, water, and the environment [30]. Nanosensors play an indispensable role in monitoring the ecological quality of air, water, and environment with precise data. Various nanostructured materials have been developed for the detection of different components. Potable, clean water is one of the most important needs of almost every society and is generally limited. Especially, a large population of the Earth's population has great concerns with the ever-increasing need for water, and it gradually becomes one of the most important problems of this century. It has been determined that approximately 780 million people have significant difficulties in accessing potable and clean water resources. It is of great importance to develop innovative, inexpensive, practical, and widely used techniques and methods together with nanotechnologies against the limited possibilities of known water treatment and processing, and the production of potable water from seawater. Environmental remediation involves processes that remove chemical and radiological contaminants without posing risks to human health, along with techniques such as separation and filtration. The use of nanomaterials enables more rapid and cost-efficient purification and cleaning processes. In nanotechnology-based methods, the most effective strategy focuses on selectivity, ensuring efficient removal and elimination of both organic and inorganic pollutants [31].

Food and Agriculture

Nanotechnology applications in the food industry are handled by the most important companies in this sector. Giant companies such as Nestle, Kraft, Heinz, and Unilever support many research and innovation projects and programs in order to lead the future nanofood market. With the development of high nutritional value and delicious products based on "on demand, " desired products can be produced with thousands of nanocapsules to taste, colors, additives, and vitamins

CONCLUSION

Nanotechnology is already reshaping everyday life through the development of advanced technologies and innovative products. It harnesses the unique phenomena and properties that emerge at the nanoscale, offering potential solutions for millions of people in developing countries who lack access to essential services such as clean water, sustainable energy, healthcare, and education. Nanomaterials are defined as materials in which at least one dimension falls within the range of 1 to 100 nm, commonly referred to as the nanoscale. Due to their extremely small size, these materials often exhibit distinctive optical, electronic, thermophysical, and mechanical characteristics. As a result, nanomaterials find applications across a wide range of fields, including the automotive industry, energy sector, defense, environmental management, food and agriculture, as well as in industries such as cosmetics and sports.

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