

A comprehensive review of nanoparticles: Their characteristics, synthesis methods, applications, and associated challenges

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Abstract- Nanoparticles (NPs) play a crucial role in technological advancements due to their unique and tunable properties, which often result in superior performance compared to their bulk counterparts. Traditionally, NPs are synthesized by reducing metal ions using chemical agents that are often toxic and environmentally hazardous. In response to these concerns, recent efforts have focused on developing green synthesis approaches that utilize natural and sustainable resources as alternatives to harmful chemicals. Green synthesis leverages biological systems—such as bacteria, actinomycetes, fungi, algae, yeast, and plants—for nanoparticle production. These biological methods are considered environmentally friendly, safe, simple, cost-effective, and efficient. This paper aims to provide a comprehensive overview of nanoparticles, encompassing their types, properties, synthesis techniques, applications, and future prospect

Keywords: green synthesis, nanoparticles, nanotechnology, biological synthesis, microbial nanotechnology.

1. INTRODUCTION

Nanotechnology is the fascinating branch of Science which encompasses study of systems having nano scale size. The prefix 'nano' comes from Latin word 'nanus' meaning dwarf or tiny. With the convention of International System of Units (SI) it issued to indicate a reduction factor of 10⁹ times (1nm corresponding to 10⁻⁹ m). Nobel Laureate Richard P. Feynman first presented 'Nanotechnology' during his well famous 1959 lecture, 'There's Plenty of Room at the Bottom'. Since then, there have been various innovative and revolutionary developments in this field.

Nanotechnology evolved as the achievement of science in the 21st century. The synthesis, management, and application of those materials with a size smaller than 100 nm fall under the interdisciplinary umbrella of this field. Nanoparticles have significant applications in

different sectors such as the environment, agriculture, food, biotechnology, biomedical, medicines, etc. like; for treatment of waste water¹, environment monitoring², as a functional food additives³, and as a antimicrobial agents⁴. Cutting-edge properties of NPs such as; nature, biocompatibility, anti-inflammatory and antibacterial activity, effective drug delivery, bioactivity, bioavailability, tumor targeting, and bio-absorption have led to a growth in the biotechnological, and applied microbiological applications of NPs.

A particle of matter with a diameter of one to one hundred nanometers (nm) is commonly referred to as a nanoparticle or ultrafine particle. Nanoparticles frequently exhibit distinctive size-dependent features, mostly due to their tiny size and colossal surface area. The periodic boundary conditions of the crystalline particle are destroyed when the size of a particle approaches the nano-scale with the characteristic length scale close to or smaller than the de Broglie wavelength or the wavelength of light⁵. Because of this, many of the physical characteristics of nanoparticles differ significantly from those of bulk materials, leading to a wide range of their novel uses⁶.

2. EMERGENCE OF NANOTECHNOLOGY

Nanotechnology emerged in the 1980s due to the convergence of experimental advances such as the invention of the scanning tunneling microscope in 1981 and the discovery of fullerenes in 1985⁷, with the elucidation. The popularization of a conceptual framework for nanotechnology goals began with the publication of the book *Engines of Creation* in 1986.

2.1. Early stage of NPs

Carbon nanotubes have been discovered in pottery from Keeladi, India, dating from around 600–300 BC⁸. Cementite nanowires have been discovered in

Damascus steel, a material that dates back to around 900 AD; nevertheless, its origin and creation method are unclear. However, it is unknown how they developed or whether the material containing them was used on purpose.

2.2. Discovery of C, Ag, Zn, Cu, and Au nanoparticles

Carbon NPs were found in 1991, and Iijima and Ichihashi announced the single-wall carbon nanotube synthesis with a diameter of 1 nanometer in 1993⁹. Carbon nanotubes (CNTs), also known as Bucky tubes, are a kind of nanomaterial made up of a two-dimensional hexagonal lattice of carbon atoms. They are bent one way and joined to produce a hollow cylindrical cylinder. Carbon nanotubes are carbon allotropes that fall between Fullerene (0 dimensional) and Grapheme (2 dimensional).

In addition, M. C. Lea reported that the synthesis of citrate-stabilized silver colloid almost 120 years ago¹⁰. This process produces particles with an average diameter of 7 to 9 nm. Nanoscale size and citrate stabilization are analogous to recent findings on nanosilver production employing silver nitrate and citrate¹¹. The use of proteins to stabilize nanosilver has also been documented as early as 1902¹². Since 1897, a nanosilver known as “Collargol” has been made commercially and used for medicinal purposes. Collargol, a type of silver nanoparticle, has a particle size of about 10 nanometers (nm). This was determined as early as 1907, and it was found that the diameter of Collargol falls within the nanoscale range. In 1953, Moudry developed a different type of silver nanoparticle called gelatin-stabilized silver nanoparticles, with a diameter ranging from 2–20 nm. These nanoparticles were produced using another method than Collargol. The necessity of nanoscale silver was recognized by the creators of nanosilver formulations decades ago, as seen by the following remark from a patent: “for optimal efficiency, the silver must be disseminated as particles of colloidal size less than 25 nm in crystallite size”.

Gold NPs (AuNPs) have a long history in chemistry, going back to the Roman era when they were used to decorate glassware by staining them. With the work of Michael Faraday, who may have been the first to notice that colloidal gold solutions have characteristics different from bulk gold, the contemporary age of AuNP synthesis began more than 170 years ago. Michael Faraday investigated the making and factors of colloidal suspensions of

“Ruby” gold in 1857. They are among the magnetic nanoparticles due to their distinctive optical and electrical characteristics. Under specific illumination circumstances, Faraday showed how gold nanoparticles might create solutions of various colors¹⁴.

3. CLASSIFICATION OF NPS

Nanoparticles (NPs) are categorized into the following classes based on their shape, size, and chemical characteristics

3.1. Carbon-based NPs

Fullerenes and carbon nanotubes (CNTs) are the two essential sub-categories of carbon-based NPs. NPs of globular hollow cages, like allotropic forms of carbon, are found in fullerenes. Due to their electrical conductivity, high strength, structure, electron affinity, and adaptability, they have sparked significant economic interest. These materials have organized pentagonal and hexagonal carbon units, each of which is sp² hybridized. While CNTs are elongated and form 1–2 nm diameter tubular structures. These fundamentally resemble graphite sheets rolling on top of one another. Accordingly, they are referred to as single-walled (SWNTs), double-walled (DWNTs), or multi-walled carbon nanotubes (MWNTs) depending on how many walls are present in the rolled sheets^{14,15}.

3.2. Metal NPs

Metal NPs are purely made of metals. These NPs have distinctive electrical properties due to well-known localized surface Plasmon resonance (LSPR) features. Cu, Ag, and Au nanoparticles exhibit a broad absorption band in the visible region of the solar electromagnetic spectrum. Metal NPs are used in several scientific fields because of their enhanced features like facet, size, and shape-controlled synthesis of metal NPs¹⁶.

3.3. Ceramics NPs

Ceramic NPs are tiny particles made up of inorganic, non-metallic materials that are heat-treated and cooled in a specific way to give particular properties. They can come in various shapes, including amorphous, polycrystalline, dense, porous, and hollow, and they are known for heat resistance and durable properties. Ceramic NPs are used in various applications, including coating, catalysts, and batteries¹⁷.

3.4. Lipid-based NPs

These NPs are helpful in several biological applications because they include lipid moieties. Lipid NPs typically have a diameter of 10–1,000 nm and are spherical. Lipid NPs, i.e., polymeric NPs, have a solid lipid core and a matrix consisting of soluble lipophilic molecules¹⁶.

3.5. Semiconductor NPs

Semiconductor NPs have qualities similar to metals and non-metals. That is why Semiconductor NPs have unique physical and chemical properties that make them useful for various applications. For example, semiconductor NPs can absorb and emit light and can be used to make more efficient solar

cells or brighter light-emitting diodes (LEDs). They can make smaller and faster electronic devices, such as transistors, and can be used in bio imaging and cancer therapy¹⁸.

3.6. Polymeric NPs

Polymeric NPs with a size between 1 and 1,000 nm can have active substances surface-adsorbed onto the polymeric core or entrapped inside the polymeric body. These NPs are often organic, and the term polymer nanoparticle (PNP) is commonly used in the literature to refer to them. They resemble Nano spheres or Nano capsules for the most part¹⁹.

4. SYNTHESIS OF NANOPARTICLES

Nanoparticles synthesized different way

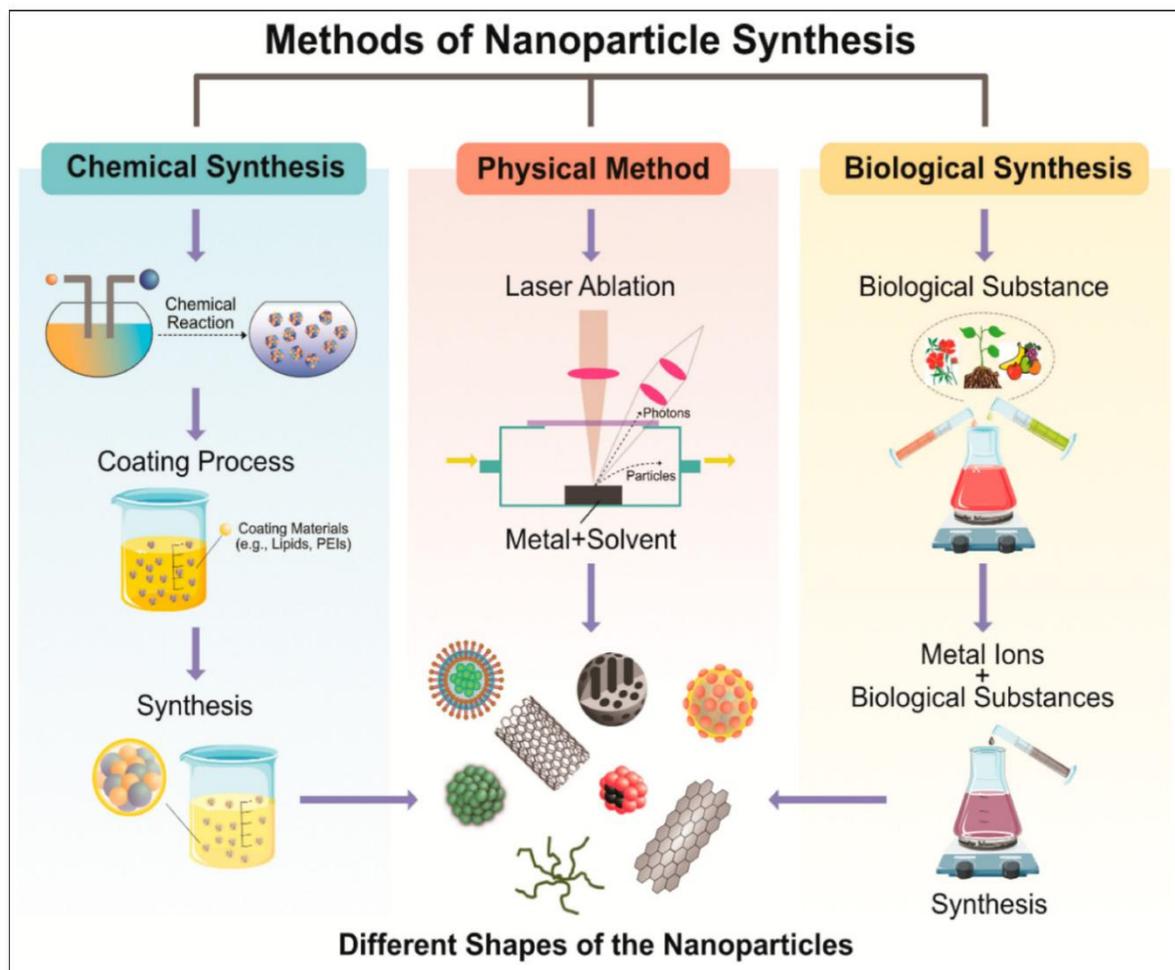


Figure 1: Synthesis of Nanoparticle

4.1. Chemical Synthesis

Chemical synthesis is one of the most widely used methods for producing nanoparticles (NPs). It involves transforming metal precursors into nanoparticles through chemical reactions, often

using reducing agents, stabilizers, and solvents. This approach allows precise control over the size, shape, and distribution of nanoparticles and is scalable for industrial production. These methods include following methods

- A. Reduction of metal ions
- B. Sol-gel techniques
- C. Microemulsion methods.

A. Reduction of metal ions:

Metal salts (precursors) are reduced or reacted to form nanoscale particles. The reaction typically includes:

- Metal precursor: e.g., silver nitrate (AgNO_3), gold chloride (HAuCl_4), zinc acetate ($\text{Zn}(\text{CH}_3\text{COO})_2$)
- Reducing agent: converts metal ions to zero-valent metal atoms (e.g., sodium borohydride, hydrazine, citrate)
- Stabilizing/capping agent: prevents agglomeration and controls particle size (e.g., PVP, citrate, PEG)
- Solvent: usually water or organic solvents like ethanol or ethylene glycol

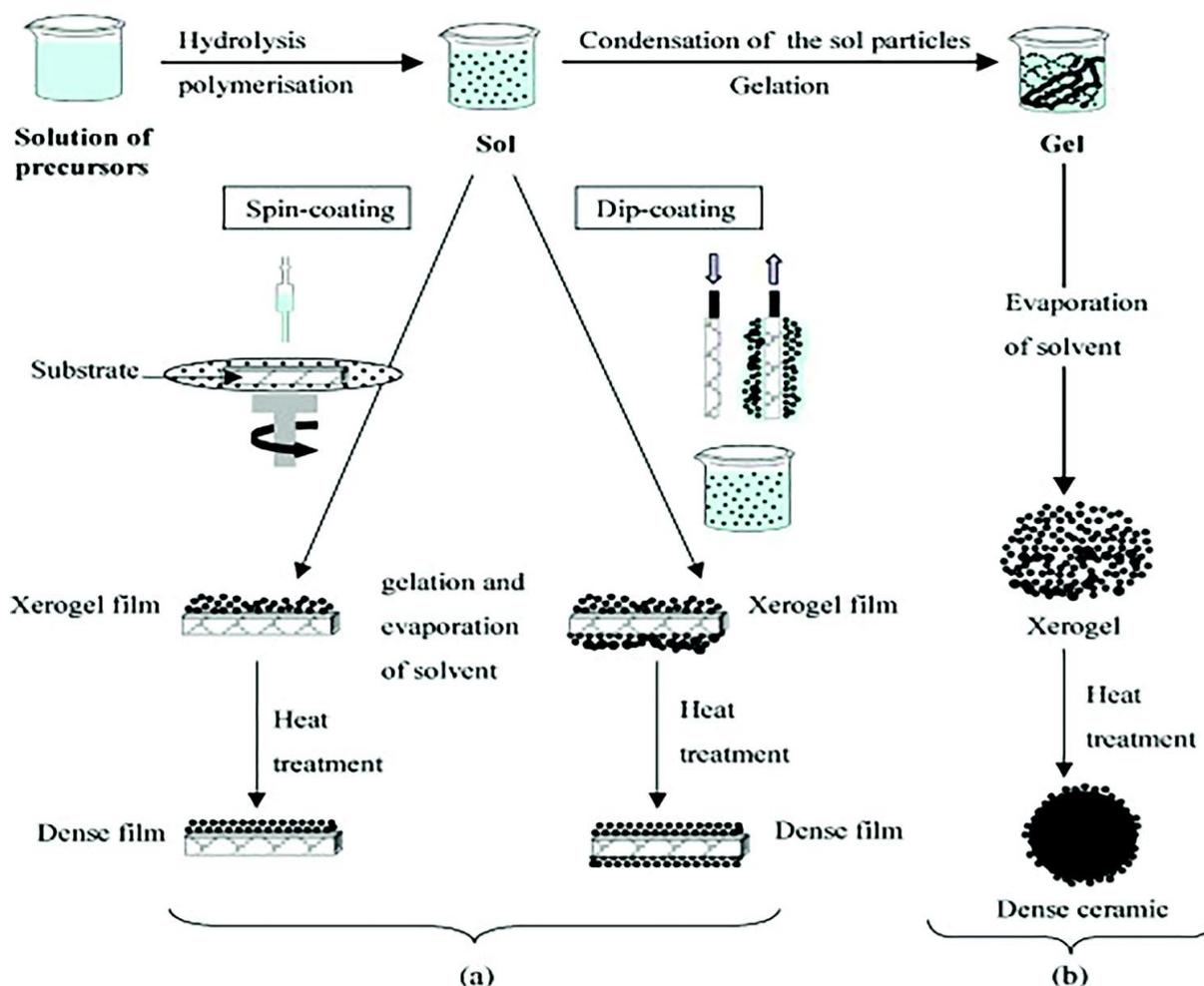
B. Sol-gel techniques:

The sol-gel method is a well-established wet-chemical technique extensively employed for the synthesis of nanomaterials, particularly metal oxide-based nanoparticles. This method is highly regarded for its ability to produce high-purity, homogenous materials with controlled particle size and morphology. The term "sol-gel" refers to the characteristic transformation that occurs during the process, wherein a liquid precursor undergoes hydrolysis and polycondensation reactions to form a colloidal solution or *sol*. Over time, the sol gradually transitions into a semi-solid, interconnected network known as a *gel*. This method offers significant advantages in terms of compositional control, low processing temperatures, and the ability to fabricate complex structures, making it highly suitable for a

wide range of applications in materials science and nanotechnology.

Metal alkoxides are commonly used as conventional precursors in the sol-gel synthesis of nanomaterials. The process typically involves several sequential steps. Initially, hydrolysis of the metal alkoxide occurs in the presence of water or alcohol, leading to the formation of a colloidal suspension, or *sol*. This is followed by a condensation reaction, during which the viscosity of the solution increases, resulting in the formation of a porous gel-like network. As the condensation or more specifically, polycondensation—progresses, metal centers are linked through hydroxo (M-OH-M) or oxo (M-O-M) bridges, leading to the formation of metal-hydroxo or metal-oxo polymeric structures in the solution. These reactions collectively result in the development of a stable gel, which can then undergo aging, drying, and further processing to obtain the desired nanomaterial

During the aging process, polycondensation continues, with changes to the structure, properties, and porosity. During aging, the porosity decreases, and the distance between the colloidal particles increases. After the aging process, drying takes place, in which water and organic solvents are removed from the gel. Lastly, calcination is performed to achieve nanoparticles. The factors that affect the final product obtained *via* the sol-gel method are the precursor nature, hydrolysis rate, aging time, pH, and molar ratio between H_2O and the precursor. The sol-gel method is economically friendly and has many other advantages, such as the produced material being homogeneous in nature, the processing temperature being low, and the method being a facile way to produce composites and complex



C. Microemulsion methods:

The microemulsion technique is a widely utilized method for the synthesis of nanoparticles due to its ability to provide a controlled and reproducible reaction environment. Microemulsions are thermodynamically stable, isotropic mixtures comprising oil, water, and surfactants, often with the addition of cosurfactants. They are generally categorized into two types: direct (oil-in-water) and reverse (water-in-oil) microemulsions. In reverse systems, nanometer-sized aqueous droplets, or micelles, are dispersed in the continuous oil phase and stabilized by surfactant molecules. These micelles can encapsulate dissolved salts or reactants, enabling confined-space reactions. Nanoparticle formation occurs through intermicellar exchange and coalescence, with surfactants playing a critical role in controlling particle nucleation and growth (Lopez-Quintela and Rivas, 1993).

This method has been successfully applied in the synthesis of Fe₃O₄ nanoparticles (Feltin and Pileni, 1997), which can be further modified with silica shells to enhance stability and functionality.

Additionally, the microemulsion approach facilitates the fabrication of Fe₃O₄/Au core-shell nanoparticles, which serve to prevent oxidation of the magnetic core and improve biocompatibility (Boutonnet et al., 1982). The inverse microemulsion method, in particular, offers a straightforward route for producing multifunctional nanostructures by enabling the formation of a silica matrix in the aqueous phase that immobilizes individual particles.

4.2. Physical synthesis:

Physical synthesis of nanoparticles involves methods that manipulate materials at the nanoscale using physical forces like heat, energy, or mechanical pressure, without the need for chemical reactions or solvents. Common physical methods include laser ablation, inert gas condensation, and ball milling.

Laser Ablation:

Laser ablation is a versatile technique for producing nanoparticles by vaporizing a target material with a focused laser beam, followed by condensation

and/or growth in a surrounding medium. This method allows for the synthesis of various nanomaterials, including carbon nanotubes, metal nanoparticles, and quantum dots. The process is particularly useful for creating high-purity nanoparticles with controlled sizes and shapes, often without the need for surfactants.

A high-energy laser beam is directed at a target material (solid or liquid), which can be a metal, semiconductor, or other material. The laser energy is absorbed by the target material, causing it to vaporize and form a high-temperature plasma plume. The vaporized material expands into the surrounding medium (liquid or gas), cools down rapidly, and condenses into nanoparticles. The size and shape of the nanoparticles can be controlled by adjusting parameters such as laser wavelength, pulse duration, pulse energy, and the surrounding medium.

Inert gas condensation:

The inert gas condensation (IGC) method is a physical vapor deposition technique used to produce nanoparticles. It involves evaporating a material in a chamber filled with an inert gas, followed by the condensation of the vaporized material into nanoparticles. The inert gas helps control the particle size and prevents agglomeration.

A solid or liquid material is heated (e.g., by resistive heating, electron beam, or laser) to evaporate it into a gaseous state. An inert gas (like helium or argon) is introduced into the chamber at low pressure (typically a few Torr). The evaporated material collides with the inert gas atoms, losing kinetic energy and condensing into small clusters. These clusters then grow into nanoparticles through further collisions and condensation. The nanoparticles are then collected on a substrate, often a cold surface, to prevent further agglomeration.

Ball milling:

Ball milling is a mechanical method used to produce nanomaterials by reducing the size of bulk materials into nanoparticles through repeated impacts and friction. This "top-down" approach involves rotating a cylindrical vessel partially filled with the material to be milled and grinding media (balls). The balls, often made of steel or ceramic, crush the material into smaller particles as they collide with each other and the vessel walls, and with the material.

Ball milling relies on the mechanical energy generated by the rotating balls to break down larger particles. The process involves both impact, where the balls collide with the material, and attrition, where the balls rub against each other and the material. The milling process can generate heat, and the temperature can influence the final particle size and properties. Various materials like steel, ceramic, or even tungsten carbide can be used as grinding media, depending on the desired outcome and material being processed. The milling time, speed, ball size, and ball-to-powder ratio are key parameters that affect the final particle size and properties of the nanomaterial.

4.3. Biological synthesis for nanoparticle:

Biological methods for nanoparticle synthesis, also known as green synthesis, utilize natural sources like plants, bacteria, fungi, and algae to produce nanoparticles²⁰ in an eco-friendly manner. These methods often involve using enzymes, proteins, or other biomolecules present in these organisms to reduce metal ions and form nanoparticles. This approach is gaining popularity due to its simplicity, cost-effectiveness, and reduced use of harsh chemicals.

Green-mediated nanoparticle synthesis is a low-cost, environmentally friendly method with no toxic properties. This method uses various stabilizing and reducing substances, such as plants, microbes, and some natural agents, to develop NPs. The green-mediated obtaining of nanoparticles has gained popularity due to their low cost, non-toxicity, and high stability. The green-mediated synthesizing approach was an eco-friendly method to manipulate nanoparticles that did not cause toxic effects on the environment or human health. The conventional approach might manipulate nanoparticles in large amounts with defined shapes and sizes. Furthermore, these approaches necessitate massive economies, are difficult, and adhere to outdated protocols. The green synthesis method has numerous advantages over chemical and physical methods, including ease of development, simplicity, low cost, and low waste in the development of NPs

Application of Nanoparticles:

1. Medicine and healthcare:

Targeted Drug Delivery: Nanoparticles can be engineered to deliver drugs precisely to specific diseased cells or tissues, minimizing damage to

healthy cells and reducing side effects. Examples include liposomes, dendrimers, and micelles.

Medical Imaging: Nanoparticles serve as advanced contrast agents for improved medical imaging techniques like MRI (using iron oxide nanoparticles), fluorescence imaging (using quantum dots), and CT scans (using gold nanoparticles).

Disease Diagnostics: Nanosensors and lab-on-a-chip devices incorporating nanoparticles allow for the rapid and sensitive detection of biomarkers and pathogens, enabling earlier disease diagnosis.

2. Industrial and manufacturing applications:

Stronger, Lighter Materials: Nanoscale fillers in materials like polymers, metals, and composites create lighter, stronger, and more durable products. Examples include nanoparticle-strengthened steel in car bodies and carbon nanotubes in lightweight composites for aircraft.

Coatings and Surface Enhancements: Nanocoatings improve surfaces by imparting properties like scratch resistance (antimony-tin oxide), water and stain repellency (nanofibers and nanocoatings in textiles), anti-fogging, and antimicrobial activity.

Electronics: Nanomaterials like carbon nanotubes, graphene, and quantum dots are crucial in creating smaller, faster, and more energy-efficient electronic components, displays, and sensors.

3. Energy applications

Solar Cells: Nanomaterials like quantum dots and nanowires improve the efficiency of solar cells by optimizing light absorption and energy conversion.

Energy Storage: Nanomaterials like graphene nanosheets, nanoparticles of lithium cobalt oxide, and nanostructured electrodes significantly enhance the capacity, charging rate, and lifespan of batteries (e.g., Lithium-ion batteries and supercapacitors).

Energy Conservation: Nanomaterial coatings and smart windows can improve insulation and thermal efficiency in buildings, while nanomaterials enhance the efficiency of lighting systems (e.g., LEDs).

4. Environmental applications

Remediation and Filtration: Nanomaterials such as iron oxide nanoparticles, carbon nanotubes, and nanofilters effectively remove pollutants like heavy metals, organic contaminants, and pathogens from water and soil.

Pollution Sensing: Nanosensors provide real-time detection of toxic gases, water pollutants, and environmental radiation.

Wastewater Treatment: Nano-adsorbents, nanocatalysts, and membranes incorporating nanoparticles can effectively treat industrial and domestic wastewater.

Challenges and future prospects:

Despite the widespread applications, challenges associated with nanoparticles need to be addressed for safe and efficient utilization.

- **Toxicity and Biocompatibility:** The potential toxicity and long-term effects of nanoparticles on human health and the environment require further investigation.
- **Biodegradability and Clearance:** Ensuring controlled biodegradability and efficient clearance mechanisms for nanoparticles, particularly in biomedical applications, is crucial.
- **Scalability and Reproducibility:** Scaling up the synthesis of nanoparticles with consistent properties and ensuring reproducibility of results remains a challenge for certain methods.
- **Regulation and Safety:** Developing robust regulatory frameworks and safety guidelines for the production, use, and disposal of nanoparticles is essential for responsible innovation.

CONCLUSION

Nanoparticles represent a vast and exciting field with the potential to revolutionize various industries. Advancements in synthesis methods, particularly green synthesis approaches, are leading to the development of more sustainable and biocompatible nanoparticles. Addressing the challenges related to toxicity, biodegradability, and scalability will pave the way for further advancements and widespread applications of these remarkable materials.

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