

Review Article

A Review on the Classification, Characterisation, Synthesis of Nanoparticles and Their Application

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Abstract

Nanoparticles (NPs) have become a central focus in scientific and technological research due to their exceptional physical, chemical, and biological properties. With sizes ranging typically from 1 to 100 nanometers, these particles possess a high surface area-to-volume ratio, quantum confinement effects, and tunable surface functionalities, enabling their application in a wide variety of disciplines. Their unique characteristics have made them invaluable in medicine, environmental science, energy storage and conversion, catalysis, and advanced material design. This review provides a detailed examination of the classification, synthesis methods, characterization techniques, and diverse applications of nanoparticles. Classification is discussed based on origin (natural or engineered), composition (metallic, metal oxide, carbon-based, polymeric, and composite), and morphology (spherical, rod-like, tubular). Various synthesis routes are explored, categorized broadly into top-down and bottom-up approaches. These include physical methods like mechanical milling and laser ablation, chemical methods such as sol-gel and hydrothermal techniques, and biological or green synthesis that uses plant extracts or microorganisms to produce eco-friendly nanoparticles. A wide range of characterization techniques electron microscopy (SEM, TEM), spectroscopy (UV-Vis, FTIR, XRD), and surface area analysis (BET) are essential for evaluating the size, shape, structure, composition, and surface properties of nanoparticles. The paper also highlights key applications of nanoparticles in targeted drug delivery, cancer treatment, environmental remediation (water purification and pollutant degradation), energy devices (solar cells and batteries), and industrial processes. While the potential of nanoparticles is vast, several challenges persist, including toxicity, environmental impact, cost-effective synthesis, and regulatory issues. The review concludes by emphasizing the need for sustainable synthesis methods, improved characterization standards, and interdisciplinary research to fully harness the promise of nanotechnology for societal and industrial advancement.

Keywords

Nanoparticles, Synthesis Methods, Characterization Techniques, Nanotechnology Applications, Nanomaterials Classification

1. Introduction

Nanotechnology is an interdisciplinary field that involves the design, synthesis, and application of materials at the nanoscale, typically ranging from 1 to 100 nanometers [1]. At this scale, matter exhibits unique and often enhanced proper-

ties that differ significantly from their bulk counterparts [2]. The development of nanomaterials, particularly nanoparticles, has opened new frontiers in science and engineering by offering unprecedented control over physical, chemical, and

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biological processes [3].

Nanoparticles (NPs) are of particular interest due to their high surface area-to-volume ratio, quantum confinement effects, and enhanced surface reactivity [4]. These characteristics impart distinctive optical [5], electrical [27], magnetic [35], thermal [40], and mechanical properties [22], making them highly desirable for a wide range of applications [39]. As a result, nanoparticles have been recognized as key building blocks in the development of innovative technologies and products that promise improved efficiency, sensitivity, and functionality [6].

The rapid advancement in nanotechnology has led to the integration of nanoparticles into numerous sectors including electronics [2], biomedicine [5], energy storage [11], catalysis [12], and environmental protection [7]. In electronics, they contribute to the miniaturization of components and enhancement of device performance. In biomedicine, nanoparticles play a vital role in drug delivery, diagnostic imaging, and cancer therapy. Similarly, their catalytic properties are exploited in chemical manufacturing, while their adsorptive and reactive surfaces are used in environmental remediation efforts such as water and air purification [9].

This review paper presents a comprehensive overview of the current state of research on nanoparticles. It focuses on their classification based on composition, origin, and morphology; explores various synthesis approaches ranging from physical and chemical to biological methods; outlines key characterization techniques for determining nanoparticle properties; and highlights their diverse applications across different scientific and industrial fields. The paper also addresses current challenges and outlines future directions for advancing nanoparticle technology [9].

2. Classification of Nanoparticles

Nanoparticles can be classified based on their physical, chemical, and morphological characteristics:

2.1. Based on Origin

Nanoparticles can be broadly classified based on their origin into natural and anthropogenic categories [10]. Natural nanoparticles are those that occur without human intervention, arising from a variety of physical, chemical, and biological processes in nature [11]. Common examples include volcanic ash, which contains ultrafine mineral particles released during eruptions; sea spray, which carries salt and organic nanoparticles into the atmosphere; and biogenic particles such as viruses, proteins, and other cellular fragments produced by living organisms [12]. These natural nanoparticles have been part of Earth's ecosystem for millennia and play significant roles in atmospheric chemistry, climate regulation, and biological interactions [13].

In contrast, anthropogenic nanoparticles are either deliberately engineered or unintentionally generated through human

activities. Engineered nanoparticles are synthesized for specific purposes in industrial, medical, or technological applications and include materials such as silver nanoparticles for antimicrobial coatings, titanium dioxide in sunscreens, or carbon nanotubes in electronics [17]. On the other hand, incidental nanoparticles are byproducts of various combustion and manufacturing processes, such as welding fumes, vehicle exhaust, and emissions from coal-fired power plants [27]. These particles often enter the environment and atmosphere, potentially posing health and ecological risks due to their high reactivity and ability to penetrate biological systems [14].

Understanding the origin of nanoparticles is crucial for evaluating their behavior, environmental fate, and potential impacts on health and ecosystems [8]. While natural nanoparticles generally exist in equilibrium with their surroundings, anthropogenic nanoparticles especially those unintentionally released may accumulate in air, water, and soil, necessitating regulatory measures and sustainable manufacturing practices [15]. The distinction between natural and anthropogenic origins also informs the development of appropriate detection, monitoring, and mitigation strategies in environmental and occupational health fields [19].

2.2. Based on Composition

Nanoparticles can also be classified based on their chemical composition, which significantly influences their physical and functional properties. One major category is metallic nanoparticles, composed of pure metals such as silver (Ag), gold (Au), platinum (Pt), and iron (Fe) [16]. These nanoparticles are well known for their unique optical, electrical, and catalytic properties [17]. For instance, silver nanoparticles are widely used for their strong antimicrobial effects, while gold nanoparticles are commonly applied in biomedical imaging and drug delivery systems due to their biocompatibility and surface plasmon resonance characteristics [18].

Another important group is metal oxide nanoparticles, which include materials like titanium dioxide (TiO₂), zinc oxide (ZnO), iron oxide (Fe₃O₄), and copper oxide (CuO) [17]. These nanoparticles possess high thermal and chemical stability and exhibit photocatalytic, magnetic, and semiconducting properties, making them suitable for applications in environmental remediation, sensors, and solar energy conversion [33]. For example, TiO₂ is extensively used in photocatalysis and self-cleaning surfaces due to its strong oxidative properties under UV light [19].

Polymeric nanoparticles, synthesized from natural or synthetic polymers, offer excellent versatility in terms of biodegradability, biocompatibility, and controlled drug release capabilities [37]. These are particularly useful in pharmaceutical and biomedical applications, where they serve as carriers for drugs, genes, and vaccines. Natural polymers like chitosan and alginate, or synthetic ones like polylactic acid (PLA) and polyethylene glycol (PEG), are commonly used

[20].

Carbon-based nanoparticles represent another key category, encompassing fullerenes, carbon nanotubes (CNTs), and graphene. These materials are known for their exceptional mechanical strength, electrical conductivity, and thermal stability. Their unique properties have made them valuable in electronics, composite materials, energy storage, and nanomedicine [21].

Lastly, composite nanoparticles are engineered by combining two or more different types of materials at the nanoscale to create multifunctional systems. These composites are designed to leverage the advantages of each component, resulting in enhanced or synergistic properties such as improved stability, reactivity, or targeting capability. Such nanoparticles are increasingly used in complex applications like targeted therapy, advanced catalysis, and smart materials [22].

2.3. Based on Shape

Nanoparticles can also be classified based on their shape or morphology, which plays a crucial role in determining their physical, chemical, and biological behavior [8]. Common shapes include spherical, rod-shaped, tubular, cubic, dendritic, and various other complex geometries. Among these, spherical nanoparticles are the most widely studied and synthesized due to their thermodynamic stability and ease of production. They are commonly used in drug delivery systems, imaging, and sensing applications [23].

Rod-shaped nanoparticles, including nanorods and nanowires, exhibit anisotropic properties, meaning their behavior differs along different axes. This unique characteristic makes them particularly useful in photonic and electronic applications, where directionality affects performance, such as in sensors and optical devices [47]. Tubular nanoparticles, such as carbon nanotubes (CNTs) and halloysite nanotubes, possess a hollow cylindrical structure and offer high surface area, mechanical strength, and conductivity, making them suitable for applications in nanocomposites, energy storage, and drug encapsulation [24].

Cubic nanoparticles, with their sharp edges and well-defined facets, provide specific surface interactions and catalytic behaviors, often leading to enhanced activity in chemical reactions. These are commonly seen in materials like cerium oxide and silver nanoparticles designed for catalysis and antibacterial applications. Dendritic nanoparticles, which resemble tree-like branched structures, offer a high degree of surface functionality and internal cavities. This makes them particularly effective for multivalent drug delivery, imaging agents, and advanced polymeric systems [25].

The shape of nanoparticles influences not only their functional performance but also their interaction with biological systems, stability, and mobility in different environments. As a result, shape-controlled synthesis has become a major focus in nanomaterial research, aimed at tailoring nanoparticles for specific tasks in medicine, electronics, catalysis, and en-

vironmental science [26].

3. Synthesis of Nanoparticles

Nanoparticles can be synthesized via two primary approaches: *top-down* and *bottom-up*.

3.1. Top-Down Approaches

Top-down approaches refer to techniques that begin with bulk materials and break them down into nanoscale structures through physical or mechanical means [27]. One of the most common top-down methods is mechanical milling, where bulk materials are ground into nanoparticles using high-energy ball mills. This technique is widely used due to its simplicity and scalability for large-scale production, although it often results in particles with irregular shapes and surface defects [27].

Another prominent top-down method is laser ablation, which involves the use of high-energy laser pulses to vaporize a solid material in a controlled environment, often in a liquid or gas medium. The rapid condensation of the vapor leads to the formation of nanoparticles. Laser ablation allows for the production of high-purity nanoparticles with relatively uniform size distribution and is commonly used for metallic and ceramic nanoparticles [28].

Etching techniques, particularly used in semiconductor and thin-film technologies, involve the removal of layers from a substrate to create nanoscale patterns and structures. Chemical or plasma etching can achieve highly precise dimensions, making this approach essential in the fabrication of nanodevices and microelectronic components [27].

The primary advantage of top-down methods lies in their ability to precisely control the size and shape of nanoparticles, especially when combined with lithographic or patterning techniques. These methods are also relatively mature, benefiting from established industrial processes [57]. However, they come with notable limitations, such as high energy consumption, the generation of surface defects, and limited uniformity, which may affect the performance and stability of the produced nanoparticles. Additionally, some methods are expensive and may not be suitable for all materials, especially when high purity or biocompatibility is required. Despite these challenges, top-down techniques remain valuable for producing nanoparticles with defined geometries, particularly in electronics and structural materials [28].

3.2. Bottom-Up Approaches

Bottom-up approaches involve the construction of nanoparticles from atoms, ions, or molecules through chemical or biological processes [20]. These methods enable precise control over particle composition, crystallinity, and size at the molecular level [30]. One widely used technique is Chemical Vapor Deposition (CVD), where gaseous reactants are intro-

duced into a reactor, and nanoparticles form on a substrate as the chemical reaction occurs. CVD is commonly used in the semiconductor industry for producing high-purity nanomaterials and coatings [29].

Another popular method is the sol-gel process, which involves the transition of a solution system from a liquid "sol" (mostly colloidal) into a solid "gel" phase. This technique is particularly suited for synthesizing metal oxide nanoparticles such as TiO₂ and SiO₂ and is valued for its simplicity, low processing temperature, and ability to produce homogenous materials [31].

Co-precipitation is a chemical method where metal ions are precipitated simultaneously from a solution, typically under controlled pH and temperature. It is frequently used for synthesizing magnetic nanoparticles like Fe₃O₄ due to its ease, speed, and scalability. Similarly, hydrothermal synthesis uses high-pressure and high-temperature aqueous conditions in sealed vessels to grow crystalline nanoparticles. This method is ideal for producing well-defined shapes and sizes of nanomaterials, particularly those that are difficult to synthesize through other means [32].

An increasingly popular and sustainable approach is biological or green synthesis, which employs plant extracts, fungi, or bacteria as reducing and stabilizing agents. These methods are eco-friendly, non-toxic, and suitable for biomedical applications, as they avoid the use of hazardous chemicals [33].

The advantages of bottom-up methods include cost-effectiveness, better control over particle structure, and environmental friendliness, especially in green synthesis. However, there are limitations, such as scalability challenges, impurity control, and reproducibility issues, which may hinder their application in industrial-scale production. Nonetheless, bottom-up approaches remain central to the advancement of nanotechnology due to their versatility and potential for innovation [34].

4. Characterisation of Nanoparticles

To understand and utilize nanoparticles effectively, various characterization techniques are employed:

4.1. Structural and Morphological Characterization

Understanding the structure and morphology of nanoparticles is essential for correlating their physical properties with their performance in various applications. Several advanced analytical tools are employed to investigate the size, shape, crystal structure, and surface features of nanoparticles. Among these, Transmission Electron Microscopy (TEM) is one of the most powerful techniques, capable of providing high-resolution images at the atomic level. TEM enables detailed visualization of internal structures, crystal defects, and grain boundaries, making it invaluable for analysing

nanoparticles in the range of 1–100 nm [35].

Scanning Electron Microscopy (SEM), on the other hand, offers surface morphology and topographical information by scanning the sample with a focused beam of electrons. Although SEM generally provides lower resolution than TEM, it is particularly useful for examining surface features and particle aggregation with three-dimensional-like imaging capabilities. It is widely used for both qualitative and quantitative analysis of nanoparticle morphology [36].

Atomic Force Microscopy (AFM) is a non-destructive technique that provides three-dimensional surface profiles of nanoparticles at nano-meter-scale resolution [57]. It operates by scanning a sharp probe over the sample surface and measuring forces between the tip and the sample. AFM is particularly valuable for imaging soft materials and biological samples, where electron beam methods might cause damage [37].

Another essential tool for structural characterization is X-ray Diffraction (XRD), which identifies the crystalline phases present in nanoparticles and provides information about their crystal structure, lattice parameters, and average crystallite size. XRD is crucial for confirming the successful synthesis of nanomaterials and detecting any phase impurities [38].

Together, these characterization techniques offer comprehensive insights into the structural and morphological properties of nanoparticles, which are critical for tailoring their functionality for targeted applications in nanotechnology, medicine, electronics, and catalysis [39].

4.2. Surface and Compositional Analysis

Surface and compositional characterization of nanoparticles is essential to understand their chemical makeup, bonding nature, and surface functionalities, which significantly influence their reactivity, stability, and interaction with other substances [1]. One commonly used technique is Fourier Transform Infrared Spectroscopy (FTIR), which provides information about the functional groups present on the surface of nanoparticles [11–15]. FTIR is particularly valuable in identifying organic ligands, polymers, or biomolecules that are used as capping or stabilizing agents in nanoparticle synthesis. It is also useful in confirming the success of surface modifications or functionalization's [40].

X-ray Photoelectron Spectroscopy (XPS) is another powerful surface-sensitive technique that provides both qualitative and quantitative data on the elemental composition and oxidation states of atoms present within the top few nanometers of the nanoparticle surface. XPS is widely used to determine surface chemistry, chemical bonding, and electronic states, which are critical in catalysis, biomedical applications, and nanocomposites [41].

Energy Dispersive X-ray Spectroscopy (EDX or EDS) is often coupled with electron microscopy techniques such as SEM and TEM to provide elemental analysis. EDX detects

characteristic X-rays emitted from a sample when it is bombarded with high-energy electrons, allowing for the identification and mapping of elements in nanoparticles [21-26]. It is particularly useful for confirming the purity of nanoparticles and detecting trace elements or contaminants [42].

Together, these techniques enable a comprehensive understanding of the surface characteristics and elemental composition of nanoparticles. Such information is crucial for tailoring nanoparticles for specific applications, enhancing their performance, and ensuring compatibility in various fields such as drug delivery, catalysis, and environmental remediation [43].

4.3. Optical Properties

The optical properties of nanoparticles play a pivotal role in determining their behavior in applications ranging from sensors to energy harvesting. One of the most common techniques used to study these properties is UV-Visible Spectroscopy, which provides information about the absorption characteristics of nanoparticles across the ultraviolet and visible regions of the electromagnetic spectrum. UV-Visible spectroscopy is particularly useful in investigating surface plasmon resonance (SPR) effects, which are exhibited by noble metal nanoparticles like gold and silver. These SPR effects can be tuned by varying the size, shape, and aggregation of nanoparticles, making UV-Vis a crucial tool for applications in imaging, biosensing, and photothermal therapy [44].

Another important technique for analyzing the optical properties of nanoparticles is Photoluminescence Spectroscopy (PL). PL spectroscopy measures the emission of light from a nanoparticle after it has absorbed photons. The intensity and wavelength of the emitted light provide insights into the electronic band structure, defects, and surface states of the material. PL is particularly valuable for studying semiconductor and carbon-based nanoparticles such as quantum dots, graphene, and carbon nanotubes, where the optical properties are sensitive to size, shape, and surface modifications. By analyzing PL spectra, researchers can assess nanoparticle quality, optimize synthesis processes, and design nanoparticles for applications like optoelectronics, solar cells, and drug delivery. Together, UV-Visible and Photoluminescence Spectroscopy offer essential insights into the light-matter interaction properties of nanoparticles, guiding their design and integration into a wide range of technologies, from sensors to advanced optoelectronic devices [45].

4.4. Particle Size and Surface Area

The size and surface area of nanoparticles are key factors that influence their reactivity, stability, and performance in various applications. Accurate determination of these parameters is crucial for optimizing nanoparticle design [32-37]. Dynamic Light Scattering (DLS) is a widely used technique

for measuring the hydrodynamic diameter of nanoparticles in suspension. DLS works by analyzing the fluctuations in the scattering of light as particles move due to Brownian motion. This method is particularly effective for determining the size distribution of nanoparticles in colloidal systems and provides rapid results, making it a popular choice in both research and industrial settings. However, DLS measurements can be affected by particle aggregation and the presence of larger particles, which can complicate size determination [46].

To assess the surface area and porosity of nanoparticles, Brunauer Emmett Teller (BET) analysis is commonly employed. BET is based on the adsorption of gas molecules (usually nitrogen) onto the surface of nanoparticles at liquid nitrogen temperatures. The amount of gas adsorbed is measured, and the data is used to calculate the specific surface area and pore volume using the BET equation. This technique is crucial for understanding the surface characteristics of nanoparticles, especially for applications in catalysis, drug delivery, and adsorption processes [41-44]. A larger surface area typically correlates with higher reactivity and more effective interactions with surrounding materials, which is why BET analysis is widely used in the development of nanomaterials for various applications [47].

Together, DLS and BET provide comprehensive data on the size and surface area of nanoparticles, helping researchers and engineers to design materials with the optimal properties for their intended use in fields such as medicine, energy storage, and environmental remediation [48].

5. Applications of Nanoparticles

Nanoparticles are revolutionizing many fields:

5.1. Biomedical Applications

Nanoparticles have shown remarkable potential in the field of biomedicine due to their unique properties, such as small size, high surface area, and the ability to be easily functionalized. One of the most significant biomedical applications is drug delivery systems [1-5]. Nanoparticles can encapsulate therapeutic agents and deliver them to specific sites within the body, improving the bioavailability, stability, and controlled release of drugs. For instance, nanoparticles like liposomes, dendrimers, and polymeric nanoparticles can be engineered to release drugs in response to specific stimuli, such as pH or temperature, ensuring targeted treatment with minimal side effects [49-53].

Nanoparticles also play a crucial role in imaging and diagnostics. Their small size allows for deep tissue penetration, and their surface can be modified with imaging agents, making them ideal for enhancing contrast in techniques like magnetic resonance imaging (MRI), computed tomography (CT), and fluorescence imaging [38]. Additionally, nanoparticles can be designed to target specific biomarkers associat-

ed with diseases, allowing for early detection and precise diagnosis of conditions such as cancer, cardiovascular diseases, and neurological disorders [50].

In cancer therapy, nanoparticles are being explored for advanced treatments such as photothermal and photodynamic therapies. In photothermal therapy, nanoparticles, particularly those made from gold or carbon-based materials, can absorb light and convert it into heat, selectively destroying cancer cells when irradiated with near-infrared light [33-36]. Similarly, in photodynamic therapy, nanoparticles loaded with photosensitive drugs can produce reactive oxygen species upon light activation, leading to the destruction of tumor cells [51].

Nanoparticles also show great promise as antibacterial and antiviral agents. Due to their small size, large surface area, and surface charge, nanoparticles can interact with microbial cells in ways that bulk materials cannot, disrupting their membranes and inhibiting growth [28]. Silver nanoparticles, for example, have been widely studied for their antimicrobial properties, while other nanoparticles can be engineered to target viral particles, offering a potential alternative for combating infections, especially in the face of rising antibiotic resistance [52].

Together, these diverse biomedical applications underscore the versatility and transformative potential of nanoparticles in healthcare, paving the way for more effective, targeted, and less invasive treatments for a wide range of diseases [53].

5.2. Environmental Applications

Nanoparticles have demonstrated significant potential in addressing various environmental challenges due to their high surface area, reactivity, and the ability to interact with a wide range of pollutants. One of the most promising applications is in water purification, where nanoparticles are employed in processes like nanofiltration and the adsorption of heavy metals [22-27]. Nanoparticles, such as those made from activated carbon, titanium dioxide, or magnetite, can effectively remove harmful substances, including heavy metals like lead, arsenic, and mercury, as well as organic contaminants, from water. Their large surface area allows for enhanced adsorption, making them highly effective in both preventing and mitigating water contamination. Additionally, the incorporation of nanoparticles in filtration systems allows for more efficient and cost-effective water treatment processes [54].

In air purification, nanoparticles have been explored as catalysts for pollutant degradation. Nanocatalysts, particularly those made from metals like platinum, gold, and copper, can facilitate the breakdown of harmful gases, such as nitrogen oxides (NO_x), volatile organic compounds (VOCs), and carbon monoxide, into less toxic by-products. These catalysts can be used in air filtration systems, industrial exhaust treatments, and in improving air quality in both urban and

industrial environments. Nanoparticles' high surface area and unique electronic properties enable them to act as efficient catalysts, offering a sustainable solution to combat air pollution [55].

Moreover, nanoparticles have shown promise in soil remediation by aiding in the removal of pollutants like heavy metals, pesticides, and hydrocarbons from contaminated soils. Through processes such as nanoremediation, nanoparticles can either absorb pollutants or catalyze the breakdown of contaminants into less harmful substances [18]. For example, iron-based nanoparticles have been used to degrade chlorinated organic compounds, while other nanoparticles help in immobilizing hazardous substances, reducing their bioavailability and toxicity. These methods offer an innovative approach to cleaning up contaminated soils, providing a more efficient and environmentally friendly solution than traditional techniques [56].

Together, these environmental applications highlight the transformative role nanoparticles can play in tackling pollution and contributing to sustainable environmental management practices. Their versatility and efficiency in addressing both water, air, and soil pollution position them as key components in advancing green technologies for a cleaner, healthier planet [57].

5.3. Industrial Applications

Nanoparticles have found numerous applications in various industries due to their unique properties that enhance the performance and functionality of products. In the field of catalysis, nanoparticles are highly sought after for their ability to speed up chemical reactions while providing higher efficiency and selectivity. Due to their large surface area and high reactivity, metal nanoparticles such as platinum, palladium, and gold are used as catalysts in a wide range of industrial processes, including the production of fuels, chemicals, and in environmental applications like pollutant degradation. The use of nanoparticles in catalysis offers several advantages, such as reducing energy consumption, increasing reaction rates, and enabling reactions under milder conditions [58].

In the paints and coatings industry, nanoparticles, such as silica, titanium dioxide, and aluminum oxide, are incorporated to improve the performance of coatings. These nanoparticles can enhance the scratch resistance, durability, UV protection, and anti-corrosive properties of paints [55]. Additionally, they can improve the clarity and strength of coatings, making them ideal for use in automotive, aerospace, and architectural applications. The inclusion of nanoparticles also allows for the formulation of paints with self-cleaning properties and resistance to microbial growth, contributing to cleaner surfaces and reduced maintenance costs [59].

The cosmetics and sunscreens industries have also embraced nanoparticles for their ability to improve the delivery and effectiveness of active ingredients. Zinc oxide and titani-

um dioxide nanoparticles are commonly used in sunscreens to provide broad-spectrum UV protection while maintaining a transparent appearance on the skin. Furthermore, nanoparticles in cosmetics, such as liposomes and dendrimers, are used to enhance the absorption and controlled release of active agents, leading to more effective skincare products. Their ability to penetrate deeper layers of the skin while minimizing irritation has made nanoparticles invaluable in these industries [60]. Nanoparticles also play a crucial role in the development of nanocomposites, which combine nanoparticles with polymers, metals, or ceramics to enhance the mechanical properties of materials [50]. These nanocomposites exhibit improved strength, stiffness, thermal stability, and impact resistance compared to their conventional counterparts. In industries such as aerospace, automotive, and construction, nanoparticles like carbon nanotubes, graphene, and nanosilica are used to produce lightweight, durable, and high-performance materials. These advanced materials are contributing to the development of more sustainable and energy-efficient products [51].

In summary, the incorporation of nanoparticles into industrial applications enhances product performance, durability, and functionality, revolutionizing industries ranging from chemicals and paints to cosmetics and manufacturing. Their unique properties make them a driving force in the development of next-generation materials and technologies [2].

5.4. Energy Applications

Nanoparticles are playing an increasingly important role in enhancing energy technologies due to their unique properties, such as high surface area and improved charge transfer capabilities. In batteries and supercapacitors, nanoparticles are used to improve the energy storage capacity, charging/discharging rates, and overall efficiency [9]. For instance, carbon-based nanoparticles, such as graphene and carbon nanotubes, are incorporated into electrodes to increase conductivity and surface area, enabling faster electron flow and higher energy density. Additionally, metal oxide nanoparticles like titanium dioxide and manganese oxide are utilized in the development of advanced battery systems, such as lithium-ion batteries and supercapacitors, which are essential for portable electronics and electric vehicles [3].

In solar cells, nanoparticles are enhancing the efficiency of photovoltaic devices by improving light absorption and charge transport. Metal nanoparticles, such as gold, silver, and copper, are used to form plasmonic structures that enhance the light-harvesting capabilities of solar cells, leading to increased efficiency [42]. Additionally, quantum dots and organic-inorganic hybrid nanoparticles are being explored for use in next-generation solar cells, such as perovskite and dye-sensitized solar cells. These innovations hold the promise of lowering production costs and improving the performance of solar energy systems, contributing to the global transition to renewable energy sources [4].

Nanoparticles also play a key role in fuel cells and hydrogen production, offering advancements in both energy conversion and generation. In fuel cells, nanoparticles, particularly platinum and palladium, are used as catalysts to improve the efficiency of the electrochemical reactions that generate electricity from hydrogen. Their high surface area facilitates faster reaction rates, enhancing the overall performance of fuel cells [22-27]. Similarly, nanoparticles are being explored in hydrogen production through water splitting processes. Materials like nickel, iron, and copper-based nanoparticles are being investigated to reduce the energy requirements and increase the efficiency of hydrogen production from water, a crucial step for the sustainable production of hydrogen as a clean fuel [5].

Together, these energy applications demonstrate the transformative potential of nanoparticles in advancing energy technologies. By improving the performance and efficiency of energy storage, conversion, and generation systems, nanoparticles contribute significantly to the development of more sustainable and efficient energy solutions, which are vital for meeting the growing global energy demand and reducing environmental impact [7].

6. Challenges and Future Perspectives

Despite the substantial advancements in the field of nanoparticles, several challenges persist that need to be addressed for their widespread adoption in various applications. One of the most pressing concerns is toxicological effects and environmental impacts [21]. As nanoparticles are increasingly integrated into consumer products, healthcare, and environmental systems, understanding their interactions with biological systems and ecosystems becomes critical. Toxicity studies are essential to ensure that nanoparticles do not pose unforeseen risks to human health or the environment, particularly when released into ecosystems or when used in medical applications [45]. Another challenge lies in developing cost-effective and scalable synthesis methods. While laboratory-scale synthesis techniques for nanoparticles are well-established, scaling these methods for mass production remains difficult. Many top-down and bottom-up approaches require expensive materials, high energy consumption, or complex equipment, limiting their practical application in large-scale industries. Research into more economical, sustainable, and efficient methods for nanoparticle production is crucial to overcome this barrier [11].

In terms of characterization, a major challenge is the lack of standardization. The diverse array of techniques used to characterize nanoparticles often produces inconsistent results due to variations in equipment, sample preparation, and measurement protocols. Standardized methods for nanoparticle characterization are essential for ensuring reproducibility and comparability of data across different laboratories and industries. This is particularly important for regulatory approval processes and the scaling up of nanotechnology-based

products. Furthermore, regulatory and safety issues pose significant challenges. As nanoparticles are used in diverse fields, ranging from medical applications to environmental remediation, comprehensive regulatory frameworks need to be established to address safety concerns. These regulations must balance innovation with the protection of public health and the environment. Furthermore, ensuring that nanoparticles are manufactured, used, and disposed of in a way that minimizes environmental and health risks is vital [19].

Looking ahead, the future of nanoparticle research should focus on green synthesis methods that minimize the environmental impact of nanoparticle production, as well as improving biocompatibility for safer use in medical and environmental applications. Additionally, integrating nanoparticles into real-world technologies presents an exciting avenue for future exploration, including their use in smart devices, energy storage systems, and advanced environmental solutions. Overall, addressing these challenges will be key to unlocking the full potential of nanoparticles and driving their successful application across various sectors [20].

7. Conclusion

Nanoparticles are integral to the ongoing advancement of nanotechnology, playing a pivotal role in addressing a wide range of challenges in healthcare, environmental management, and industrial applications. Due to their unique physical, chemical, and biological properties, nanoparticles offer transformative potential across several domains, including drug delivery, energy storage, water purification, and catalysis. Understanding the classification, synthesis, and characterization of nanoparticles is critical to unlocking their full potential and ensuring their effective integration into various technologies. The diverse range of nanoparticle types, from metallic and polymeric nanoparticles to carbon-based and composite materials, allows for tailored solutions to meet the specific demands of different industries. Despite the remarkable progress made, significant challenges remain. These include concerns about the toxicological effects and environmental impacts of nanoparticles, difficulties in developing cost-effective and scalable synthesis methods, the need for standardization in characterization techniques, and addressing regulatory and safety issues. These challenges highlight the need for further research and the development of more sustainable, environmentally friendly, and safer practices in nanoparticle production and application.

Looking to the future, continued progress will depend on overcoming these obstacles through interdisciplinary research that brings together experts from materials science, environmental science, toxicology, and engineering. Special emphasis should be placed on developing green synthesis methods, improving the biocompatibility of nanoparticles, and ensuring their safe integration into real-world applications. As such, nanoparticles hold immense promise, but realizing their full potential will require careful consideration

of both technological advancements and the associated risks. Future developments in nanotechnology will continue to shape the next generation of solutions for global challenges, paving the way for more sustainable, efficient, and innovative applications across various sectors.

Abbreviations

NP (s)	Nanoparticle (s)
TEM	Transmission Electron Microscopy
SEM	Scanning Electron Microscopy
XRD	X-ray Diffraction
FTIR	Fourier Transform Infrared Spectroscopy
UV-Vis	Ultraviolet–Visible Spectroscopy
DLS	Dynamic Light Scattering
BET	Brunauer–Emmett–Teller (Surface Area Analysis)
SAED	Selected Area Electron Diffraction
AFM	Atomic Force Microscopy
EDX or EDS	Energy Dispersive X-ray Spectroscopy
TGA	Thermogravimetric Analysis
DSC	Differential Scanning Calorimetry
PDI	Polydispersity Index
ZP	Zeta Potential
FESEM	Field Emission Scanning Electron Microscopy
HRTEM	High-Resolution Transmission Electron Microscopy
SPR	Surface Plasmon Resonance
ICP-MS	Inductively Coupled Plasma Mass Spectrometry
XPS	X-ray Photoelectron Spectroscopy
NMR	Nuclear Magnetic Resonance
MRI	Magnetic Resonance Imaging
CT	Computed Tomography
DMSO	Dimethyl Sulfoxide
ROS	Reactive Oxygen Species
MOFs	Metal–Organic Frameworks

Conflicts of Interest

The authors declare no conflicts of interest.

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