

A Comprehensive Review on Nanoparticles: Synthesis Methodologies, Structural Classification, and Biomedical Applications

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Abstract

Nanotechnology refers to the design, manipulation, and application of materials and structures at the nanoscale, typically with at least one dimension ranging from 1 to 100 nm. At this scale, materials exhibit unique physicochemical properties that differ significantly from those of their bulk counterparts owing to quantum confinement effects, increased surface-area-to-volume ratio, and altered surface characteristics. These distinctive properties enable nanoparticles to exhibit enhanced electrical, magnetic, optical, mechanical, and catalytic behaviours, making them highly valuable across diverse fields, including biotechnology, medicine, electronics, energy, and environmental science. The objective of this review is to provide a comprehensive overview of the classification, synthesis, and applications of nanoparticles. In recent years, nanoparticles have gained considerable attention because of their broad range of applications, including biomedical therapies, targeted drug delivery, antimicrobial coatings, cancer treatment, biosensors, optical devices, catalysis, solar energy conversion, solid oxide fuel cells, rechargeable batteries, cosmetics, textiles, and environmental remediation. Their exceptional properties, such as high surface reactivity, superior thermal conductivity, excellent catalytic efficiency, enhanced antibacterial activity, and remarkable oxidative stability, have further accelerated their use in advanced technological applications. Nanoparticles can be synthesized using two major approaches: chemical and biological methods. This review also highlights the classification of nanoparticles, their cellular interactions, and the underlying mechanisms involved in their biological synthesis.

Keywords: Nanotechnology, optical devices, Nanoparticles.

Introduction to Nanotechnology

Nanotechnology is an interdisciplinary field of science and technological innovation that encompasses the synthesis, characterization, and development of nanomaterials by integrating principles from engineering, molecular biology, chemistry, and physics [1]. Nanoparticles, typically ranging in size from 1 to 100 nm, exhibit physicochemical properties that differ significantly from those of their bulk counterparts due to their unique structural characteristics, high surface-area-to-volume ratio, and quantum size effects. In recent years, the synthesis and production of various metallic and metal oxide nanomaterials, including iron, gold, silver, zinc, copper, magnesium, and titanium-based nanoparticles, have expanded rapidly [2]. By controlling their size, shape, and surface morphology, these nanomaterials exhibit enhanced properties that have enabled their widespread application in medical treatments, specialized cosmetics, antimicrobial textiles, biological and biomedical fields, solar energy conversion, and energy storage systems, including batteries and solid oxide fuel cells [3].

Nanoparticle Synthesis Methodologies

Nanoparticles are generally synthesized using two major approaches: chemical and biological methods. Although chemical synthesis enables the large-scale production of nanoparticles with controlled size and morphology, it often involves the use of hazardous chemicals that may remain adsorbed on the nanoparticle surface, potentially causing environmental and biological toxicity [4]. Conventional physical synthesis methods are also associated with high energy consumption and expensive instrumentation. Consequently, chemical and physical methods are increasingly being complemented or replaced by environmentally friendly biological approaches that utilize plant extracts, fungi,

microorganisms, algae, and enzymes as natural reducing and stabilizing agents [5]. Among these, plant-mediated green synthesis has gained considerable attention because it is simple, cost-effective, sustainable, and eco-friendly. In biological synthesis, phytochemicals such as flavonoids, phenolic compounds, alkaloids, terpenoids, proteins, and sugars present in plant extracts serve as reducing, capping, and stabilizing agents, thereby eliminating or significantly reducing the need for toxic chemicals during nanoparticle synthesis [6].

The Green Synthesis Paradigm Shift

Chemical synthesis methods have several limitations, as they often require the use of stabilizing agents, organic solvents, and chemical reducing agents, many of which are toxic and may pose risks to both human health and the environment [7]. Consequently, green synthesis has emerged as an environmentally friendly alternative and has gained considerable attention as a sustainable approach for nanoparticle synthesis. This method utilizes eco-friendly biological resources under mild reaction conditions, including plant extracts, enzymes, fungi, microorganisms, and algae [8]. Among these biological resources, plant extracts are particularly important because they are rich in natural phytochemicals. These phytochemicals perform dual functions by acting as reducing agents that convert metal ions into nanoparticles and as capping or stabilizing agents that prevent nanoparticle aggregation and improve their stability [9]. As a result, green synthesis enables the production of nanoparticles in a more efficient, less toxic, cost-effective, and environmentally sustainable manner than conventional chemical synthesis methods [10].

Biochemical Mechanisms of Biosynthesis

Biogenic synthesis of nanoparticles using microorganisms is mediated by a variety of biochemical and enzymatic processes that occur within living cells. A wide range of prokaryotic and eukaryotic microorganisms, including bacteria, fungi, algae, and actinomycetes, has been employed for the synthesis of metallic and metal oxide nanoparticles [11]. These microorganisms are capable of producing nanoparticles of various metals and metal oxides, such as silver, gold, platinum, cadmium, iron, zinc oxide, titanium dioxide, and zirconium oxide [12]. Depending on the site of metal ion reduction and nanoparticle formation, microbial synthesis can be classified into two types: intracellular synthesis, in which nanoparticles are formed within the microbial cells, and extracellular synthesis, in which nanoparticles are produced outside the cells through the action of secreted bio molecules and enzymes [13].

Intracellular Bio reduction: The intracellular bio reduction mechanism involves the active transport of metal ions across the microbial cell membrane into the cytoplasm, where they are reduced in the presence of intracellular enzymes and other bio molecules, leading to the formation of nanoparticles [14]. The intracellular environment provides favourable conditions for the nucleation and controlled growth of nanoparticles [15]. These newly formed nanoparticles interact with proteins, enzymes, and other cellular bio molecules, which facilitate metal ion reduction, stabilize the nanoparticles, and regulate their size and morphology [16].

Extracellular Bio reduction: Extracellular synthesis has gained considerable attention because it utilizes extracellular proteins, enzymes, and other bio molecules secreted by microorganisms to mediate nanoparticle formation [17]. Unlike intracellular synthesis, where nanoparticles are formed within microbial cells, extracellular synthesis occurs in the surrounding medium through the action of secreted bio molecules, thereby eliminating the need for cell disruption during nanoparticle recovery [18]. Fungi are particularly effective in extracellular nanoparticle synthesis because they secrete large amounts of extracellular reductases, proteins, and other metabolites capable of reducing metal ions and facilitating nanoparticle formation. During this process, extracellular enzymes and bio molecules convert metal ions into nanoscale materials while simultaneously acting as capping and stabilizing agents [19]. Compared with intracellular synthesis, extracellular synthesis generally produces nanoparticles with better size uniformity and purity, offers simpler downstream processing, is more cost-effective and scalable, and represents a more environmentally sustainable approach for large-scale nanoparticle production [20].

Structural Classification and Functional Profiles:

Nanomaterials are broadly classified based on their morphology, chemical composition, structural characteristics, and functional properties, as shown below:

Silver Nanoparticles (AgNPs): Among the various metallic nanoparticles, silver nanoparticles (AgNPs) have attracted significant attention because of their remarkable antimicrobial properties and wide range of applications [21]. They exhibit excellent antimicrobial activity against bacteria, viruses, fungi, and certain other eukaryotic pathogens. Owing to their unique physicochemical characteristics, including high surface-area-to-volume ratio and enhanced surface reactivity, AgNPs have been extensively employed in water filtration membranes, antimicrobial coatings, textiles, medical devices, water treatment technologies, wound dressings, biosensors, and personal care products [22]. In recent years, the green synthesis of silver nanoparticles using plant extracts, such as *Capsicum annuum* (chilli), *Carica papaya* (papaya), and *Azadirachta indica* (neem), has emerged as an environmentally friendly and sustainable alternative to conventional chemical synthesis, offering reduced toxicity, improved biocompatibility, and lower environmental impact [23].

Gold Nanoparticles (AuNPs): Gold nanoparticles (AuNPs) exhibit unique localized surface plasmon resonance (LSPR) properties, making them highly valuable in molecular diagnostics, biotechnology, biomedical research, and analytical applications [24]. Their exceptional optical properties have enabled their use in immunoassays for studying protein-protein interactions, DNA fingerprinting, nucleic acid detection, biosensing, and as labels or tracers in molecular and genetic analyses [25]. In addition, AuNPs have been employed for the sensitive detection of aminoglycoside antibiotics, including neomycin, gentamicin, and streptomycin. Recent advances in gold nanotechnology have further highlighted the potential of gold nanorods for the selective identification of cancer stem cells, early cancer diagnosis, and the rapid detection and classification of pathogenic bacteria, demonstrating their significant potential in modern biomedical diagnostics [26].

Alloy and Bimetallic Nanoparticles: Alloy and bimetallic nanoparticles exhibit unique electronic, structural, and physicochemical characteristics that differ significantly from those of corresponding bulk alloys [27]. Bimetallic alloy formed from combining two or more metallic elements at the nanoscale level gives distinctive properties that contribute to high electrical conductivity, outperforming catalytic efficiency, stability, and unique structural activity [28]. Silver-containing alloys are extensively employed in conductive materials, which utilize the excellent electrical conductivity of silver and relatively higher conductivity of its oxide derivatives. This synergistic effect can lead to improved catalytic activity, stability, optical behavior, and electrical conductivity, making alloy nanoparticles attractive for a broad range of technological and industrial applications [29].

Magnetic Nanoparticles: Magnetic nanoparticles, due to their excellent biocompatibility and unique properties, particularly like magnetite (Fe_3O_4) and maghemite ($\gamma\text{-Fe}_2\text{O}_3$), have attracted significant attention in the modern nanomedicine era [30]. These nanoparticles have been actively researched for targeted treatment of cancer through magnetic hyperthermia, stem cell separation, manipulation, targeted drug delivery systems, gene therapies, in addition to DNA analysis, diagnostic imaging techniques like magnetic resonance imaging (MRI), and serve as the core thermal agents in magnetic hyperthermia treatments to selectively destroy cancerous tumors [31].

Micro-organism Mediated Synthesis Data

To illustrate the structural diversity achieved through biogenic synthesis, Table 1 details documented combinations of microbial strains, targeted metals, synthesis locations, and resulting particle size ranges.

Table.1

Synthesis of metallic nanoparticles by different microorganisms

Microbial Strain	Organism	Metal Type	Synthesis Location	Particle Size Range (nm)
Phoma sp. (Fungi)		Ag (Silver)	Extracellular	71.05 – 74.45 nm
Fusarium oxysporum (Fungi)		Au (Gold)	Extracellular	20.01 – 40.01 nm
Verticillium sp. (Fungi)		Ag (Silver)	Intracellular	25.01 ± 12.01 nm
Aspergillus fumigatus (Fungi)		Ag (Silver)	Extracellular	5.01 – 25.05 nm
Trichoderma asperellum (Fungi)		Ag (Silver)	Extracellular	13.01 – 18.01nm
Phaenerochaete chrysosporium (Fungi)		Ag (Silver)	Extracellular	50.05 – 200.06 nm

Applications

Nanomedicine has emerged as a promising field with the potential to significantly improve healthcare through advanced diagnostic, therapeutic, and drug delivery strategies. Among the various green synthesis approaches, microbial synthesis of nanoparticles offers a sustainable and environmentally friendly route for nanomaterial production by utilizing microorganisms as biological factories for nanoparticle synthesis. This approach minimizes the use of hazardous chemicals, reduces environmental impact, and provides an eco-friendly alternative to conventional synthesis methods. Furthermore, continuous advancements in nanotechnology are expected to revolutionize biotechnology and nanomedicine by enabling the development of innovative, cost-effective, portable, and user-friendly technologies for disease diagnosis, targeted therapy, biosensing, and personalized healthcare.

Conclusion and Future Directions

Nanoparticle architectures possess unique and remarkable physicochemical properties that have attracted significant attention across a wide range of scientific and technological fields. They play a pivotal role in advancing modern science by offering innovative solutions for energy conservation, environmental management, clinical medicine, and sustainable agriculture. Their ability to improve the stability, solubility, bioavailability, and targeted delivery of biologically active compounds highlights their transformative potential in biomedical and industrial applications. Despite these advances, further research is required to scale up green synthesis processes, achieve precise control over nanoparticle morphology and physicochemical properties, and expand their integration into personalized medicine, advanced biomedical technologies, and sustainable industrial manufacturing. Continued progress in these areas is expected to accelerate the development of safer, more efficient, and environmentally sustainable nanomaterials for future applications.

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