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Green Synthesis of Metallic Nanoparticles: Methods, Applications, and Future Perspectives

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Abstract

Nanoparticles (NPs) have emerged as essential components in various fields such as biomedicine, agriculture, environmental science, and industry. Their unique physicochemical properties at the nanoscale enable novel applications ranging from drug delivery and antimicrobial agents to bioremediation and nanocatalysis. Traditional physical and chemical synthesis techniques, though effective, often involve harsh operating conditions and toxic reagents that raise environmental and health concerns.

Green synthesis of metallic nanoparticles (MNPs) using plants, microorganisms, algae, fungi, and viruses has emerged as a sustainable, eco-friendly, and cost-effective alternative. This review integrates insights from recent literature on green synthesis techniques, characterization methods, key applications, challenges, and future prospects. We emphasize that despite remarkable advances, the translation of green nanotechnology into commercial applications requires standardized protocols, mechanistic understanding, and toxicity evaluations.

Keywords: green synthesis, metal nanoparticles, plant-mediated synthesis, biomedical, agriculture, environment, food application.

Introduction

Nanotechnology has transformed modern science, enabling the design and manipulation of materials at the nanoscale (1–100 nm). At this scale, nanoparticles exhibit distinct optical, catalytic, mechanical, and biological properties not observed in bulk materials due to their high surface-to-volume ratio and quantum confinement effects[1]. NPs exhibit extensive applicability across diverse scientific and industrial domains, including magnetic storage systems, photocatalysis, microelectronic device fabrication, anticorrosive coating development, biomedical engineering, electrocatalysis, and powder metallurgy[2].

Metallic nanoparticles (MNPs) are particularly attractive because of their wide-ranging applications in medicine, agriculture, catalysis, environmental remediation, and electronics[3,4,5]. The scope of biotechnological applications of nanoparticles (NPs) has progressively expanded due to their unique physicochemical and biological attributes, such as excellent biocompatibility, pronounced anti-inflammatory and antimicrobial properties, high efficiency in targeted drug delivery, superior bioactivity and bioavailability, selective tumor-targeting potential, and enhanced bioabsorption capacity[5,6,7]. Recently, magnetic nanoparticles (NPs) have gained prominence for their applications in multidisciplinary field such as cancer therapy, targeted drug delivery, tumor detection, MRI enhancement, and separation processes[8].

Traditional methods for synthesizing nanoparticles, such as laser ablation, electrochemical reduction, and thermal decomposition often rely on expensive physical or chemical procedures that use hazardous substances, which can introduce risks such as potential environmental hazards[5], cellular toxicity, and even carcinogenic effects[9]. These issues mainly arise from the use of organic solvents, chemical reducing agents, and stabilizing compounds that prevent particle aggregation but pose safety concerns. In addition, the

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nanoparticles produced through these routes may also exhibit toxicity influenced by factors such as their chemical composition, particle size, morphology, and surface characteristics[10]. Such concerns, including the presence of toxic residues on the final nanomaterials, limit their direct use in biomedical and clinical applications. Consequently, there is growing emphasis on designing sustainable, non-toxic, biocompatible, and environmentally benign green synthesis strategies for nanoparticle production. Biological or green synthesis methods offer a way to regulate these parameters more safely. Therefore, there is increasing interest in developing eco-friendly, biocompatible, and sustainable biological approaches for nanoparticle fabrication[11].

The green synthesis utilizes biological entities - plants, fungi, bacteria, algae, viruses - as natural factories for NP production[12,13]. These biological routes avoid hazardous reducing or stabilizing agents and operate under ambient conditions, making them sustainable and cost-effective.

This review consolidates advances in green synthesis of metallic NPs, outlines the mechanisms and methods employed, highlights diverse applications, and discusses limitations and future perspectives for safe and scalable nanotechnology.

2. Methods of Green Synthesis or Biological Synthesis

Green synthesis of nanoparticles (NPs) can be achieved using a wide range of biological materials, including plant extracts, algae, fungi, yeasts, bacteria, and viral systems[14]. In these methods, metal salt solutions are combined with biologically derived components, where naturally occurring molecules - such as proteins, alkaloids, flavonoids, reducing sugars, and polyphenols - function as reducing agents and stabilizers during nanoparticle formation[15].

The conversion of metal ions to nanoparticles is often evident through a distinct color change in the reaction mixture, reflecting the development of nanoscale optical properties[16]. Recent research has documented the successful production of various metal nanoparticles - including Ag, Au, Cu, Pt, Cd, Pd, Ru, and Rh - using diverse biological sources[17,18].

2.1 Plant-Mediated Synthesis

Plant-mediated synthesis of nanoparticles is the most widely studied biological approach due to simplicity, scalability, and speed. Plant extracts contain a variety of biomolecules—flavonoids, alkaloids, phenolics, sugars, proteins that act simultaneously as reducing and capping agents[4].

The process typically involves mixing metal salt precursors (e.g., $AgNO_3$, $HAuCl_4$) with plant extracts under controlled pH and temperature, where phytochemicals reduce the ions into metallic nanoparticles[19]. Advantages of plant-mediated synthesis include low cost, non-pathogenic nature, and suitability for large-scale production.

Several studies demonstrate efficient synthesis of silver (AgNPs), gold (AuNPs), palladium, platinum, copper, and zinc oxide NPs from plant parts such as leaves, seeds, flowers, roots, and latex[20]. For instance, *Phyllanthus emblica* fruit extract yields spherical AgNPs, while *Moringa oleifera* flower extract produces triangular AuNPs.

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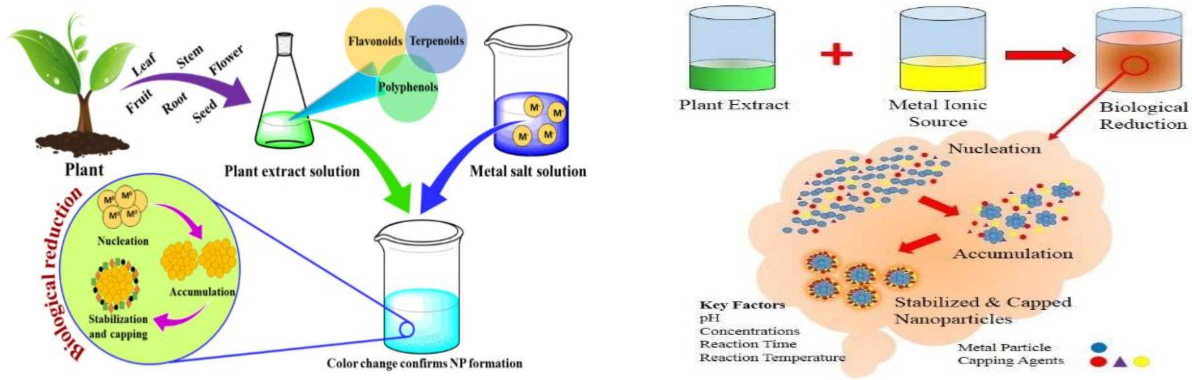

Figure: *Plant mediated biosynthesis of nanoparticles*

2.2 Microbial Synthesis

Microorganisms including bacteria, fungi, yeast, and actinomycetes have innate abilities to uptake, reduce, and accumulate metal ions from their environment. Microbial synthesis can be extracellular, where secreted enzymes and metabolites reduce ions or intracellular, where reduction occurs within the cell wall or cytoplasm[21]. Bacteria such as *Bacillus thuringiensis* produces AgNPs with larvicidal activity; *Escherichia coli* has been used for CdS NPs.

Fungi such as *Fusarium oxysporum* and *Aspergillus niger* are prolific producers due to high secretion of enzymes and ease of biomass handling. Actinomycetes such as *Streptomyces* species can synthesize silver, copper, and zinc nanoparticles with antimicrobial properties. Microbial synthesis is advantageous for controlled morphology, but culturing and maintaining sterile conditions can be complex compared to plants[22].

2.3 Algal and Viral Mediated Synthesis

Marine and freshwater algae also serve as biofactories for MNPs. For example, *Sargassum wightii* synthesizes Au and Ag nanoparticles extracellularly. Algal metabolites act as reducing agents, stabilizers, and shape controllers. Viruses, particularly bacteriophages and plant viruses, act as templates for nanoparticle assembly, enabling precise arrangement into nanowires and nanotubes[23,24]. Though less explored, viral-mediated synthesis offers unique structural precision.

2.4 Mechanisms of Biosynthesis

As mentioned above nanoparticles can be biosynthesized using a diverse range of biological systems, including actinomycetes, algae, bacteria, fungi, plants, viruses, and yeast. Each biological entity possesses distinct biochemical pathways and metabolic capabilities that determine its ability to reduce metal ions and facilitate the formation of specific metallic or metal oxide nanoparticles.

However, not all organisms are capable of nanoparticle synthesis, as this process depends on the presence of suitable enzymatic activities and reductive metabolic mechanisms. Consequently, the selection of an appropriate biological system is critical for obtaining nanoparticles with controlled physicochemical attributes, such as size, shape, and surface characteristics[25].

Organisms capable of bioaccumulating heavy metals generally exhibit enhanced potential for the synthesis of metallic nanoparticles. Green synthesis is typically a bottom-up approach. The mechanism involves three main stages[26].

- **Reduction** of metal ions to neutral atoms via biomolecules (enzymes, phenolics).
- **Nucleation and growth**, where atoms aggregate to form nanoclusters.
- **Stabilization**, where biomolecules cap nanoparticles, controlling size and preventing aggregation.

However, the exact roles of individual biomolecules remain poorly understood, making mechanistic elucidation a major research gap.

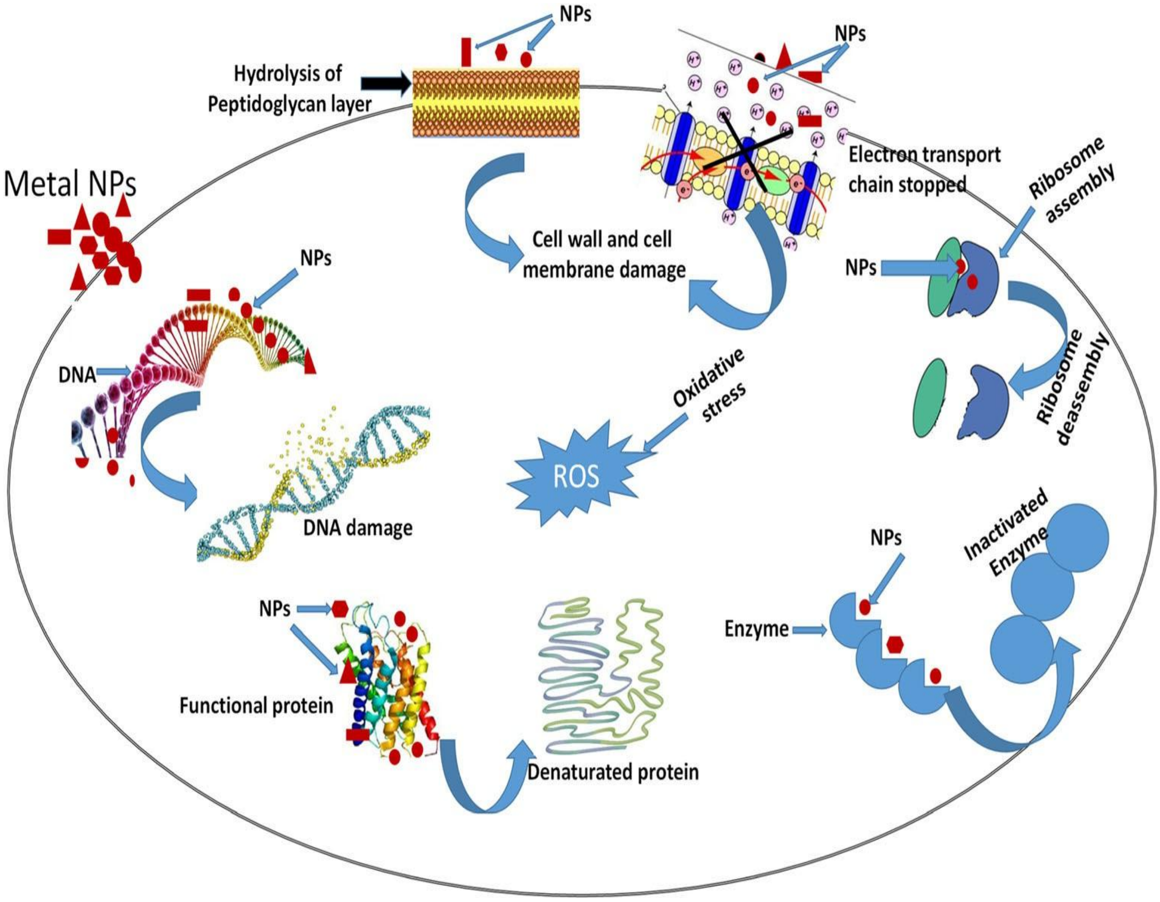

Figure 2 : Prospective mechanism for antimicrobial activity of metallic nanoparticles

3. Characterization of Green-Synthesized Nanoparticles

Physicochemical characterization of synthesized nanoparticles (NPs) is a critical step that must be rigorously conducted prior to their practical application. Comprehensive evaluation of parameters such as particle size, morphology, surface area, structural uniformity, and colloidal stability provides essential information about nanoscale systems. These characteristics offer key insights into the quality and reproducibility of the synthesis process and are vital for ensuring that nanoparticles meet the required specifications for commercial and technological applications. Characterization ensures nanoparticles are suitable for intended applications. Most common techniques include: *UV-Visible Spectroscopy*-detects surface plasmon resonance peaks (AgNPs at 400–450 nm; AuNPs at 500–550 nm), *Dynamic Light Scattering (DLS)*-determines size distribution and surface charge, *Electron Microscopy (SEM, TEM)*- provides morphological and structural details, *X-Ray Diffraction (XRD)*-identifies crystalline phases and crystallite size. *Fourier-Transform Infrared Spectroscopy (FTIR)*-detects biomolecules involved in capping/stabilization, *Zeta Potential*- assesses stability of colloidal

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dispersions. Using these techniques in combination provides robust insight into nanoparticle size, shape, crystallinity, and surface chemistry[18].

4. Applications of Green-Synthesized Metallic Nanoparticles

4.1 Biomedical Applications

Green-synthesized nanoparticles show remarkable potential in healthcare. Few biomedical applications are discussed as follow:

Antimicrobial agents: AgNPs exhibit broad-spectrum antibacterial, antifungal, and antiviral activity, making them useful in wound dressings, medical coatings, and disinfectants[5].

Anticancer and Antitumor: Gold nanoparticles are used for photothermal therapy and targeted drug delivery.

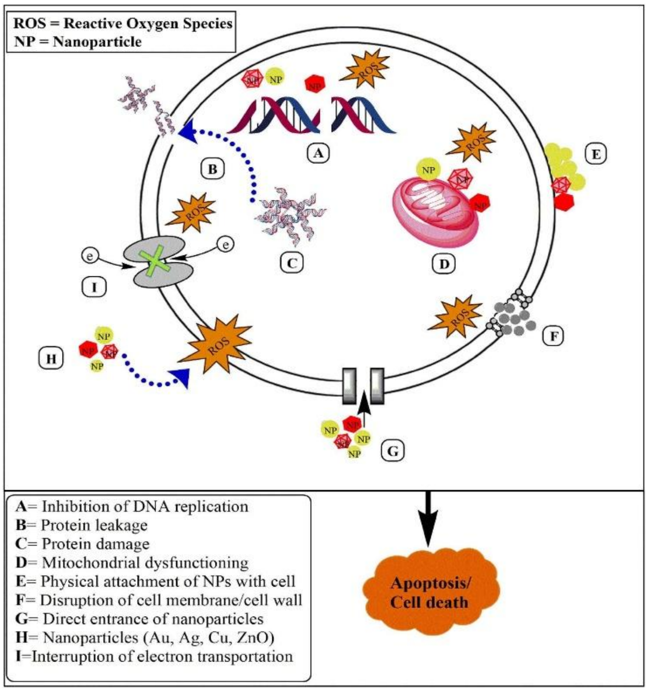

Figure: *Antibacterial mechanism of action of biosynthesized metal nanoparticles*

Anti Fungal : The antifungal activity of nanoparticles has been shown to be strongly influenced by particle size, with smaller nanoparticles exhibiting significantly higher antifungal efficacy. This enhanced bioactivity is primarily attributed to their increased surface-area-to-volume ratio, which facilitates greater interaction with cellular targets, particularly binding sites on the fungal plasma membrane. As a result, smaller nanoparticles can more effectively disrupt membrane integrity and impair fungal cell function.

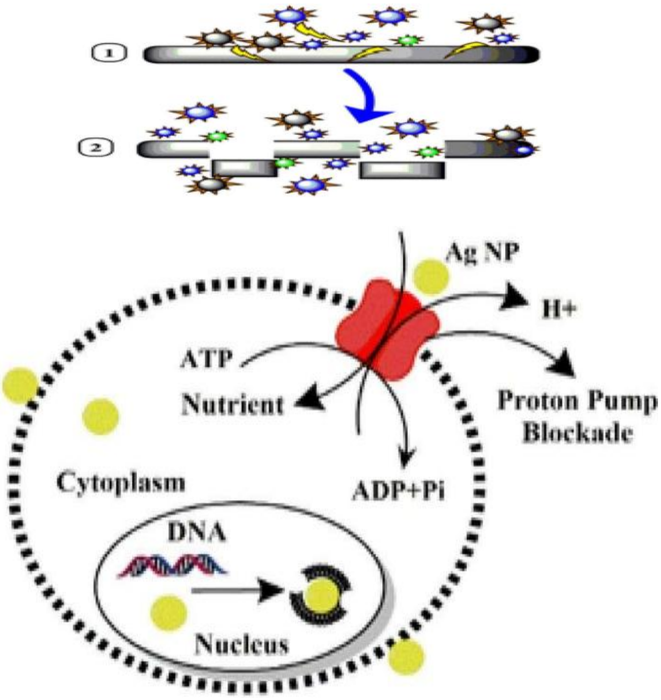

Figure: *Antifungal mechanism of action of biosynthesized metal nanoparticles*

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Drug delivery and imaging: Nanocarriers improve solubility, bioavailability, and targeted delivery of drugs, while serving as contrast agents in imaging[27].

4.2 Agricultural Applications

Agriculture is a primary sector responsible for producing human food, animal feed, and various raw materials for industries, including fibers, leather, and biochemical products such as starch, xylan, and sugars. Enhancing agricultural practices positively influences multiple downstream sectors. Nanotechnology offers significant benefits to agriculture, particularly in managing plant pathogens. Nanoparticles can be formulated as nanopesticides, nanoinsecticides, and nanofertilizers, enabling improved crop protection and nutrient delivery[5]. Nanotechnology addresses critical agricultural challenges:

Nano-fertilizers and pesticides: Enhance nutrient uptake and pest control.

Pathogen control: Metallic NPs act against phytopathogens and improve crop resistance[4].

4.3 Environmental Applications

NPs are effective in environmental remediation due to high surface reactivity:

Wastewater treatment: Removal of dyes, heavy metals, and organic pollutants.

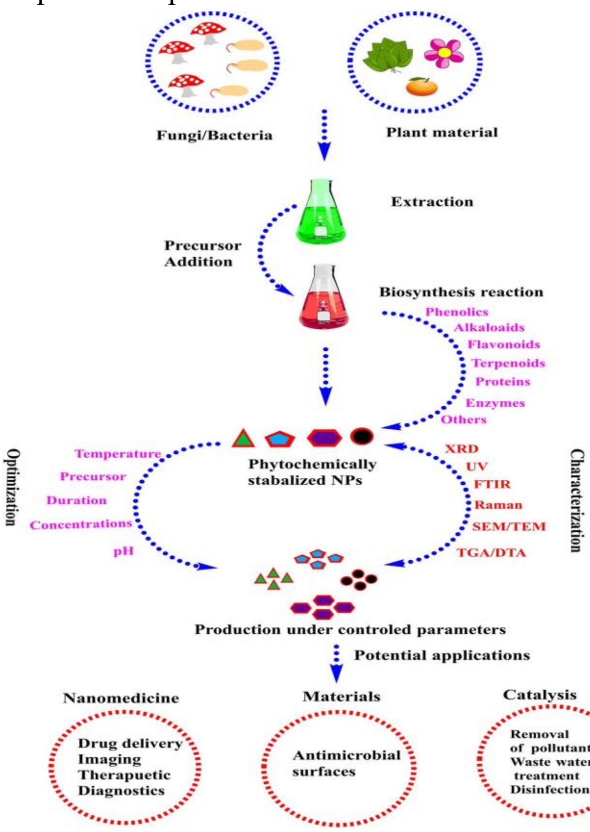
Bioremediation: Degradation of toxic compounds facilitated by nano-catalytic activity.

4.4 Industrial and Food Applications

Food packaging: Nanocoatings and nanocomposites extend shelf life by inhibiting microbial growth.

Textiles: Antibacterial fabrics treated with AgNPs.

Catalysis: Pt and Pd nanoparticles function as efficient catalysts in chemical and electrochemical reactions.



5. Limitations and Challenges

Despite extensive promise, several barriers hinder commercial translation[28]:

Scalability: Laboratory-scale synthesis does not easily translate to industrial levels due to variability in biomass and conditions[5].

Reproducibility: Lack of standardized protocols leads to variations in NP size, shape, and stability.

Mechanistic Gaps: Exact pathways of reduction and stabilization are unclear, complicating process optimization.

Toxicity Concerns: While green synthesis avoids harsh chemicals, nanoparticle toxicity to human health and ecosystems remains unresolved[4].

Regulatory Barriers: Absence of unified guidelines for production, usage, and disposal of green-synthesized NPs.

6. Future Perspectives

The major challenges associated with green synthesis of nanoparticles (NPs) include:

Achieving precise control over NP size, shape, and physicochemical properties requires extensive optimization, particularly for biomedical applications. The mechanistic pathways underlying NP formation in green synthesis remain insufficiently understood. Comprehensive characterization of metabolites in biological extracts is needed to clarify their specific roles in NP biofabrication. Scaling up green synthesis processes for commercial production remains difficult. Ensuring NPs stability and high yield depends on optimizing parameters such as pH, salt concentration, contact time, and temperature, which vary across different biological sources. Thus, future research must focus on mechanistic Insights, genetic engineering, toxicological studies, standardization and scale-up and smart integration. Interdisciplinary collaboration among chemists, biologists, engineers, and policymakers will be crucial to transform green synthesis into a commercially viable and socially acceptable technology.

7. Conclusion

Green synthesis of metallic nanoparticles represents a paradigm shift towards sustainable nanotechnology. By leveraging biological entities as reducing and stabilizing agents, researchers have developed eco-friendly routes that bypass the limitations of conventional synthesis. Applications span healthcare, agriculture, environment, and industry, highlighting the transformative potential of biogenic nanoparticles. However, challenges of reproducibility, scalability, mechanistic understanding, and biosafety must be addressed. With continued innovation and regulatory support, green nanotechnology promises to be a cornerstone of future scientific and industrial advancement.

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