

A Review Green Synthesis of Nanoparticles for Environmental Applications: Recent Advances, Mechanistic Understanding, and Future Perspectives

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Abstract—The increasing burden of environmental pollution has intensified the search for sustainable and efficient remediation technologies capable of addressing complex contaminants in water, air, and soil systems. In this context, green synthesis of nanoparticles has emerged as a transformative approach that combines the advantages of nanotechnology with the principles of green chemistry and environmental sustainability. Unlike conventional physicochemical synthesis routes that rely on toxic reagents and energy-intensive conditions, green synthesis exploits biological resources such as plant extracts, microorganisms, and biopolymers to produce functional nanomaterials under mild and eco-friendly conditions. This review presents a comprehensive and critical assessment of recent advances (2020–2025) in the green synthesis of nanoparticles for environmental applications, with particular emphasis on mechanistic insights, synthesis–structure–property relationships, and practical remediation performance. Various biological synthesis strategies are systematically discussed, highlighting the roles of phytochemicals, enzymes, and natural polymers in nanoparticle nucleation, growth, and stabilization. The environmental applications of green-synthesized nanoparticles—including wastewater treatment, heavy metal sequestration, photocatalytic degradation of persistent organic pollutants, air purification, and antimicrobial remediation—are critically evaluated with respect to efficiency, reusability, and sustainability.

Keywords—Green synthesis; Nanoparticles; Environmental remediation; Sustainable nanotechnology; Biogenic nanomaterials

I. INTRODUCTION

The rapid pace of industrialization, population growth, and urban expansion over the last few decades has resulted in unprecedented pressure on natural ecosystems. Large quantities of untreated or partially treated industrial effluents, agricultural runoff enriched with pesticides and fertilizers, and municipal wastes are continuously discharged into the environment, leading to severe contamination of water, air, and soil systems {1,2}. Conventional

remediation technologies, including chemical precipitation, activated carbon adsorption, coagulation–flocculation, and biological treatment, often suffer from inherent limitations such as low efficiency at trace pollutant levels, high operational costs, generation of secondary waste, and limited reusability {3,4}. Consequently, there is an urgent demand for innovative, efficient, and sustainable remediation strategies.

Nanotechnology has emerged as a transformative discipline capable of addressing these challenges by exploiting the unique physicochemical properties of materials at the nanoscale. Nanoparticles exhibit exceptionally high surface-area-to-volume ratios, tunable surface chemistry, quantum size effects, and enhanced catalytic activity, making them highly effective for pollutant adsorption, degradation, sensing, and disinfection {5,6}. Over the past two decades, nanoparticles based on metals, metal oxides, carbon, and polymeric systems have been extensively investigated for diverse environmental applications, particularly wastewater treatment and pollution control {7,8}.

Despite their promising performance, the large-scale deployment of nanomaterials synthesized via conventional physical and chemical routes raises significant environmental and health concerns. These traditional synthesis methods often involve toxic reducing agents (e.g., sodium borohydride, hydrazine), hazardous organic solvents, high energy consumption, and extreme reaction conditions, which collectively undermine the sustainability of nanotechnology-driven solutions {9–11}. Moreover, residual chemicals and by-products from such processes may introduce additional ecological risks, contradicting the very purpose of environmental remediation {12}.

In response to these limitations, the concept of green synthesis of nanoparticles has gained substantial

attention as a sustainable and environmentally responsible alternative. Green synthesis integrates the principles of green chemistry—such as waste minimization, use of renewable resources, and avoidance of toxic substances—into nanoparticle fabrication processes {13}. Biological systems, including plant extracts, microorganisms, enzymes, and biopolymers, act as natural reducing, stabilizing, and capping agents, enabling nanoparticle formation under mild and eco-friendly conditions {14,15}. These biologically mediated routes not only reduce environmental burden but also often yield nanoparticles with improved biocompatibility and surface functionality.

In recent years, a growing body of literature has demonstrated the successful synthesis of a wide range of nanoparticles—such as silver, gold, zinc oxide, titanium dioxide, iron oxide, copper oxide, and their composites—using green routes, followed by their application in environmental remediation {16–18}. However, many published studies remain largely descriptive, focusing on synthesis and basic characterization without sufficiently addressing mechanistic aspects, scalability, reproducibility, and long-term environmental implications. Furthermore, critical evaluation of recent advances, comparative analysis of different green synthesis strategies, and identification of research gaps are still lacking in several reviews.

Therefore, the present review aims to provide a comprehensive, critical analysis of green synthesis of nanoparticles for environmental applications, written in line with the depth and structure of contemporary high-impact review articles. The manuscript systematically discusses fundamental mechanisms underlying green synthesis, recent advancements in biological synthesis routes, detailed characterization approaches, and diverse environmental applications, including wastewater treatment, heavy metal removal, photocatalytic degradation, air purification, and antimicrobial remediation. In addition, current challenges, toxicological considerations, and future research directions are critically examined. By integrating recent literature (2020–2025) and emphasizing sustainability and translational potential, this review seeks to serve as a valuable reference for researchers and practitioners working at the interface of nanotechnology and environmental science.

II. FUNDAMENTALS AND MECHANISMS OF GREEN NANOPARTICLE SYNTHESIS

Green synthesis of nanoparticles is governed by a complex interplay of physicochemical and biochemical processes that occur at the bio–inorganic interface. Unlike conventional chemical reduction, where well-defined reagents act through predictable redox pathways, biological systems involve a diverse array of metabolites, enzymes, proteins, and macromolecules that collectively drive nanoparticle formation {19,20}. Understanding these mechanisms is critical for controlling nanoparticle size, morphology, crystallinity, and surface functionality, which ultimately dictate environmental performance.

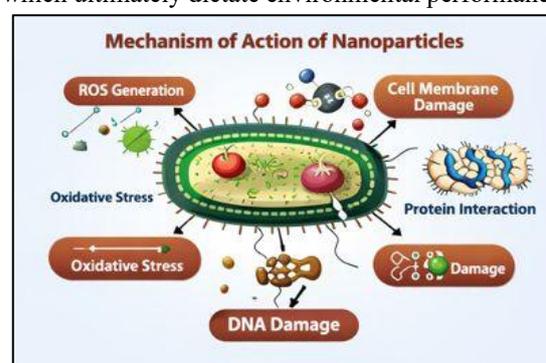


Fig. 1 Mechanism of action of nanoparticles

In plant-mediated synthesis, phytochemicals such as flavonoids, polyphenols, tannins, terpenoids, alkaloids, and reducing sugars act as electron donors, reducing metal ions (e.g., Ag^+ , Au^{3+} , Fe^{3+}) to their zero-valent or oxide forms {21,22}. Simultaneously, these molecules adsorb onto the growing nanoparticle surface through hydroxyl, carbonyl, and amine functional groups, providing steric and electrostatic stabilization {23}. The nucleation–growth mechanism is strongly influenced by reaction parameters such as pH, temperature, metal precursor concentration, and extract composition {24}.

Microbial synthesis involves enzymatic reduction pathways, where intracellular or extracellular reductase enzymes catalyze electron transfer from cofactors such as NADH to metal ions {25}. In some systems, nanoparticles accumulate within the cell wall or cytoplasm, while in others they are secreted extracellularly, simplifying downstream processing {26}. Biopolymer-assisted synthesis relies on macromolecular templates that control nucleation and prevent aggregation, resulting in nanoparticles with narrow size distributions and enhanced stability {27}.

III. GREEN SYNTHESIS STRATEGIES

3.1 Plant-Mediated Synthesis

Plant-mediated synthesis remains the most widely investigated green route due to its operational simplicity, low cost, and scalability. Extracts derived from leaves, roots, fruits, seeds, bark, and agricultural waste materials have been successfully employed to synthesize a broad range of nanoparticles, including Ag, Au, ZnO, TiO₂, Fe₃O₄, CuO, and bimetallic systems {28–31}. The diversity of phytochemicals present in plant extracts enables rapid reduction and effective stabilization without the need for external surfactants.

Recent studies have emphasized the role of extract standardization and kinetic control in achieving reproducible nanoparticle properties {32}. Optimization of synthesis parameters has been shown to significantly influence particle morphology, with spherical, rod-shaped, and hierarchical nanostructures reported in the literature {33}. Importantly, the use of plant waste materials aligns with circular economy principles and enhances the sustainability of green nanotechnology {34}.

3.2 Microbial-Assisted Synthesis

Microorganisms such as bacteria, fungi, yeast, and algae possess intrinsic metal tolerance and reduction capabilities, making them suitable platforms for nanoparticle synthesis {35}. Fungal systems, in particular, are attractive due to their high biomass yield and secretion of extracellular enzymes and proteins {36}. However, microbial synthesis often requires longer reaction times and stringent control of culture conditions, which may limit scalability {37}.

3.3 Biopolymer-Based and Hybrid Systems

Biopolymers such as chitosan, gelatin, cellulose, starch, and alginate play a dual role as reducing and stabilizing agents. These materials facilitate the synthesis of nanocomposites with enhanced adsorption capacity and mechanical stability {38,39}. Hybrid systems combining biopolymers with metal oxides or carbon-based nanomaterials are increasingly explored for multifunctional environmental applications {40}.



Fig. 2 Green Synthesis of nanoparticles

IV. CHARACTERIZATION TECHNIQUES

Comprehensive characterization is essential for correlating green synthesis routes with nanoparticle functionality. UV–Visible spectroscopy provides preliminary confirmation of nanoparticle formation through surface plasmon resonance bands {41}. X-ray diffraction (XRD) analysis yields information on crystallographic phase, lattice parameters, and crystallite size {42}. Fourier transform infrared spectroscopy (FTIR) identifies functional groups involved in reduction and capping processes {43}.

Advanced imaging techniques such as scanning electron microscopy (SEM) and transmission electron microscopy (TEM) reveal particle morphology, size distribution, and dispersion state {44}. Surface chemistry and oxidation states are increasingly analyzed using X-ray photoelectron spectroscopy (XPS), while Brunauer–Emmett–Teller (BET) analysis provides insights into surface area and porosity, which are critical for adsorption-based applications {45}.

V. ENVIRONMENTAL APPLICATIONS

5.1 Wastewater Treatment and Dye Removal

Green-synthesized nanoparticles have demonstrated exceptional potential in wastewater treatment through adsorption, catalytic degradation, and membrane integration mechanisms {46}. Metal oxide nanoparticles exhibit high affinity for organic dyes, pharmaceuticals, and personal care products, enabling rapid pollutant removal even at low concentrations {47}. Magnetic nanomaterials allow facile separation and reuse, improving process sustainability {48}.

5.2 Heavy Metal Sequestration

Biogenic nanoparticles interact with heavy metal ions via surface complexation, ion exchange, and redox reactions {49}. Studies report efficient removal of Pb^{2+} , Cd^{2+} , Hg^{2+} , and As^{3+} from contaminated water, with regeneration capabilities over multiple cycles {50,51}.



Fig. 3 Environmental applications of nanoparticles

5.3 Photocatalytic Degradation of Organic Pollutants

Photocatalysis using green-synthesized TiO_2 , ZnO , and doped nanostructures has attracted significant attention due to enhanced visible-light absorption and reduced recombination rates {52–54}. These materials enable degradation of persistent organic pollutants such as dyes, pesticides, and antibiotics under solar irradiation {55}.

5.4 Air Purification and Antimicrobial Remediation

Biogenic nanoparticles are increasingly incorporated into air filters, coatings, and antimicrobial surfaces. Silver and zinc oxide nanoparticles exhibit broad-spectrum antimicrobial activity, making them suitable for water disinfection and indoor air quality improvement {56–58}.

VI. TOXICOLOGICAL AND ENVIRONMENTAL CONSIDERATIONS

Although green synthesis minimizes the use of hazardous chemicals, the environmental fate and toxicity of nanoparticles must be critically assessed. Recent studies emphasize that nanoparticle size, surface charge, and functionalization strongly influence ecotoxicological behavior {59}. Life-cycle assessment and risk evaluation frameworks are essential for responsible deployment {60–62}.



Fig. 4 Nanoparticles in environmental remediation

VII. CHALLENGES AND FUTURE PERSPECTIVES

Despite significant progress, several challenges remain. Batch-to-batch variability of biological extracts, limited control over particle uniformity, and scale-up constraints hinder industrial translation {63}. Future research should focus on protocol standardization, mechanistic modeling, and integration with advanced manufacturing techniques such as continuous-flow synthesis {64–66}. The incorporation of machine learning tools for process optimization represents an emerging and promising direction {67,68}.

VIII. CONCLUSIONS

Green synthesis of nanoparticles has evolved from a conceptual alternative to conventional fabrication methods into a robust and versatile platform for sustainable nanotechnology. By harnessing the reducing and stabilizing capabilities of biological systems, green synthesis offers a pathway to fabricate functional nanomaterials while minimizing environmental impact and health risks. The present review has critically examined the mechanistic foundations, synthesis strategies, characterization techniques, and environmental applications of green-synthesized nanoparticles, with particular emphasis on recent advancements reported over the last five years.

The reviewed studies clearly demonstrate that biogenic nanoparticles exhibit excellent performance in wastewater treatment, heavy metal sequestration, photocatalytic degradation of organic pollutants, air purification, and antimicrobial remediation. Plant-mediated synthesis remains the most scalable and economically viable approach, while microbial and biopolymer-assisted methods offer unique

opportunities for precise functionalization and hybrid material design. Nevertheless, challenges such as batch-to-batch variability, limited control over particle morphology, scale-up constraints, and insufficient toxicological assessment continue to hinder full-scale implementation.

Future research should focus on developing standardized synthesis protocols, improving mechanistic understanding through advanced spectroscopic and computational tools, and integrating green nanomaterials into pilot-scale and real-world remediation systems. Life-cycle assessment, environmental fate analysis, and regulatory considerations must be incorporated at early stages to ensure safe and responsible deployment. Overall, green synthesis of nanoparticles holds immense promise for addressing pressing environmental challenges and advancing the global transition toward sustainable and circular technological solutions.

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