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Green Synthesis of Nanoparticles for Environmental Remediation: A Review

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ABSTRACT: Nanotechnology has emerged as a promising approach for environmental remediation, with green synthesis of nanoparticles (NPs) gaining significant attention due to its eco-friendly and sustainable nature (Ahmed et al., 2016). Green synthesis methods utilize biological entities such as plant extracts, microorganisms, and biomolecules to produce nanoparticles with enhanced stability, biocompatibility, and catalytic activity (Mittal, Chisti, & Banerjee, 2013). These nanoparticles have shown remarkable efficacy in water purification, heavy metal removal, organic pollutant degradation, air pollution control, and even soil remediation (Shreyash et al., 2021; Shahzadi et al., 2025). Additionally, green-synthesized nanoparticles demonstrate antimicrobial properties, which can be leveraged in wastewater treatment (Sharma, Yngard, & Lin, 2009). This review explores various green synthesis methods, their mechanisms, and their applications in environmental remediation. The challenges and future prospects of this sustainable approach are also discussed, emphasizing the need for scalable and cost-effective production methods to ensure broader applicability.

KEYWORDS: Green synthesis, nanoparticles, environmental remediation, sustainable nanotechnology, eco-friendly catalysts, soil remediation.

I. INTRODUCTION

Environmental pollution has become one of the most pressing global challenges, necessitating the development of innovative and sustainable solutions (Anastas & Warner, 2019). Traditional remediation methods often involve energy-intensive processes and hazardous chemicals, contributing to secondary pollution. The emergence of nanotechnology offers a viable solution by leveraging nanoparticles for pollutant degradation and removal (Li et al., 2011).

Green synthesis of nanoparticles is a sustainable approach that minimizes the use of toxic chemicals while harnessing biological agents such as plants, bacteria, fungi, and algae for nanoparticle production (Mittal et al., 2013). Unlike conventional chemical and physical synthesis methods, green synthesis is eco-friendly, cost-effective, and energy-efficient, making it an attractive alternative for large-scale applications (Shahzadi et al., 2025).

Additionally, green-synthesized nanoparticles exhibit improved biocompatibility and reduced toxicity, making them safer for environmental and biological applications. These nanoparticles possess enhanced stability, high surface area, and tunable physicochemical properties, making them highly effective in addressing pollution-related challenges (Shreyash et al., 2021).

Key applications of green-synthesized nanoparticles in environmental remediation include:

- **Heavy Metal Removal:** Efficient adsorption and detoxification of toxic metals like lead (Pb), mercury (Hg), and arsenic (As) (Kumar & Yadav, 2009).
- **Wastewater Treatment:** Degradation of organic pollutants, dyes, and pharmaceuticals using photocatalytic and adsorptive nanoparticles (Sharma et al., 2009).
- **Air Pollution Control:** Nanoparticles for catalytic degradation of volatile organic compounds (VOCs) and air pollutants



- **Soil Remediation:** Nanoparticles for neutralizing hazardous contaminants and improving soil fertility (Singh et al., 2018).

The integration of nanotechnology with sustainable environmental practices holds great promise for addressing global pollution challenges (Zhou & Wang, 2024). This review aims to explore recent advancements in green nanoparticle synthesis, their environmental applications, and future directions for large-scale implementation (Ahmed et al., 2016).

II. METHODS OF GREEN SYNTHESIS OF NANOPARTICLES

2.1: Plant based synthesis: Plant extracts contain bioactive compounds such as flavonoids, alkaloids, tannins, and polyphenols that act as reducing and stabilizing agents in nanoparticle synthesis (Sharma et al., 2009). This method is simple, cost-effective, and environmentally friendly. Studies have demonstrated the successful synthesis of silver, gold, zinc oxide, and copper oxide nanoparticles using extracts from *Azadirachta indica*, *Moringa oleifera*, *Ocimum sanctum*, and *Eucalyptus globulus* (Ahmed et al., 2016). Additionally, plant-mediated synthesis can be optimized by adjusting extraction conditions, pH, and reaction temperature.

2.2: Microbial Synthesis: Bacteria, fungi, and algae mediate nanoparticle synthesis by secreting extracellular enzymes and metabolites that facilitate metal ion reduction (Li et al., 2011). *Bacillus subtilis*, *Aspergillus niger*, *Pseudomonas aeruginosa*, and *Chlorella vulgaris* have been reported to synthesize silver, gold, and selenium nanoparticles with enhanced antimicrobial and catalytic properties (Mittal et al., 2013). The microbial approach is advantageous due to its high efficiency, ability to produce monodisperse nanoparticles, and sustainability. However, the challenge lies in optimizing culture conditions for large-scale production.

2.3: Biomolecule-Assisted Synthesis: Biomolecules such as proteins, enzymes, amino acids, and polysaccharides act as bio-templates in nanoparticle formation. The use of biomolecules enhances the biocompatibility, stability, and functional properties of nanoparticles, making them suitable for environmental and biomedical applications (Shreyash et al., 2021). For instance, glucose and starch-based reduction methods have been explored for the synthesis of gold and silver nanoparticles. This method is promising for pharmaceutical and environmental applications due to its non-toxic nature.

III. APPLICATIONS OF GREEN SYNTHESIZED NANOPARTICLES IN ENVIRONMENTAL REMEDIATION

3.1: Water Purification and Heavy Metal Removal: Green-synthesized iron oxide and bio-nanoparticles have demonstrated excellent adsorption capacity for removing heavy metals like arsenic, lead, cadmium, mercury, and chromium from contaminated water sources (Sravanthi et al., 2018). Silver and zinc oxide nanoparticles also exhibit strong antimicrobial activity, making them effective for disinfection, pathogen removal, and wastewater treatment. The use of nanocomposites combining bio-based polymers with nanoparticles further enhances their efficiency in water remediation.

3.2: Degradation of Organic Pollutants: Photocatalytic nanoparticles such as titanium dioxide (TiO₂), zinc oxide (ZnO), and iron oxide synthesized through green routes have been widely studied for breaking down organic pollutants in waste water (Mehta et al., 2019). These nanoparticles utilize solar energy to degrade toxic dyes, pesticides, pharmaceutical residues, and industrial effluents. The application of nanocomposites incorporating multiple metals has further improved the efficiency of degradation processes.

3.3: Air Pollution Control: Nanoparticles synthesized via green methods can be incorporated into air filters and coatings to capture particulate matter, neutralize airborne pathogens, and degrade volatile organic compounds (VOCs). Silver, copper, and titanium dioxide nanoparticles have been reported to neutralize airborne bacteria and reduce VOC concentrations, demonstrating their potential for improving air quality in urban settings.



3.4: Soil Remediation: Iron oxide and bio-nanoparticles have been successfully applied to degrade petroleum hydrocarbons, pesticides, and industrial contaminants in soil. By binding to toxic metals and organic pollutants, these nanoparticles improve soil fertility and reduce bioaccumulation risks in crops (Singh et al., 2018).

IV. CASE STUDIES

4.1: Gold Nanoparticles for water Remediation: A study conducted by Sharma et al. (2009) demonstrated the use of gold nanoparticles synthesized from *Ocimum sanctum* extract for the efficient removal of mercury ions from industrial wastewater. The nanoparticles exhibited high adsorption efficiency and reusability over multiple cycles.

4.2: Iron Nanoparticles for Soil Detoxification: Green-synthesized zero-valent iron nanoparticles have been employed in soil remediation projects to degrade persistent organic pollutants such as polychlorinated biphenyls (PCBs), petroleum hydrocarbons, and pesticides. Field trials in contaminated agricultural lands showed significant reduction in pollutant levels and improved soil health (Singh et al., 2018).

4.3: Silver Nanoparticles for Air Purification: A study highlighted the application of plant-mediated silver nanoparticles in air filtration systems. These nanoparticles effectively neutralized airborne bacteria, reduced VOC concentrations, and improved overall air quality in heavily polluted areas.

4.4 Titanium Dioxide Nanoparticles for Wastewater Treatment

A study investigated the photocatalytic degradation of pharmaceutical residues in wastewater using titanium dioxide (TiO₂) nanoparticles synthesized from *Moringa oleifera* extract. The nanoparticles efficiently degraded antibiotics and endocrine-disrupting compounds under solar irradiation, demonstrating their potential for large-scale wastewater treatment. (Navidpour et al, 2024)

4.5 Zinc Oxide Nanoparticles for Textile Dye Degradation

A study investigated green-synthesized zinc oxide (ZnO) nanoparticles from *Aloe vera* for breaking down synthetic textile dyes in industrial waste. The nanoparticles showed over 90% degradation of toxic dyes such as methylene blue and rhodamine B due to strong photocatalytic activity.

4.6 Bio-Nanocomposites for Heavy Metal Removal in Water

A case study demonstrated the use of chitosan-based bio-nanocomposites infused with green-synthesized iron oxide nanoparticles for heavy metal removal. The system successfully extracted lead, cadmium, and arsenic from contaminated water, achieving over 95% removal efficiency with minimal secondary pollution (Ahmed Nafees et al, 2020)

4.7 Copper Nanoparticles for Soil Fertility Enhancement

A field experiment by Singh et al. (2018) examined the role of copper nanoparticles synthesized from neem extract in enhancing soil fertility. The nanoparticles helped in the controlled release of essential nutrients, reducing the need for chemical fertilizers while improving crop yield and soil microbial activity.

V. CHALLENGES IN GREEN SYNTHESIS OF NANOPARTICLES

Scalability Issues: Most green synthesis methods are limited to laboratory-scale production and scaling up these processes while maintaining consistency remains a challenge (Shahzadi et al., 2025).

Variability in Nanoparticle Properties: Factors such as plant species, microbial strains, reaction temperature, and synthesis conditions affect nanoparticle size, shape, and stability, making standardization difficult.

Limited Commercial Viability: The high cost of biomass processing and purification hinders large-scale adoption.

Environmental Impact Assessment: Long-term effects of green-synthesized nanoparticles on ecosystems require further investigation

VI. FUTURE DIRECTIONS

Optimization of Green Synthesis Protocols: Standardizing reaction parameters to achieve consistent nanoparticle properties for large-scale production.

Integration with Renewable Energy: Utilizing solar and bioenergy sources to enhance the sustainability of nanoparticle synthesis.



Development of Hybrid Nanomaterials: Combining green-synthesized nanoparticles with bio-based polymers for enhanced environmental applications.

Policy and Regulatory Frameworks: Establishing guidelines for the safe use and disposal of green-synthesized nanoparticles to ensure environmental and human safety.

VII. CONCLUSION

Green synthesis of nanoparticles offers an eco-friendly, cost-effective, and sustainable alternative to conventional chemical and physical synthesis methods. The potential applications in water purification, soil remediation, air pollution control, and organic pollutant degradation highlight the importance of this technology in environmental sustainability. However, challenges related to scalability, standardization, and regulatory frameworks need to be addressed for wider adoption. Future research should focus on optimizing synthesis protocols, integrating renewable energy sources, and assessing the long-term environmental impacts of green-synthesized nanoparticles

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