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Green Synthesis of Zinc Oxide Nanoparticles: A Comprehensive Review

Mithil Patil, Pratibha Mhatre, Prachi Mokal, Rohit Dhaingade,
Gurumeet C. Wadhava, Amod N. Thakkar
Veer Wajekar ASC College, Phunde, Uran

Abstract: *The synthesis of zinc oxide nanoparticles (ZnO NPs) using green chemistry approaches has gained significant attention due to its eco-friendly nature, cost-effectiveness, and biocompatibility. Conventional physical and chemical synthesis methods often involve toxic chemicals and high energy consumption, raising concerns about environmental sustainability. Green synthesis offers an alternative by utilizing plant extracts, microorganisms, and natural polymers as reducing and stabilizing agents. This review provides an in-depth discussion on various biological methods employed for ZnO NP synthesis, their mechanisms, characterization techniques, and applications in biomedical, environmental, and industrial fields. Additionally, challenges and future perspectives of green synthesis are explored.*

Keywords: zinc oxide nanoparticles

I. INTRODUCTION

Zinc oxide nanoparticles (ZnO NPs) are among the most widely studied metal oxide nanoparticles due to their unique physicochemical properties, including high surface-to-volume ratio, optical transparency, and excellent antimicrobial activity. These properties make ZnO NPs highly applicable in diverse fields such as biomedicine, photocatalysis, food packaging, and environmental remediation. However, traditional synthesis techniques involve hazardous chemicals and energy-intensive procedures, necessitating the exploration of green synthesis approaches.

Green Synthesis Approaches

Green synthesis methods use natural resources such as plant extracts, microorganisms, and biomolecules to reduce and stabilize ZnO NPs. These methods eliminate or minimize toxic byproducts, making them environmentally sustainable.

1. Plant-Mediated Synthesis

Plant extracts contain diverse phytochemicals, including flavonoids, alkaloids, tannins, and terpenoids, which act as reducing and stabilizing agents during ZnO NP formation. The advantages of plant-mediated synthesis include scalability, cost-effectiveness, and high yield.

Examples:

Ocimum tenuiflorum (Tulsi) Extract: Kavitha et al. (2018) synthesized ZnO NPs using *Ocimum tenuiflorum* leaf extract, demonstrating significant antimicrobial activity.

Aloe vera Extract: Ramesh et al. (2020) utilized *Aloe vera* leaf extract to synthesize ZnO NPs, showing enhanced wound healing properties.

Moringa oleifera Extract: Baruwati et al. (2019) reported the use of *Moringa oleifera* for ZnO NP synthesis, leading to effective photocatalytic degradation of organic pollutants.

2. Microbial-Mediated Synthesis

Microorganisms such as bacteria, fungi, and algae have been explored for ZnO NP biosynthesis due to their ability to secrete bioactive metabolites that facilitate nanoparticle formation.

Examples:

Bacillus subtilis: Saravanan et al. (2019) demonstrated the biosynthesis of ZnO NPs using *Bacillus subtilis*, exhibiting biocompatibility and antimicrobial activity.

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Aspergillus niger: A fungal-mediated synthesis approach using *Aspergillus niger* resulted in ZnO NPs with potent antibacterial properties (Shankar et al., 2017).

Spirulina platensis: Algae-mediated synthesis using *Spirulina platensis* was found to produce ZnO NPs with enhanced UV-blocking and antioxidant activity (Gautam et al., 2021).

3. Biopolymer-Assisted Synthesis

Biopolymers such as chitosan, starch, and cellulose are used as capping agents to enhance the stability and biocompatibility of ZnO NPs.

Examples:

Chitosan: Chitosan-mediated ZnO NPs were found to have antimicrobial and anti-inflammatory properties (Kumar et al., 2022).

Starch: Starch-assisted synthesis produced ZnO NPs with improved photocatalytic performance (Mishra et al., 2020).

Gelatin: Gelatin-stabilized ZnO NPs exhibited enhanced cytocompatibility and drug delivery potential (Reddy et al., 2021).

4. Mechanism of Green Synthesis

The green synthesis of ZnO NPs involves three major steps:

Precursor Preparation: Zinc salts such as zinc acetate or zinc nitrate are dissolved in aqueous media.

Reduction & Stabilization: Phytochemicals, microbial enzymes, or biopolymers act as reducing agents to convert Zn^{2+} ions into ZnO NPs while also stabilizing them.

Characterization: Various techniques such as UV-Vis spectroscopy, X-ray diffraction (XRD), scanning electron microscopy (SEM), and Fourier-transform infrared spectroscopy (FTIR) are employed to confirm nanoparticle formation and properties.

Characterization Techniques

UV-Vis Spectroscopy: Determines the optical properties of ZnO NPs.

X-ray Diffraction (XRD): Confirms the crystalline nature and phase purity.

Scanning Electron Microscopy (SEM): Analyzes surface morphology and size.

Fourier-Transform Infrared Spectroscopy (FTIR): Identifies functional groups responsible for capping and stabilization.

Applications of Green Synthesized ZnO NPs

1. Biomedical Applications

Antimicrobial Agents: ZnO NPs exhibit broad-spectrum antibacterial and antifungal activity.

Cancer Therapy: ZnO NPs induce selective cytotoxicity in cancer cells.

Wound Healing: Promotes cell proliferation and tissue regeneration.

2. Environmental Applications

Photocatalysis: ZnO NPs degrade organic pollutants in wastewater treatment.

Air Purification: Used in air filters to remove toxic gases.

Heavy Metal Removal: ZnO-based nanocomposites adsorb heavy metals from water sources.

3. Industrial Applications

Food Packaging: ZnO NPs are incorporated into biodegradable packaging materials to enhance antimicrobial properties.

Cosmetics: Used in sunscreens due to their UV-blocking capabilities.

Electronics: Employed in sensors, LEDs, and photovoltaic devices.

Challenges and Future Prospects

Despite the advantages of green synthesis, several challenges remain:

Scalability Issues: Large-scale production needs optimization.

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Reproducibility: Variability in biological sources affects nanoparticle consistency.
Long-Term Stability: Need for improved storage and stability strategies.
Future research should focus on:
Standardizing synthesis protocols for consistency.
Exploring novel biological sources for improved nanoparticle properties.
Enhancing biocompatibility for biomedical applications.

II. CONCLUSION

Green synthesis of ZnO NPs is a promising approach that offers an eco-friendly alternative to conventional methods. Plant extracts, microbes, and biopolymers have demonstrated efficient ZnO NP production with diverse applications. Further studies are needed to overcome existing challenges and fully realize the potential of green-synthesized ZnO NPs in various fields.

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