

Green Synthesis of Nanoparticles for Pharmaceutical Applications: A Sustainable Approach

Hina Shaikh^{a*}

a. Department of Chemistry, Wilson college, Mumbai, India.

Article Info:

Received: November 2025

Accepted: January 2026

Published online:
January 2026

* Corresponding Author:

Hina Shaikh

Email:
hina.shaikh@wilsoncollege.edu

ABSTRACT:

Nanotechnology has significantly influenced pharmaceutical sciences by enabling advanced platforms for drug delivery, diagnostics, and therapeutics. Conventional nanoparticle (NP) synthesis methods often rely on toxic chemicals and high-energy inputs and generate hazardous by-products, which may limit biomedical translation. Green synthesis offers an alternative approach by employing biological entities such as plant extracts, microorganisms, algae, and natural polymers as reducing and stabilizing agents. This review summarizes major green synthesis strategies for metallic (e.g., silver, gold, zinc oxide, and iron oxide) and polymeric nanoparticles, outlines general formation mechanisms, and highlights commonly used physicochemical characterization techniques. Selected pharmaceutical and biomedical applications—including drug delivery, antimicrobial therapy, anticancer applications, wound healing, and diagnostics—are discussed with representative examples from the literature. Finally, key challenges related to reproducibility, scalability, regulatory compliance, and future research directions are critically examined. Overall, green nanotechnology represents a promising but still evolving route toward more sustainable pharmaceutical nanomaterials.

Keywords: Green synthesis; Nanoparticles; Sustainable nanotechnology; Drug delivery; Phytochemicals; Biocompatibility.

Please Cite this article as: Shaikh H. Green Synthesis of Nanoparticles for Pharmaceutical Applications: A Sustainable Approach. Int. Pharm. Acta. 2025; 8(1):e10.

DOI: <https://doi.org/10.22037/ipa.v9i1.50862>

1. Introduction

Nanotechnology enables the manipulation of materials at the 1–100 nm scale, where size-dependent optical, electronic, and surface properties emerge. In the pharmaceutical sciences, nanoparticles have been explored to improve drug solubility, bioavailability, controlled release, and site-specific delivery [1, 2]. Conventional synthesis approaches—such as chemical reduction, sol–gel processing, thermal decomposition, and microemulsion techniques—can provide precise control over particle characteristics but frequently involve toxic reagents, high temperatures, or energy-intensive conditions [3]. Residual chemicals on nanoparticle surfaces and difficulties in large-scale purification raise concerns regarding biocompatibility and environmental impact. To address these limitations, green synthesis approaches have been developed. These methods use biological

materials—plants, microorganisms, algae, or biopolymers—as reducing and capping agents, often under mild aqueous conditions. Such systems may reduce chemical toxicity and improve surface compatibility with biological environments [4].

This review summarizes recent advances in green nanoparticle synthesis, including biological sources, mechanistic aspects, and characterization methods. Pharmaceutical and biomedical applications are discussed with emphasis on experimentally supported examples. Finally, bottlenecks and future perspectives are critically evaluated.

2. Principles of Green Nanotechnology

Green nanotechnology adapts principles of green chemistry to nanoscale material synthesis, emphasizing renewable feedstocks, safer solvents, reduced energy consumption, and minimal waste generation [1]. In nanoparticle synthesis, this typically involves aqueous reactions, biological reducing agents, and avoidance of

hazardous stabilizers. Importantly, green methods must also address reproducibility, scalability, and regulatory compatibility for pharmaceutical translation⁵.

3. Biological Sources for Green Synthesis

Plant-mediated synthesis Plant extracts derived from leaves, roots, stems, flowers, or seeds are widely used due to their availability and rich phytochemical content. Polyphenols, flavonoids, terpenoids, and related compounds can reduce metal ions and simultaneously cap nanoparticles. Reaction parameters such as pH, temperature, extract concentration, and metal precursor concentration strongly influence particle size and morphology.

Shahzadi et al. (2025) reported silver nanoparticles synthesized using *Ocimum sanctum* and *Azadirachta indica* extracts with particle sizes typically ranging from 10–50 nm under mild heating conditions. Similarly, Das and Chakraborty (2018) summarized plant-mediated synthesis of Ag and ZnO nanoparticles, reporting antibacterial activity against multidrug-resistant strains with particle sizes generally below 40 nm [5, 6].

3.2 Microbial synthesis Microorganisms can generate nanoparticles either intracellularly or extracellularly through enzymatic reduction mechanisms. Fungal species such as *Fusarium* and *Penicillium* have been shown to produce relatively uniform silver nanoparticles (often 5–30 nm) via extracellular enzymes, facilitating downstream recovery. *Bacillus* species have also been reported to generate extracellular metal nanoparticles through secreted proteins and reductases [7].

3.3 Algae and cyanobacteria Algal systems provide polysaccharides and proteins capable of reducing and stabilizing metal nanoparticles. Raman et al. (2022) reviewed marine algae-mediated synthesis of silver and gold nanoparticles, reporting particle sizes commonly in the 10–60 nm range with demonstrated antimicrobial and antioxidant activities [8].

3.4 Natural polymers and biomolecules Biopolymers such as chitosan, cellulose derivatives, gelatin, and proteins can function as stabilizing matrices and, in some cases, mild reducing agents. For example, chitosan-stabilized silver nanoparticles have been incorporated into wound dressings, showing enhanced antimicrobial performance and biocompatibility [9].

4. Mechanism of Nanoparticle Formation

Green synthesis generally proceeds through reduction, nucleation, growth, and stabilization stages. Biological molecules donate electrons to metal ions, forming nuclei that grow into nanoparticles while being capped by surrounding biomolecules. Polyphenols may oxidize to quinones during this process, while proteins and polysaccharides adsorb to particle surfaces, limiting aggregation [10].

Kinetics and influencing factors Reaction kinetics are influenced by metal ion concentration, biological extract composition, pH, temperature, and reaction time. For example, plant-mediated silver nanoparticle synthesis has been reported to follow pseudo-first-order kinetics based on UV–Vis absorbance monitoring, with equilibrium reached within 12–24 h and average particle sizes around 15–20 nm [11].

5. Characterization Techniques

Common characterization methods include UV–Vis spectroscopy (formation confirmation), FTIR (surface functional groups), XRD (crystallinity), SEM/TEM (morphology and size), DLS (hydrodynamic size), and zeta potential (colloidal stability). TEM is widely used for detailed size and lattice analysis, while FTIR provides insight into biomolecular capping.

6. Pharmaceutical and Biomedical Applications

6.1 Drug delivery Green-synthesized gold nanoparticles have been conjugated with chemotherapeutic agents such as doxorubicin, demonstrating improved cellular uptake and reduced systemic toxicity in in vitro cancer models [12].

Antimicrobial and wound-healing applications Plant-mediated silver and zinc oxide nanoparticles exhibit antibacterial activity through membrane disruption and reactive oxygen species generation. Lithi et al. (2025) summarized multiple studies showing that green-synthesized AgNPs effectively inhibited Gram-positive and Gram-negative bacteria. Chitosan–silver nanoparticle hydrogels have also been reported to enhance wound healing while reducing infection rates [13].

Anticancer applications Biosynthesized nanoparticles have demonstrated anticancer activity via ROS-mediated apoptosis, mitochondrial dysfunction, and DNA damage. For instance, plant-derived ZnO nanoparticles induced apoptosis in breast cancer cell lines through oxidative stress mechanisms [13].

7. Advantages and Challenges

Although promising, many published studies remain empirical, with limited mechanistic or kinetic analysis, which hampers rational optimization and scale-up. Batch-to-batch variability, purification challenges, and regulatory compliance remain significant barriers [12]. Recent studies have begun exploring machine-learning-assisted optimization of nanoparticle synthesis parameters, enabling prediction of size and stability outcomes based on reaction conditions (recent nanomaterials optimization studies). Such approaches, combined with standardized extract characterization and continuous-flow reactors, may improve reproducibility and scalability [13].

4. Conclusion

Green synthesis offers a sustainable and eco-friendly approach for producing nanoparticles with significant pharmaceutical and biomedical potential. Despite promising applications in drug delivery, antimicrobial therapy, wound healing, and cancer treatment, challenges related to reproducibility, scalability, and regulatory approval remain. Continued research and standardization are essential to translate green-synthesized nanoparticles into safe and effective pharmaceutical products..

Acknowledgements

The author acknowledges institutional support and colleagues who contributed through scientific discussions.

Ethical statement

Not applicable.

Conflict of interest

There is no conflict of interest.

Funding

This study received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Authors' ORCIDs

Hina Shaikh:

<https://orcid.org/0000-0002-0650-8601>

References

1. Anastas PT, Warner JC. *Green chemistry: theory and practice*. 2nd ed. Oxford: Oxford University Press; 2019.
2. Kumar V, et al. Green synthesis of silver nanoparticles and their biomedical applications. *J Nanobiotechnol*. 2020;18(1):1–15.
3. Patra JK, et al. Nano-biotechnology in sustainable drug delivery. *Int J Nanomedicine*. 2018;13:2435–2452.
4. Raman S, et al. Marine algae mediated synthesis of nanoparticles: biomedical potential. *J Appl Phycol*. 2022;34(2):789–805.
5. Singh P, et al. Phytochemical mediated green synthesis of nanoparticles. *Front Chem*. 2021;9:643203.
6. Lithi IJ, Nakib KIA, Chowdhury AMS, Hossain MS. A review on the green synthesis of metal (Ag, Cu, Au) and metal oxide (ZnO, MgO, Co₃O₄, TiO₂) nanoparticles using plant extracts for developing antimicrobial properties. *Nanoscale Adv*. 2025;7:2446–2473.
7. Shahzadi S, Fatima S, Ul Ain Q, Shafiq Z, Janjua MRSA. A review on green synthesis of silver nanoparticles (SNPs) using plant extracts: a multifaceted approach in photocatalysis, environmental remediation, and biomedicine. *RSC Adv*. 2025;15:3858–3903.
8. Borehalli Mayegowda R, Roy NG, Pandit R, Alghamdi S, Almeahmadi M, Allahyani S, et al. Eco-friendly synthesized nanoparticles as antimicrobial agents: an updated review. [Journal name not specified]. 2023.
9. Samuel MS, Ravikumar M, John JA, Selvarajan E, Patel H, Chander PS, et al. A review on green synthesis of nanoparticles and their diverse biomedical and environmental applications. *Catalysts*. 2022;12(5):459.
10. Mirzaei H, Darroudi M. Zinc oxide nanoparticles: biological synthesis and biomedical applications. *Ceram Int*. 2017;43(1):907–914.
11. Das S, Chakraborty T. A review on green synthesis of silver nanoparticles and zinc oxide nanoparticles from different plant extracts and their antibacterial activity against multidrug-resistant bacteria. *J Innov Pharm Biol Sci*. 2018;5(4):63–73.
12. Singh, P., et al. (2021). Phytochemical-mediated green synthesis of nanoparticles. *Frontiers in Chemistry*, 9, 643203.
13. Borehalli Mayegowda, R., Roy, N. G., Pandit, Alghamdi, Almeahmadi, Allahyani, Awwad, Sharma (2023). Eco-friendly synthesized nanoparticles as antimicrobial agents: An updated review.