ACTA BIOLOGY FORUM

Review Article
ISSN: 2583-7419
Journal homepage: biologyforum.actabotanica.org

Medicinal Plant-Based Nanotechnology for Antimicrobial, Antifungal, and Biomedical Applications: Current Progress and Future Perspectives

Anjum Aara

Department of Botany, College: Anwarul Uloom College, Hyderabad, Affiliated to Osmania University, Hyderabad, Telangana, India

Citation: Anjum Aara (2026). Hydrogeochemical Characterisation, Heavy Metal Bioaccumulation in Fish and Aquatic Species, and Public Health Risk Assessment of River Benue, Nigeria. *Acta Biology Forum*. **DOI: https://doi.org/10.51470/ABF.2026.5.1.37**

Corresponding Author: **Anjum Aara** | E-Mail: **(anjum_aara83@yahoo.co.in)**

Received 10 February 2026 | Revised 13 March 2026 | Accepted 05 April 2026 | Available Online 02 May 2026

ABSTRACT

Nanotechnology has emerged as a transformative interdisciplinary field with extensive applications in medicine, agriculture, pharmaceuticals, and biotechnology. In recent years, medicinal plant-based nanotechnology has gained considerable scientific attention owing to its eco-friendly, cost-effective, and biologically active nature. Green synthesis of nanoparticles using medicinal plant extracts offers a sustainable alternative to conventional physical and chemical synthesis approaches, which are often associated with toxic reagents, high energy consumption, and environmental hazards. Medicinal plants contain diverse phytochemicals such as flavonoids, alkaloids, phenolics, terpenoids, tannins, and proteins that act as natural reducing, stabilizing, and capping agents during nanoparticle synthesis. Plant-mediated nanoparticles, particularly silver, gold, zinc oxide, copper oxide, and titanium dioxide nanoparticles, have demonstrated significant antimicrobial, antifungal, antioxidant, anticancer, anti-inflammatory, and wound-healing properties. The present review critically examines recent progress in medicinal plant-based nanoparticle synthesis and their applications in antimicrobial, antifungal, and biomedical fields. The article further discusses the mechanisms underlying nanoparticle-mediated microbial inhibition, biomedical therapeutic potential, toxicity concerns, and future research perspectives. The review highlights that medicinal plant-based nanotechnology represents a promising and sustainable platform for developing advanced therapeutic and biomedical systems with enhanced efficacy and reduced environmental impact.

Keywords: *Green nanotechnology, medicinal plants, nanoparticles, antimicrobial activity, antifungal activity, biomedical applications, phytochemicals, nanomedicine.*

1. Introduction

Nanotechnology has revolutionized modern scientific research through the manipulation of materials at the nanoscale level, generally ranging between 1 and 100 nm. Nanomaterials possess unique physicochemical, optical, catalytic, electrical, and biological properties that differ significantly from their bulk counterparts due to their extremely small particle size and high surface-area-to-volume ratio. These distinctive characteristics have facilitated extensive applications of nanotechnology in medicine, pharmaceuticals, agriculture, food science, environmental remediation, and biotechnology [1]. Conventional methods for nanoparticle synthesis primarily involve physical and chemical approaches. However, these methods often require hazardous chemicals, elevated temperatures, sophisticated instrumentation, and substantial energy consumption, resulting in environmental and biological concerns. Consequently, green synthesis approaches have emerged as environmentally sustainable alternatives for nanoparticle production. Among these approaches, medicinal plant-mediated synthesis has gained exceptional importance because plant extracts contain diverse bioactive compounds capable of reducing metal ions into stable nanoparticles. Medicinal plants are rich sources of secondary metabolites such as alkaloids, flavonoids, phenolic acids, terpenoids, tannins, saponins, and glycosides. These phytochemicals not only facilitate nanoparticle synthesis but also enhance the biological activities of the synthesized nanomaterials. Plant-mediated nanoparticles exhibit significant antimicrobial, antifungal, antioxidant, anti-inflammatory, anticancer, antiviral, and wound-healing activities, making them promising candidates for biomedical and pharmaceutical applications. The increasing prevalence of antimicrobial resistance among pathogenic microorganisms has intensified the demand for novel therapeutic strategies [2]. Plant-based nanoparticles have shown remarkable efficacy against multidrug-resistant bacteria and pathogenic fungi through multiple mechanisms, including membrane disruption, oxidative stress induction, enzyme inhibition, and interference with microbial genetic material. Furthermore, medicinal plant-derived nanoparticles have demonstrated considerable potential in drug delivery systems, biosensing, tissue engineering, bioimaging, and cancer therapy. This review critically explores the synthesis, characterization, antimicrobial mechanisms, antifungal potential, and biomedical applications of medicinal plant-based nanoparticles. The article also highlights current challenges, toxicity concerns, and future perspectives for sustainable nanomedicine development.

2. Green Synthesis of Medicinal Plant-Based Nanoparticles

Green synthesis of nanoparticles using medicinal plant extracts has become an environmentally friendly and sustainable alternative to conventional nanoparticle production methods. Plant-mediated synthesis involves the reduction of metal ions into nanoparticles through bioactive phytochemicals naturally present in medicinal plant extracts. These phytoconstituents function as reducing agents, stabilizing agents, and capping molecules during nanoparticle formation. Compared with chemical synthesis approaches, green synthesis is simpler, cost-effective, non-toxic, and requires minimal energy input. Medicinal plants such as *Azadirachta indica*, *Ocimum sanctum*, *Moringa oleifera*, *Aloe vera*, *Curcuma longa*, *Camellia sinensis*, and *Origanum vulgare* are widely utilized for nanoparticle biosynthesis due to their rich phytochemical composition [3]. Flavonoids, phenolic compounds, proteins, polysaccharides, terpenoids, and alkaloids play critical roles in metal ion reduction and nanoparticle stabilization. Commonly synthesized nanoparticles include silver nanoparticles (AgNPs), gold nanoparticles (AuNPs), zinc oxide nanoparticles (ZnONPs), copper oxide nanoparticles (CuONPs), and titanium dioxide nanoparticles (TiO_2NPs). The synthesis process generally involves preparation of plant extracts, mixing with metal salt precursors, incubation under controlled conditions, and purification of the synthesized nanoparticles. Characterization techniques such as UV–visible spectroscopy, Fourier-transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), scanning electron microscopy (SEM), transmission electron microscopy (TEM), dynamic light scattering (DLS), and zeta potential analysis are commonly employed to evaluate nanoparticle size, morphology, crystallinity, surface chemistry, and stability.

Table 1: Common Medicinal Plants Used for Green Synthesis of Nanoparticles and Their Biomedical Applications

Medicinal Plant	Major Phytochemicals	Type of Nanoparticles Synthesized	Reported Biological Activities	Biomedical Applications
Azadirachta indica	Flavonoids, terpenoids, tannins	Silver (AgNPs), Zinc oxide (ZnONPs)	Antibacterial, antifungal, antioxidant	Wound healing, antimicrobial coatings
Aloe vera	Polysaccharides, phenolics, anthraquinones	Silver (AgNPs), Gold (AuNPs)	Anti-inflammatory, antimicrobial	Tissue regeneration, drug delivery
Curcuma longa	Curcumin, phenolics	Gold (AuNPs), Copper oxide (CuONPs)	Antioxidant, anticancer	Cancer therapy, nanomedicine
Ocimum sanctum	Eugenol, flavonoids	Silver (AgNPs), Titanium dioxide (TiO_2NPs)	Antibacterial, antiviral	Biomedical coatings, biosensors
Moringa oleifera	Alkaloids, flavonoids, proteins	Silver (AgNPs), Zinc oxide (ZnONPs)	Antioxidant, antimicrobial	Pharmaceutical formulations
Camellia sinensis	Catechins, polyphenols	Gold (AuNPs), Silver (AgNPs)	Antioxidant, antibacterial	Drug delivery, diagnostic imaging
Origanum vulgare	Essential oils, phenolics	Silver (AgNPs)	Antifungal, antibacterial	Food preservation, antimicrobial therapy

Table 2: Antimicrobial and Antifungal Mechanisms of Medicinal Plant-Based Nanoparticles

Nanoparticle Type	Target Microorganisms	Mechanism of Action	Biological Effects	Potential Applications
Silver nanoparticles (AgNPs)	*Escherichia coli*, *Staphylococcus aureus*, *Candida albicans*	Membrane disruption, ROS generation, DNA damage	Cell death and inhibition of biofilm formation	Antimicrobial agents, wound dressings
Gold nanoparticles (AuNPs)	Bacterial and fungal pathogens	Protein interaction and oxidative stress induction	Enzyme inhibition and reduced microbial growth	Drug delivery and cancer therapeutics
Zinc oxide nanoparticles (ZnONPs)	*Aspergillus flavus*, *Fusarium oxysporum*	ROS production and membrane permeability alteration	Fungal growth inhibition	Agricultural fungicides and biomedical coatings
Copper oxide nanoparticles (CuONPs)	Gram-positive and Gram-negative bacteria	Cellular oxidative damage and metabolic disruption	Antibacterial activity	Antimicrobial packaging and therapeutics
Titanium dioxide nanoparticles (TiO_2NPs)	Bacteria and fungi	Photocatalytic ROS generation	Oxidative microbial destruction	Surface sterilization and water purification
Plant-extract capped nanoparticles	Multidrug-resistant pathogens	Synergistic phytochemical and nanoparticle interactions	Enhanced antimicrobial efficacy	Nanomedicine and pharmaceutical applications

3. Antimicrobial Applications of Plant-Based Nanoparticles

Medicinal plant-derived nanoparticles have demonstrated broad-spectrum antimicrobial activity against numerous Gram-positive and Gram-negative bacterial pathogens. The increasing emergence of multidrug-resistant microorganisms has accelerated interest in nanoparticle-based antimicrobial therapies due to their unique mechanisms of action and reduced likelihood of resistance development. Silver nanoparticles synthesized using medicinal plants are among the most extensively studied antimicrobial nanomaterials. These nanoparticles exhibit potent antibacterial activity against pathogens such as *Escherichia coli*, *Staphylococcus aureus*, *Klebsiella pneumoniae*, *Pseudomonas aeruginosa*, and *Salmonella* species. Gold, zinc oxide, and copper oxide nanoparticles also possess significant antimicrobial properties [3]. The antimicrobial mechanisms of nanoparticles involve multiple cellular targets. Nanoparticles can attach to microbial cell membranes, disrupt membrane permeability, and induce leakage of intracellular components. They also generate reactive oxygen species (ROS), causing oxidative stress, lipid peroxidation, protein denaturation, and DNA damage. Additionally, nanoparticles interfere with enzyme activity, metabolic pathways, and quorum sensing systems involved in microbial communication and biofilm formation. Plant-based nanoparticles have also shown substantial antibiofilm activity against resistant bacterial biofilms, which are major contributors to chronic infections and antibiotic resistance [4]. The synergistic effects between phytochemicals and nanomaterials further enhance antimicrobial efficacy while reducing toxicity and resistance development.

4. Antifungal Applications of Medicinal Plant Nanoparticles

Fungal pathogens are responsible for severe human, agricultural, and food-related diseases worldwide. Conventional antifungal agents often exhibit limited efficacy, toxicity concerns, and increasing resistance among fungal pathogens. Consequently, medicinal plant-based nanoparticles have emerged as promising alternatives for antifungal therapy. Plant-mediated nanoparticles exhibit significant antifungal activity against pathogenic fungi such as *Candida albicans*, *Aspergillus flavus*, *Aspergillus niger*, *Fusarium oxysporum*, *Penicillium* species, and *Cryptococcus neoformans*. Silver and zinc oxide nanoparticles have shown particularly strong inhibitory effects on fungal growth, spore germination, and biofilm formation. The antifungal activity of nanoparticles is primarily associated with membrane disruption, oxidative stress induction, mitochondrial dysfunction, and inhibition of fungal enzyme systems [5]. Nanoparticles can penetrate fungal cell walls and interfere with intracellular metabolic processes, resulting in cell death. Additionally, phytochemicals adsorbed onto nanoparticle surfaces may contribute synergistically to antifungal efficacy. In agricultural systems, medicinal plant-based nanoparticles are increasingly being investigated for plant disease management against phytopathogenic fungi. Nanoformulations may provide improved stability, controlled release, and enhanced effectiveness compared with conventional fungicides.

5. Biomedical Applications of Plant-Based Nanotechnology

Medicinal plant-based nanoparticles possess extensive biomedical applications due to their biocompatibility, multifunctionality, and enhanced therapeutic properties. One of the most promising applications involves drug delivery systems, where nanoparticles facilitate targeted drug transport, controlled release, and improved bioavailability of therapeutic agents. Nanoparticle-mediated drug delivery reduces systemic toxicity and enhances treatment efficiency in various diseases. Plant-derived nanoparticles also demonstrate remarkable anticancer activity through apoptosis induction, oxidative stress generation, inhibition of tumor angiogenesis, and disruption of cancer cell signaling pathways. Several studies have reported significant cytotoxic effects of silver and gold nanoparticles against breast, lung, colon, liver, and cervical cancer cell lines. Wound healing represents another important biomedical application of plant-based nanomaterials. Nanoparticles incorporated into hydrogels, ointments, and wound dressings exhibit enhanced antimicrobial activity, accelerated tissue regeneration, collagen synthesis, and anti-inflammatory effects [6]. Silver nanoparticles synthesized using medicinal plants are particularly effective in preventing wound infections and promoting tissue repair. Additional biomedical applications include biosensing, tissue engineering, diagnostic imaging, antiviral therapy, antioxidant therapy, and anti-inflammatory treatments. Plant-based nanotechnology has also demonstrated potential in combating viral pathogens through inhibition of viral attachment, replication, and protein synthesis.

6. Toxicological Considerations and Safety Concerns

Despite the promising biomedical applications of medicinal plant-based nanoparticles, concerns regarding nanoparticle toxicity and environmental safety remain important considerations. Nanoparticle toxicity is influenced by factors such as particle size, shape, concentration, surface charge, chemical composition, and exposure duration. Excessive accumulation of nanoparticles in biological systems may induce oxidative stress, inflammation, genotoxicity, cytotoxicity, and organ damage [7]. Although plant-mediated nanoparticles are generally considered more biocompatible than chemically synthesized nanoparticles, comprehensive toxicological evaluation remains essential before clinical and commercial applications. Standardized toxicity assessment protocols involving *in vitro*, *in vivo*, and environmental studies are necessary to evaluate long-term safety. Regulatory challenges, lack of standardized synthesis protocols, and variability in phytochemical composition among plant species may also affect nanoparticle reproducibility and therapeutic consistency. Therefore, careful optimization and safety assessment are critical for successful translational applications.

7. Current Challenges in Plant-Based Nanotechnology

Several limitations continue to hinder the large-scale application of medicinal plant-based nanotechnology. One of the primary challenges is the lack of standardization in nanoparticle synthesis procedures, which often results in variability in particle size, morphology, stability, and biological activity. Differences in plant species, extraction methods, seasonal variations, and phytochemical composition may significantly influence nanoparticle characteristics [9-10]. Large-scale production and commercialization of plant-based nanoparticles also remain difficult due to challenges in process optimization, purification, and quality control. Limited understanding of nanoparticle pharmacokinetics, biodistribution, metabolism, and long-term toxicity further restricts clinical applications. In addition, regulatory frameworks for nanomedicine development are still evolving in many countries, leading to uncertainty regarding approval and commercialization processes. Addressing these challenges requires interdisciplinary collaboration among nanotechnologists, microbiologists, pharmacologists, toxicologists, and regulatory agencies.

8. Future Perspectives

Future research in medicinal plant-based nanotechnology is expected to focus on the development of multifunctional, targeted, and environmentally sustainable nanomaterials for biomedical applications. Advances in nanobiotechnology, molecular medicine, artificial intelligence, and precision therapeutics are likely to enhance nanoparticle design, targeting accuracy, and therapeutic efficacy. The integration of medicinal plant-derived nanoparticles with advanced drug delivery systems, biosensors, and regenerative medicine technologies may open new avenues for personalized medicine and disease management [11]. Furthermore, hybrid nanocomposites combining phytochemicals with metallic or polymeric nanoparticles may provide synergistic therapeutic effects against resistant microbial pathogens and chronic diseases. Future studies should also prioritize large-scale synthesis optimization, clinical validation, toxicological assessment, and regulatory standardization to facilitate safe commercialization of plant-based nanomedicine products.

9. Conclusion

Medicinal plant-based nanotechnology represents a promising and environmentally sustainable approach for developing advanced antimicrobial, antifungal, and biomedical systems. Plant-mediated nanoparticle synthesis provides a green, cost-effective, and biocompatible alternative to conventional nanoparticle production methods while enhancing biological functionality through phytochemical integration. Plant-derived nanoparticles exhibit significant antimicrobial and antifungal activities against multidrug-resistant pathogens through diverse molecular mechanisms, including membrane disruption, oxidative stress induction, and inhibition of cellular processes. In addition to antimicrobial applications, medicinal plant-based nanoparticles have demonstrated extensive potential in drug delivery, cancer therapy, wound healing, tissue engineering, biosensing, and regenerative medicine. Despite current challenges related to toxicity assessment, standardization, large-scale production, and regulatory approval, ongoing advancements in nanotechnology and biomedical research continue to strengthen the future prospects of plant-based nanomedicine. The integration of medicinal plants with nanotechnology offers a sustainable pathway for developing safer, more effective, and eco-friendly therapeutic systems capable of addressing major global healthcare challenges associated with infectious diseases, antimicrobial resistance, and chronic disorders.

References

1. Chowdhury, S. S., Ibnat, N., Hasan, M., & Ghosh, A. (2024). Medicinal Plant-Based nanoparticle synthesis and their diverse applications. In *Ethnopharmacology and OMICS advances in medicinal plants volume 2: revealing the secrets of medicinal plants* (pp. 213-250). Singapore: Springer Nature Singapore.
2. Trivedi, Rashmi, Tarun Kumar Upadhyay, Mohd Hasan Mujahid, Fahad Khan, Pratibha Pandey, Amit Baran Sharangi, Khursheed Muzammil et al. "Recent advancements in plant-derived nanomaterials research for biomedical applications." *Processes* 10, no. 2 (2022): 338.
3. Karnwal, A., Jassim, A. Y., Mohammed, A. A., Sharma, V., Al-Tawaha, A. R. M. S., & Sivanesan, I. (2024). Nanotechnology for healthcare: plant-derived nanoparticles in disease treatment and regenerative medicine. *Pharmaceuticals*, *17*(12), 1711.
4. Chowdhury, S., Nath, D., Chanda Das, S. R., Kar, K., Chakraborty, P., Kapoor, D. U., & Prajapati, B. G. (2024). Nanotechnology based herbal drug delivery system: Current insights and future prospects. *Current Nanomedicine*.
5. Kaur, H., & Wadhwa, K. (2024). Exploration of new plant-based nanoparticles with potential antifungal activity and their mode of action. In *Advances in Antifungal Drug Development: Natural Products with Antifungal Potential* (pp. 345-371). Singapore: Springer Nature Singapore.
6. Kadir, A. S., Zerin, F. F., Tripura, S., Dutta, T., Malek, A., Rasool, A., & Batool, S. (2025). Medicinal Plant-Derived Nanoparticles Against Pathogenic Candida species. In *Medicinal Plants and Their Nanoparticles: A Double Blade Sword Against Human Diseases* (pp. 225-258). Cham: Springer Nature Switzerland.
7. Ullah, A., & Lim, S. I. (2022). Plant extract-based synthesis of metallic nanomaterials, their applications, and safety concerns. *Biotechnology and Bioengineering*, *119*(9), 2273-2304.
8. Barathi, S., Ramalingam, S., Krishnasamy, G., & Lee, J. (2024). Exploring the biomedical frontiers of plant-derived nanoparticles: synthesis and biological reactions. *Pharmaceutics*, *16*(7), 923.
9. Napagoda, M., Madhushanthi, P., Wanigasekara, D., & Witharana, S. (2022). Plant-based nanomaterials and their antimicrobial activity. In *Eco-Friendly Biobased Products Used in Microbial Diseases* (pp. 155-179). CRC Press.
10. Mohapatra, S., Hassan, N., Mirza, M. A., & Iqbal, Z. (2024). Antifungal Efficacy of Plant-Based Nanoparticles as a Putative Tool for Antifungal Therapy. In *Advances in Antifungal Drug Development: Natural Products with Antifungal Potential* (pp. 471-491). Singapore: Springer Nature Singapore.
11. Aziz, Z. A. A., & Setapar, S. H. M. (2022). Current status and future prospect of nanotechnology incorporated plant-based extracts in cosmeceuticals. In *Nanotechnology for the preparation of cosmetics using plant-based extracts* (pp. 235-261). Elsevier.