



Received on 26 April 2025; received in revised form, 28 May 2025; accepted, 14 June 2025; published 01 November 2025

GREEN NANOTECHNOLOGY IN FOCUS: PLANT-MEDIATED SYNTHESIS AND APPLICATIONS OF BISMUTH NANOPARTICLES

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Keywords:

Bismuth nanoparticles, Green synthesis, Plant extracts, Biomedical applications, Phytochemicals, environmental remediation, biomedicine

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ABSTRACT: The green synthesis of bismuth nanoparticles (BiNPs) using plant extracts presents a sustainable and eco-friendly alternative to conventional nanoparticle fabrication methods. Bismuth, a low-toxicity post-transition metal, exhibits unique physicochemical properties suitable for applications in biomedicine, imaging, catalysis, and environmental remediation. Traditional synthesis approaches often involve toxic reagents and energy-intensive processes, whereas green synthesis leverages phytochemicals such as flavonoids, phenolic, terpenoids, and alkaloids as natural reducing and stabilizing agents. This review explores various plant-mediated methods for synthesizing BiNPs, emphasizing how factors like pH, temperature, and reaction time influence nanoparticle morphology and functionality. Analytical techniques including UV-Vis, FTIR, XRD, SEM, TEM, and zeta potential analysis are discussed in relation to nanoparticle characterization. The biomedical applications of green-synthesized BiNPs, particularly their antibacterial, anticancer, and imaging potential, are examined alongside their role in photocatalytic degradation of environmental pollutants. While promising, the field faces challenges such as variability in plant extract composition, limited mechanistic understanding, and lack of standardization in synthesis protocols. Addressing these issues is essential for the scalable and reproducible production of BiNPs. This review highlights the current advances and future directions of plant-based BiNP synthesis within the framework of green chemistry.

INTRODUCTION:

Nanotechnology and the Rise of Green Synthesis: Nanotechnology has emerged as one of the most dynamic fields of scientific research, offering revolutionary advancements across domains including medicine, environmental science, catalysis, electronics, and materials engineering. Among various nanomaterials, metal and metal oxide nanoparticles have garnered significant attention due to their unique physicochemical properties that differ markedly from their bulk counterparts.

These properties such as enhanced surface area, tenable optical behaviour, and superior catalytic and antimicrobial activities stem largely from the Nano scale dimensions of this particle ¹. The synthesis of nanoparticles, however, is not devoid of challenges. Conventional methods such as chemical reduction, electrochemical deposition, and physical vapour deposition, while effective, often involve hazardous reagents, high energy consumption, and generate toxic by-products. These factors raise environmental and health concerns, urging the need for more sustainable and eco-friendly approaches ²⁻³.

Over the past few decades, nanotechnology has revolutionized multiple scientific fields, providing novel solutions to longstanding challenges. Defined broadly as the design, production, and application of materials at the nanometre scale (typically less than 100 nm), nanotechnology has enabled

QUICK RESPONSE CODE 	DOI: 10.13040/IJPSR.0975-8232.16(11).2948-53 This article can be accessed online on www.ijpsr.com DOI link: https://doi.org/10.13040/IJPSR.0975-8232.16(11).2948-53
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innovations in areas as diverse as medicine, electronics, catalysis, agriculture, and environmental remediation. At the heart of this progress are nanoparticles (NPs), which exhibit unique properties including large surface area-to-volume ratios, quantum confinement effects, and altered chemical reactivity making them markedly different from their bulk counterparts. Among metallic and metal oxide nanoparticles, research has often focused on noble metals like silver (Ag), gold (Au), and platinum (Pt), as well as transition metals such as copper (Cu), iron (Fe), and zinc (Zn). However, there has been a growing interest in exploring less conventional metals like bismuth (Bi), which possess distinct physicochemical and biological properties that are both technologically valuable and environmentally safer⁴.

The synthesis of nanoparticles has traditionally relied on physical and chemical methods, including high-temperature evaporation, laser ablation, sol-gel techniques, and chemical reduction using agents like sodium borohydride or hydrazine. While these methods offer precise control over nanoparticle size, shape, and yield, they often involve harsh conditions, hazardous chemicals, and toxic by-products. Such practices raise significant concerns regarding environmental sustainability, human health, and the economic feasibility of nanoparticle production, especially when considering large-scale applications⁵.

In response to these concerns, the field of green nanotechnology has emerged, advocating for the development of eco-friendly, cost-effective, and sustainable nanoparticle synthesis methods. Among the various green synthesis routes, the use of plant-based natural extracts as reducing and stabilizing agents has gained substantial attention due to its simplicity, scalability, and alignment with green chemistry principles⁶.

In recent years, green synthesis methods have emerged as a promising alternative to conventional techniques. These methods employ natural sources such as plant extracts, microorganisms, enzymes, and other biological entities for the reduction and stabilization of nanoparticles. Among these, plant-based synthesis has gained considerable attention due to its simplicity, cost-effectiveness, scalability, and environmental safety. Natural plant extracts are

rich in phytochemicals such as alkaloids, terpenoids, phenolic, flavonoids, and saponin, which act as both reducing and capping agents, facilitating the formation of stable nanoparticles⁷⁻⁸.

Bismuth Nanoparticles:

A Unique and Promising Material⁹⁻¹¹: Bismuth (Bi), a post-transition metal with atomic number 83, has recently attracted scientific interest as a component in nanoparticle synthesis. Traditionally overshadowed by more extensively studied metals like silver, gold, and copper, bismuth offers several advantageous properties that make it an attractive candidate for various applications.

In Nano particulate form, bismuth nanoparticles (BiNPs) demonstrate a suite of properties that make them attractive in several domains:

Biomedical Applications: Due to their low toxicity and high biocompatibility, BiNPs have shown potential in antimicrobial, anticancer, antioxidant, and anti-inflammatory applications. Their high atomic number also makes them suitable for use as contrast agents in imaging techniques like computed tomography (CT) and photo acoustic imaging.

Photo Catalysis and Environmental Remediation: Bismuth-based nanomaterial's such as Bi₂O₃, BiVO₄, and Bi₂S₃ possess photo catalytic properties under visible light, making them suitable candidates for the degradation of pollutants and dyes in wastewater.

Energy Storage and Conversion: BiNPs are also being explored for their role in lithium-ion batteries, thermoelectric devices, and solar energy harvesting.

Bismuth is known for its low toxicity, high atomic number, good X-ray attenuation properties, and photo catalytic activity, making it suitable for biomedical, pharmaceutical, and environmental applications. Unlike heavy metals such as lead and cadmium, bismuth is often considered safer for biological interactions. Moreover, its ability to form complex oxides such as Bi₂O₃ and BiVO₄ with semiconducting and photo catalytic characteristics further extends its potential utility in areas like solar energy conversion and pollutant degradation. In nanoparticle form, bismuth exhibits

enhanced surface-to-volume ratio, increased reactivity, and novel physicochemical traits not seen in the bulk state. Bismuth nanoparticles (BiNPs) demonstrate notable antibacterial, anticancer, and antioxidant activities, which are of growing interest in therapeutic and diagnostic fields.

The Role of Natural Extracts in Bismuth Nanoparticle Synthesis¹²⁻¹³: The green synthesis of bismuth nanoparticles using natural extracts represents a convergence of sustainability and innovation. In this method, aqueous or alcoholic extracts of various plants such as leaves, fruits, roots, flowers, and even barks are used to mediate the reduction of bismuth salts (commonly bismuth nitrate or bismuth chloride) to elemental bismuth or bismuth oxide nanoparticles. Natural extracts offer several benefits in nanoparticle synthesis:

Biocompatibility: The biological nature of the capping agents ensures lower toxicity and better compatibility with biological systems.

Environmental Friendliness: The absence of harsh chemicals and solvents aligns the process with green chemistry principles.

Dual Function: Plant extracts serve both as reducing agents (converting Bi^{3+} to Bi^0 or Bi_2O_3) and stabilizing agents (preventing aggregation and controlling morphology).

Cost-effectiveness: The raw materials (plant matter) are inexpensive, renewable, and widely available, reducing the overall cost of nanoparticle synthesis.

Examples of plants that have been successfully used in bismuth nanoparticle synthesis include *Ocimum sanctum* (holy basil), *Azadirachta indica* (neem), *Camellia sinensis* (green tea), *Moringa oleifera*, *Zingiber officinale* (ginger), and *Allium sativum* (garlic). These plants provide a diverse range of secondary metabolites which directly influence the size, shape, and stability of the synthesized nanoparticles¹⁴. Green synthesis refers to the use of biological entities plants, bacteria, fungi, algae, and enzymes for nanoparticle fabrication. Among these, plant-mediated synthesis has become particularly popular due to the abundance, accessibility, and wide variety of

bioactive compounds present in plants¹⁵. Plant extracts are rich in phytochemicals such as flavonoids, alkaloids, phenolics, tannins, terpenoids, saponins, and proteins. These compounds serve dual roles in nanoparticle synthesis:

Reducing agents, converting Bi^{3+} ions into elemental bismuth or bismuth oxide nanoparticles.

Capping/ Stabilizing agents, preventing aggregation and controlling the size and morphology of the particles. The general process involves mixing a solution of a bismuth salt commonly bismuth nitrate ($\text{Bi}(\text{NO}_3)_3 \cdot 5\text{H}_2\text{O}$) or bismuth chloride (BiCl_3) with a plant extract under controlled temperature and pH conditions. A visible colour change, typically to brown or black, often indicates nanoparticle formation. The reaction mixture is then purified, usually by centrifugation and washing, and the resulting nanoparticles are characterized using various analytical techniques¹⁶.

Importance of Process Parameters and Phytochemistry¹⁷⁻¹⁸: The successful synthesis of BiNPs using plant extracts is governed by several factors, including pH, temperature, precursor concentration, plant extract volume, and reaction time. These parameters must be carefully optimized to achieve desirable nanoparticle characteristics. Furthermore, the phytochemical profile of each plant species significantly affects the reduction and capping process, thus influencing the nanoparticle's morphology and function.

Several process variables must be optimized to ensure high-quality nanoparticle synthesis:

pH of the Reaction Medium: Affects the ionization of phytochemicals and the solubility of the bismuth precursor.

Temperature: Higher temperatures generally increase the rate of reduction but may also promote particle agglomeration.

Concentration of Bismuth Salt: Excessive precursor concentrations can lead to polydispersity.

Volume and Concentration of Plant Extract: Determines the availability of reducing and stabilizing agents.

Reaction Time: Must be sufficient to allow complete reduction and stabilization. These parameters not only affect the yield and stability of BiNPs but also their physicochemical and biological properties.

To confirm the formation and evaluate the properties of green-synthesized BiNPs, multiple analytical techniques are employed¹⁹:

UV-Visible Spectroscopy: Monitors surface Plasmon resonance (SPR) and helps estimate nanoparticle size.

Fourier-Transform Infrared Spectroscopy (FTIR): Identifies functional groups from the plant extract involved in reduction and capping.

X-ray Diffraction (XRD): Determines the crystalline structure and phase purity.

Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM): Reveal particle morphology, size distribution, and surface features.

Energy-Dispersive X-ray Spectroscopy (EDS): Confirms elemental composition.

Zeta Potential Analysis: Assesses surface charge and stability of colloidal nanoparticles.

Biomedical and Environmental Applications: Bismuth nanoparticles synthesized via green methods show promising biological activity, especially in antimicrobial and anticancer domains. The antibacterial activity of BiNPs has been demonstrated against both Gram-positive and Gram-negative bacteria, suggesting their potential as effective agents against antibiotic-resistant strains.

In cancer therapy, bismuth-based nanoparticles exhibit cytotoxic effects against various cancer cell lines, attributed to their ability to induce oxidative stress, DNA damage, and apoptosis. Additionally, due to their strong X-ray attenuation properties, BiNPs are also being explored as contrast agents in medical imaging, especially in computed tomography (CT). From an environmental standpoint, BiNPs have shown promising results in photocatalytic degradation of organic pollutants such as dyes and pesticides under visible light,

offering eco-friendly solutions for wastewater treatment²⁰.

Current Challenges and Future Directions: Despite the growing body of research, several challenges remain in the green synthesis of bismuth nanoparticles. These include:

1. Lack of standardization in plant extract preparation and nanoparticle synthesis protocols.
2. Variability in phytochemical content based on plant species, geographical location, and seasonality.
3. Limited mechanistic understanding of the reduction and stabilization processes.
4. Scalability and reproducibility of the green synthesis processes for industrial applications.

Addressing these challenges will require interdisciplinary collaboration, advanced analytical techniques, and the development of standardized protocols. Furthermore, detailed in vivo studies and toxicity assessments are essential before clinical translation of BiNPs can be realized.

7. Scope of the Review

This review aims to provide a comprehensive overview of the green synthesis of bismuth nanoparticles using natural extracts, with a focus on:

- ❖ Different plant species and their phytochemicals involved in BiNP synthesis.
- ❖ Characterization techniques and nanoparticle properties.
- ❖ Biological and environmental applications of synthesized BiNPs.
- ❖ Challenges and limitations of current methodologies.
- ❖ Future prospects in green nanotechnology and biomedical integration.

By consolidating the current state of knowledge, this review hopes to serve as a valuable resource for researchers, industry professionals, and

environmental scientists interested in sustainable nanomaterials and their diverse applications.

CONCLUSION: The green synthesis of bismuth nanoparticles (BiNPs) using natural plant extracts represents a promising frontier in sustainable nanotechnology. This eco-friendly approach not only mitigates the environmental and health hazards associated with traditional physical and chemical synthesis methods but also harnesses the rich phytochemistry of plants to produce biologically active and structurally diverse nanoparticles. Bismuth, a relatively underexplored yet highly functional metal, exhibits low toxicity and versatile physicochemical properties, making it particularly attractive for applications in biomedicine, imaging, catalysis, and environmental remediation. Through a growing body of research, numerous plant species have demonstrated their capacity to reduce bismuth salts and stabilize the resulting nanoparticles *via* their intrinsic biomolecules, such as flavonoids, terpenoids, and phenolic. These green-synthesized BiNPs have shown significant potential in combating multidrug-resistant pathogens, inducing cytotoxic effects in cancer cells, degrading organic pollutants, and enhancing imaging contrast all while remaining largely biocompatible and environmentally benign. However, several scientific and technical challenges remain, including the standardization of synthesis protocols, variability in phytochemical content, and the need for deeper mechanistic understanding. Addressing these challenges through interdisciplinary research, rigorous characterization, and scalable synthesis strategies will be crucial for translating laboratory findings into real-world applications. In essence, the convergence of nanotechnology, green chemistry, and phytoscience in the synthesis of BiNPs offers a compelling path forward toward the development of sustainable, high-performance nanomaterials. With continued research and innovation, green-synthesized bismuth nanoparticles could play a transformative role in next-generation biomedical technologies and environmental solutions.

ACKNOWLEDGEMENT: We express our gratitude to B. N. College of Pharmacy for providing various resources and facilities used during the research study.

CONFLICT OF INTEREST: We declare that we do not have conflict of interest.

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How to cite this article:

Sankhla P, Sarangdevot YS and Vyas B: Green nanotechnology in focus: plant-mediated synthesis and applications of bismuth nanoparticles. Int J Pharm Sci & Res 2025; 16(11): 2948-53. doi: 10.13040/IJPSR.0975-8232.16(11).2948-53.

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