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International Journal of Pharmaceutical Chemistry and Analysis

Journal homepage: https://www.ijpca.org/

Review Article

Green synthesis of phyto-nanoparticles: Recent advancements and environmentally friendly approaches

Rahul Pravin Nikam[1]*, Trupti Cholera[1], Mansi Mokal[1], Neha Joshi[1], Namrata Naware[2], Anil. G. Jadhav[3]

[1]Mahavir Institute of Pharmacy, Nashik, Maharashtra. India.
[2]Dept. of Chemistry, Mahavir Institute of Pharmacy, Nashik, Maharashtra, India.
[3]Dept. of Pharmacognosy, Mahavir Institute of Pharmacy, Nashik, Maharashtra. India.

Abstract

The green synthesis of Phyto-nanoparticles has emerged as a sustainable alternative to conventional chemical methods, leveraging plant extracts and phytochemicals as natural reducing and stabilizing agents. This review highlights recent advancements in the synthesis mechanisms, including the roles of plant-derived biomolecules and multi-component systems, which offer enhanced functionality and ecological benefits. Key developments in optimizing reaction conditions, scaling up production, and exploring novel applications are discussed. The integration of green synthesis into industrial processes underscores its potential to revolutionize nanotechnology, fostering a sustainable and eco-friendly future. This study serves as a comprehensive overview of the state-of-the-art methods and future prospects in green nanotechnology.

Keywords: Phyto-nanoparticles, Green synthesis, Plant extracts, Phytochemicals, Sustainable nanotechnology, Eco-friendly methods, Nanoparticle applications

Received: 04-02-2025; **Accepted:** 04-03-2025; **Available Online**: 21-04-2025

1. Introduction

Currently, there are numerous chemical and physical methods available in the literature for production of nanomaterials, which deliver a higher rate of production and well-controlled size and shape of nanomaterials but these approaches are discouraging due to higher loss of energy and capital, use of noxious chemicals, and production of large amount of bio-waste. These key factors influence the commercial level scale-up process of nanomaterials economically as well as environmentally. Additionally, the clinical use of nanomaterials prepared through chemical methods has been limited due to issues of biocompatibility, toxicity and stability. These components elevates requirement of eco-friendly, cheaper and biocompatible methods for production of nanomaterials. In comparison to conventional physical and chemical methods, greener route for NPs synthesis offers economical, environment-friendly and nontoxic approaches.

The synthesis of nanoparticles has gained significant attention in recent years due to their extensive applications in medicine, agriculture, and environmental remediation.[1-2] Among various synthesis methods, the green synthesis of nanoparticles using plant-based materials has emerged as a sustainable, cost-effective, and eco-friendly approach.[3-4] This review explores recent advancements in the green synthesis of phytonanoparticles, focusing on the use of plant extracts, phytochemicals, and green reducing agents.[5-6]. Furthermore, the review discusses the advantages of these methods over conventional chemical and physical approaches.[7]

Corresponding author: Rahul Pravin Nikam
Email: rahulpnikam2003@gmail.com

DOI: https://10.18231/j.ijpca.2025.006

2. Objectives of Ecofriendly Methods Use in Phyto Nanoparticle Synthesis

1. Environmental Sustainability: Traditional methods of nanoparticle synthesis often involve hazardous chemicals and processes that can harm the environment. Eco-friendly methods aim to minimize or eliminate the use of toxic substances and reduce environmental pollution.

2. Green Chemistry: The objective is to align with the principles of green chemistry by using natural, non-toxic materials and processes. This involves utilizing plant extracts or biological agents to produce nanoparticles, thereby avoiding harmful reagents and reducing waste.

3. Cost-effectiveness: Eco-friendly methods can often be more cost-effective in the long run. Plant-based or biological methods may use readily available and inexpensive resources, potentially reducing the overall cost of nanoparticle production.

4. Safety and Health: Reducing the use of hazardous chemicals enhances safety for workers and minimizes health risks associated with exposure to toxic substances. Eco-friendly methods aim to protect human health by relying on natural processes.

5. Scalability and Accessibility: Many eco-friendly methods are scalable and can be applied to large-scale production. They can also be more accessible in regions with limited resources, leveraging locally available plants or biological materials.

6. Enhanced Functionality: Plant-based synthesis can sometimes impart unique properties to nanoparticles. For instance, Phyto nanoparticles might exhibit enhanced stability, bioactivity, or specific interactions due to the presence of natural compounds in the plant extracts.

7. Public Acceptance: Eco-friendly methods often align with public and regulatory preferences for sustainable practices. Utilizing green methods can improve the acceptance and marketability of the nanoparticles in various applications.

8. Reduction of Waste: These methods typically generate less chemical waste compared to conventional methods. Byproducts are often more benign, leading to a cleaner and more efficient synthesis process.

2.1. Nanoparticles synthesizing method

Phyto nanoparticle synthesis involves various methods that utilize plant materials to produce nanoparticles in an environmentally friendly manner. **Table 1**. show a comprehensive overview of the different methods for synthesizing Phyto nanoparticles.

Table 1*:* Nanoparticle *synthesizing method*

Type of method	Overview	Process	Example
Direct Plant Extract Method	In this method, plant extracts containing bioactive compounds are used directly to reduce metal ions and stabilize nanoparticles	Plant material (leaves, roots, stems) is extracted using solvents (water, ethanol, etc.), and this extract is mixed with metal salt solutions. The phytochemicals in the extract reduce metal ions to form nanoparticles.	Green synthesis of silver nanoparticles using neem leaf extract or gold nanoparticles using green tea extract.
Plant-Mediated Biosynthesis	This method involves the use of whole plants or plant tissues for the synthesis of nanoparticles.	Plant parts are immersed in metal ion solutions, where phytochemicals in the plant reduce the metal ions and stabilize the nanoparticles	Synthesis of iron oxide nanoparticles using aloe vera leaf extract or copper nanoparticles using basil leaf extract.
Leaf/Stem/Root Infusion Method	Specific plant parts are infused to create a solution rich in phytochemicals, which is then used for nanoparticle synthesis	Plant parts are boiled or soaked in a solvent to create an infusion. This infusion is then added to metal ion solutions to produce nanoparticles	Silver nanoparticles synthesis using mint leaf infusion or zinc oxide nanoparticles using ginger root infusion
Green Chemistry Methods	Methods that incorporate green chemistry principles to minimize the use of toxic substances and enhance environmental sustainability	This includes optimizing reaction conditions, using non-toxic solvents, and employing natural reducing agents and stabilizers derived from plants	Synthesis of selenium nanoparticles using plant-derived polysaccharides as reducing agents or biosynthesis of silver nanoparticles using eco-friendly solvents and plant extracts.
Bioreactor-Assisted Synthesis	Utilizes bioreactors to control and scale up the synthesis of Phyto nanoparticles.	Plant extracts or plant cells are cultured in bioreactors, where controlled conditions (pH, temperature) optimize the synthesis and yield of nanoparticles.	Synthesis of gold nanoparticles in plant cell culture systems or silver nanoparticles using plant cell suspension cultures.
Plant-Extract Stabilized Synthesis	This technique involves using plant extracts to not only reduce metal ions but also stabilize the nanoparticles formed	The plant extract is mixed with metal ion solutions, and the phytochemicals in the extract both reduce the ions and stabilize the resulting nanoparticles	Gold nanoparticles stabilized with pomegranate peel extract or platinum nanoparticles stabilized with hibiscus extract
Microbial-Plant Synergistic Methods	Combines plant extracts with microbial systems to enhance nanoparticle synthesis	Plant extracts are used in conjunction with microorganisms (like bacteria or fungi) to facilitate the reduction and stabilization of nanoparticles	Synthesis of zinc oxide nanoparticles using plant extracts in the presence of bacteria or fungi.

• Hybrid Methods	Combines different plant-based methods or integrates other eco-friendly techniques to enhance the synthesis process	Incorporates multiple plant sources, different extraction techniques, or combines plant extracts with other green reducing agents to optimize nanoparticle synthesis	Using a combination of different plant extracts for synthesis or combining plant extracts with green reducing agents like ascorbic acid.
• Sustainable Scale-Up Techniques	Focuses on scaling up the synthesis process while maintaining environmental sustainability.	Develops protocols and systems to scale up the synthesis of Phyto nanoparticles from laboratory to industrial scale using sustainable practices	Large-scale production of silver nanoparticles using plant extracts in industrial reactors or scaled-up synthesis of gold nanoparticles using optimized plant extract methods.

3. Green Synthesis Mechanisms

The green synthesis of phytonanoparticles primarily involves three main steps: reduction, stabilization, and growth.[8-9] Plant extracts, rich in bioactive compounds such as polyphenols, flavonoids, and alkaloids, act as reducing and capping agents.[10] These phytochemicals facilitate the reduction of metal ions to their nanoparticle forms while simultaneously preventing aggregation through stabilization mechanisms.[11-12]

4. Role of Plant Extracts

Plant extracts have been widely utilized for synthesizing metallic nanoparticles such as gold, silver, and zinc oxide.[13-14] The diversity of phytochemicals in these extracts enables efficient reduction and stabilization of nanoparticles.[15-16] For instance, recent studies have demonstrated the use of *Azadirachta indica* (neem) and *Ocimum sanctum* (holy basil) extracts in synthesizing silver nanoparticles with remarkable antimicrobial properties.[17-18] The extracts' bioactive compounds provide a dual function of synthesis and biological activity, enhancing their applicability in biomedical fields.[19]

5. Phytochemicals as Reducing Agents

Phytochemicals such as tannins, terpenoids, and saponins have emerged as effective reducing agents.[20-21] For example, tannic acid has been employed to synthesize gold nanoparticles with high stability and uniform size distribution.[22] These biomolecules not only simplify the synthesis process but also eliminate the need for hazardous chemicals, aligning with green chemistry principles.[23]

6. Recent Advancements

Recent advancements in the green synthesis of phytonanoparticles have focused on optimizing reaction conditions and exploring novel plant-based sources.24-25 Studies have highlighted the influence of factors such as pH, temperature, and reaction time on the size, shape, and functional properties of nanoparticles.26 For example, researchers have synthesized spherical and anisotropic nanoparticles by controlling the synthesis parameters, enabling tailored applications in drug delivery and catalysis.[27-28]

7. Multi-Component Systems

A noteworthy advancement is the development of multi-component systems that combine plant extracts with other green reducing agents, such as honey or microbial extracts.[29-30]. These hybrid systems have demonstrated synergistic effects, leading to improved yield and functional properties of nanoparticles.[31] Such approaches exemplify the potential of interdisciplinary methodologies in enhancing green synthesis.[32]

8. Scale-Up and Industrial Applications

Efforts have also been directed toward scaling up the production of phytonanoparticles for industrial applications.[33] Techniques such as continuous flow synthesis have been explored to address challenges related to reproducibility and scalability.[34-35] Furthermore, applications in agriculture, such as nanopesticides and nanofertilizers, have highlighted the ecological benefits of using green-synthesized nanoparticles.[36-37]

9. Methods of Eco-Friendly Nanoparticle Synthesis

Recent advancements in environmentally friendly methods for synthesizing Phyto nanoparticles (PNPs) using plant extracts, phytochemicals, and green reducing agents have made significant strides, aiming to create sustainable and eco-friendly nanomaterials. Here are some key developments in this field:

9.1. Use of plant extracts

Researchers have expanded the range of plant sources used for nanoparticle synthesis. Plants like aloe vera, neem, mint, and various fruits and vegetables are being explored for their rich phytochemical content, which can act as reducing and stabilizing agents.

New techniques for extracting bioactive compounds from plants, such as ultrasonic-assisted extraction, supercritical fluid extraction, and microwave-assisted extraction, are enhancing the efficiency and yield of phytochemicals used in nanoparticle synthesis.

9.2. Optimization of extraction methods

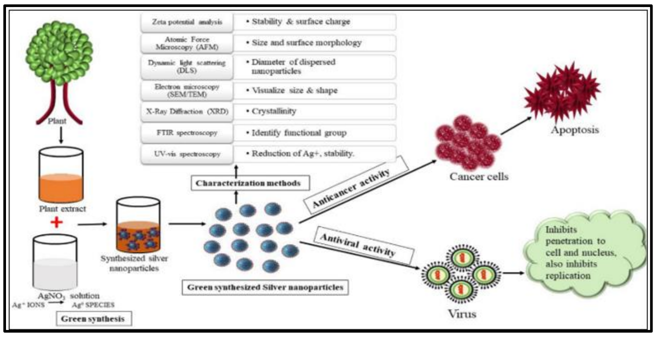

Figure 1*:* Optimization *of extraction method*

10. Phytochemicals as Reducing Agents

Green reduction pathways: Phytochemicals such as flavonoids, terpenoids, and polyphenols are increasingly recognized for their ability to reduce metal ions to nanoparticles. These compounds offer a green alternative to traditional chemical reducing agents.

Tailoring phytochemical use: Researchers are identifying specific phytochemicals that provide the best reducing and stabilizing properties for different types of nanoparticles. This customization helps in fine-tuning the size, shape, and stability of the nanoparticles.

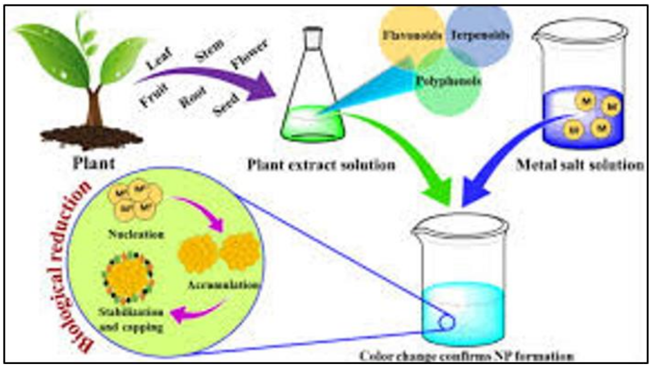

Figure 2: Phytochemicals as reducing agents

11. Innovative Synthesis Techniques

11.1. One-pot synthesis

Advances in one-pot synthesis methods, where the plant extract and metal salts are combined in a single reaction vessel, streamline the production process and reduce waste.

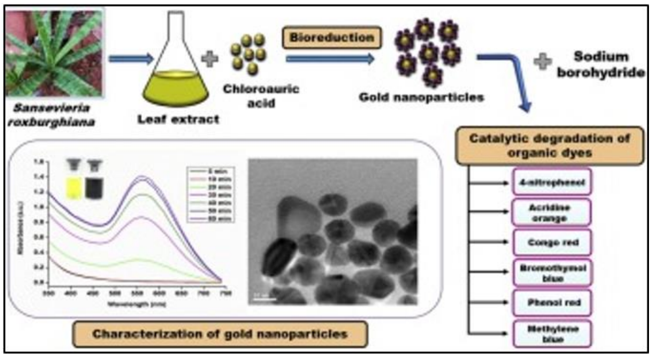

Figure 3: Innovative synthesis technique

Bioreactor-Assisted Synthesis: The use of bioreactors for nanoparticle synthesis is gaining traction. These systems allow for controlled conditions and higher production scalability, improving the efficiency of nanoparticle synthesis from plant extracts.

12. Characterization and Functionalization

Enhanced Characterization Techniques: Advances in characterization tools, such as high-resolution transmission electron microscopy (HRTEM), X-ray diffraction (XRD), and dynamic light scattering (DLS), provide more precise information about the size, shape, and distribution of Phyto nanoparticles.

Functionalization: Researchers are exploring methods to functionalize Phyto nanoparticles with additional biomolecules to enhance their properties for specific applications, such as targeted drug delivery, environmental remediation, and biosensing.

5. Applications and Sustainability

Biomedical Applications: There is growing interest in using Phyto nanoparticles for medical applications, including drug delivery, imaging, and as antimicrobial agents, due to their biocompatibility and reduced toxicity.

5.1. Environmental remediation:

Phyto nanoparticles are being developed for applications in environmental cleanup, such as the removal of pollutants and heavy metals from water and soil, leveraging their eco-friendly synthesis methods.

6. Regulatory and Standardization Efforts

6.1. Standards and guidelines

Efforts are underway to establish standards and guidelines for the synthesis and application of Phyto nanoparticles to ensure safety, consistency, and reproducibility in various applications.

13. Applications of Green-Synthesized Phytonanoparticles

13.1. Biomedical Applications

Phytonanoparticles exhibit significant potential in medical applications due to their biocompatibility and functional versatility.[38-39] For example, silver nanoparticles synthesized using *Aloe vera* extracts have demonstrated remarkable antibacterial properties, offering promising avenues in wound healing and infection control.[40] Furthermore, gold nanoparticles synthesized using plant-based methods have been applied in drug delivery systems and imaging technologies, highlighting their role in targeted cancer therapy.[41-42]

13.2. Environmental applications

Green-synthesized nanoparticles have been explored for environmental remediation, including the degradation of pollutants and water purification.[43] Iron oxide nanoparticles synthesized using *Moringa oleifera* extracts have been used in removing heavy metals from wastewater, emphasizing their potential in addressing environmental challenges.[44-45]

13.3. Agricultural applications

Phytonanoparticles are increasingly used in agriculture to develop nanopesticides, nanofertilizers, and growth-promoting agents.[46-47] For instance, zinc oxide nanoparticles synthesized using *Citrus limon* extracts have been shown to enhance plant growth and increase crop yield.[48]

14. Challenges and Future Perspectives

The green synthesis of Phyto-nanoparticles holds immense promise in revolutionizing nanotechnology through eco-friendly approaches. However, despite its numerous benefits, several challenges must be addressed to fully integrate this method into mainstream scientific and industrial applications. These challenges primarily revolve around standardization, scalability, reproducibility, resource optimization, toxicological evaluation, and regulatory frameworks. Addressing these issues will not only enhance the credibility of green synthesis but also unlock new possibilities for its implementation in medicine, agriculture, environmental sciences, and beyond.

15. Challenges in Standardization and Reproducibility

One of the most pressing challenges in green phytonanoparticle synthesis is the lack of standardized protocols. The synthesis process is highly dependent on plant species, extraction methods, climatic conditions, and geographical variations, all of which influence the composition of bioactive compounds responsible for nanoparticle formation. The inconsistency in these factors results in variability in nanoparticle size, morphology, surface charge, and functional properties, making it difficult to achieve reproducibility across different research studies. Establishing universal guidelines and standardized methodologies for plant-mediated nanoparticle synthesis is crucial to ensure consistency and reliability in both laboratory and industrial-scale production.

16. Scalability and Industrial Application

While green synthesis is widely studied at the laboratory level, its transition to large-scale production remains a significant challenge. Industrial applications require nanoparticles to be synthesized in bulk while maintaining uniform quality and desired physicochemical properties. However, achieving this at a commercial scale is complicated due to factors such as prolonged synthesis time, variable yields, and batch-to-batch inconsistencies. Moreover, large-scale production demands cost-effective strategies, improved bioreactor designs, and sustainable raw material sourcing to make the process economically viable. Addressing these concerns will be crucial in promoting the widespread industrial adoption of phytonanoparticles.

17. Exploring Underutilized Plant Resources

Currently, many studies focus on common medicinal plants and easily accessible botanical sources for nanoparticle synthesis. However, exploring underutilized plant species, agricultural byproducts, marine algae, and ethnobotanically significant flora could significantly enhance the efficiency and sustainability of the synthesis process. Utilizing agricultural and industrial plant waste as a source of reducing and stabilizing agents can further contribute to circular economy practices, minimizing environmental impact while maximizing resource utilization. Future research should emphasize the identification and characterization of novel plant-based bioactive compounds that can improve nanoparticle synthesis and functionalization.

17.1. Toxicological and environmental safety concerns

Although green synthesis is considered environmentally friendly due to the absence of toxic chemicals, comprehensive toxicological evaluations are necessary to assess the long-term effects of phytonanoparticles. Their interactions with biological systems, potential cytotoxicity, accumulation in ecosystems, and biodegradability must be thoroughly investigated before they can be widely applied in biomedical and environmental applications. Additionally, regulatory frameworks must be established to ensure the safe use, handling, and disposal of these nanoparticles. Government agencies and scientific institutions should collaborate to develop stringent guidelines and safety protocols for green nanotechnology applications.

17.2. Future directions and technological innovations

The future of phytonanoparticle synthesis is closely linked to advancements in technology, including computational modeling, artificial intelligence, and nanomaterial characterization techniques. Machine learning and AI-driven predictive models could optimize synthesis conditions, helping researchers achieve precise control over nanoparticle properties with minimal experimental trials. Additionally, advancements in high-throughput screening, spectroscopy, and imaging techniques can provide deeper insights into nanoparticle formation mechanisms and interactions with biological systems.

Integrating green synthesis into nanotechnology applications will also require innovations in extraction techniques, such as microwave-assisted and ultrasound-assisted extraction, to enhance the efficiency and yield of bioactive compounds. Bioreactor technology and automation systems will play a crucial role in improving scalability and reducing production costs. Furthermore, interdisciplinary collaborations among chemists, biologists, environmental scientists, and engineers will be essential in overcoming existing challenges and ensuring the practical implementation of green-synthesized nanoparticles across industries.[51-53]

18. Environmental and Economic Benefits

Green synthesis methods offer numerous advantages over conventional approaches, including reduced energy consumption, minimal use of toxic chemicals, and low-cost raw materials.[53]Additionally, the biocompatibility of phytonanoparticles synthesized via plant extracts enhances their environmental and biomedical applications.[54-55] These attributes make green synthesis an attractive alternative for achieving sustainability in nanotechnology.[56]

19. Conclusion

The green synthesis of phytonanoparticles has emerged as a revolutionary and sustainable approach in nanotechnology, offering an eco-friendly alternative to conventional chemical and physical synthesis methods. By utilizing plant extracts and phytochemicals, researchers have developed innovative methodologies that align with the principles of green chemistry, reducing the reliance on toxic reagents and minimizing environmental hazards. These bio-inspired nanoparticles exhibit remarkable biocompatibility, making them highly suitable for applications in medicine, agriculture, environmental remediation, and other industries.[57-58]

One of the most significant advantages of green synthesis is its ability to harness the natural reducing, stabilizing, and capping agents present in plant-based materials, eliminating the need for synthetic chemicals. This not only makes the process more sustainable but also enhances the biological activity of the synthesized nanoparticles. Furthermore, the optimization of synthesis parameters, such as pH, temperature, and precursor concentration, has led to the production of nanoparticles with controlled size, morphology, and enhanced functional properties.

Recent advancements in the field have explored novel plant sources, such as medicinal herbs, marine algae, and agricultural byproducts, further expanding the scope of green nanoparticle synthesis. The ability to repurpose biological waste materials for nanoparticle production presents an additional advantage, promoting circular economy practices and reducing overall waste generation.[59]

As research continues to evolve, integrating green synthesis methods into large-scale industrial production remains a key challenge and opportunity. The successful transition from laboratory-scale experiments to commercial applications will require the development of standardized protocols, cost-effective production strategies, and regulatory frameworks ensuring safety and efficacy. Nonetheless, with continued innovation and interdisciplinary collaboration, green phytonanoparticle synthesis holds immense potential in shaping a more sustainable future for nanotechnology and its diverse applications.[60]

20. Source of Funding

None.

21. Conflict of Interest

None.

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Cite this article:. Nikam RP, Cholera T, Mokal M, Joshi N, Naware N, Jadhav AG. Green synthesis of phyto-nanoparticles: Recent advancements and environmentally friendly approaches. *Int. J Pharma Chem Anal.* 2025;12(1):42-48.