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Green Synthesis of Nanoparticles using Plant Parts: A Bridging System in Innovative Medicine

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Abstract

The synthesis of nanoparticles using plant-based materials has emerged as a revolutionary approach in modern medicine, addressing limitations associated with traditional chemical synthesis methods. This review highlights the principles and methodologies of green synthesis, focusing on its eco-friendly, biocompatible, and cost-effective nature. Plant-mediated nanoparticles exhibit unique properties, including functionalization capabilities, which make them ideal candidates for applications such as targeted drug delivery, antimicrobial therapies, and theranostics. Furthermore, this paper explores the potential of phytopharmaceuticals derived from plant sources to bridge the gap between traditional medicine and modern pharmaceutical standards, ensuring safety, efficacy, and regulatory compliance. By integrating traditional medicinal knowledge with advanced nanotechnology, this approach promises sustainable solutions to complex biomedical challenges. The review consolidates recent advancements and case studies, providing insights into the transformative potential of green synthesis in healthcare and biotechnology.

***Key words*:** Green synthesis, Nanoparticles, Phytopharmaceuticals, Plant-mediated synthesis, Targeted drug delivery, Antimicrobial therapies, Theranostics, Sustainable nanotechnology, Traditional medicine, Biocompatibility

The green synthesis of nanoparticles has emerged as a pivotal approach in nanotechnology, aligning with the principles of sustainability and eco-friendliness. Unlike conventional physical and chemical methods, green synthesis harnesses biological resources, particularly plant-based materials, as natural reducing and stabilizing agents. This methodology reduces the dependency on hazardous chemicals, high temperatures, and expensive equipment, making it an energy-efficient and environmentally benign process [1].

Recent advances in this field emphasize the importance of plant-derived bioactive compounds such as alkaloids, flavonoids, phenolics, and terpenoids, which play a crucial role in reducing metal ions into nanoscale particles and stabilizing them through capping mechanisms [2]. These bio-compounds not only facilitate nanoparticle synthesis but also impart functional properties, such as antimicrobial, antioxidant, and anticancer activities, broadening the scope of biomedical and industrial applications. Furthermore, green synthesis reflects a significant step toward integrating traditional knowledge with modern technology. Ethnobotanical studies have highlighted the potential of medicinal plants, often used in traditional medicine, as promising candidates for nanoparticle synthesis due to their rich phytochemical composition [3]. The use of such plants reduces environmental burdens and enhances the biocompatibility and therapeutic efficacy of nanoparticles.In addition to environmental and biomedical applications, the field of green nanotechnology is expanding into diverse areas such as agriculture, environmental remediation, and energy storage. For instance, plant-synthesized nanoparticles are being explored for their potential to improve crop productivity, clean polluted water, and develop advanced materials for renewable energy systems [4-5]. Despite its vast potential, challenges such as the standardization of synthesis protocols, scalability, and understanding the mechanisms of nanoparticle formation remain areas of active research. These challenges highlight the need for interdisciplinary approaches to optimize and translate laboratory findings into real-world applications [6]. This review focuses on the current advancements in green synthesis using plant parts, with a special emphasis on its biomedical and environmental applications, while addressing the challenges and opportunities in this transformative field.

Green synthesis of nanoparticles: A sustainable approach

Nanoparticles are materials with dimensions in the range of 1-100 nm, and their properties are highly influenced by their size, shape, and surface area. The small size of nanoparticles allows them to exhibit unique physical, chemical, and biological properties compared to bulk materials. For instance, they can penetrate cellular membranes, interact with proteins, and improve solubility and stability of therapeutic agents. Nanoparticles can be synthesized via physical, chemical, and biological methods. However, the chemical synthesis of nanoparticles often involves toxic reagents, hazardous solvents, and high-energy processes, which hinder their application in biomedical fields. In contrast, the green synthesis method offers a cleaner, safer, and more cost-effective alternative. Green synthesis utilizes plant extracts to provide a natural reducing and capping agent for the synthesis of nanoparticles. This

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method involves the use of aqueous plant extracts, which are abundant in bioactive molecules that possess reductive properties, such as flavonoids, polyphenols, tannins, and alkaloids [7]. In particular, plant-mediated synthesis of silver nanoparticles (AgNPs) is well-documented due to the high antimicrobial and anticancer properties of AgNPs, which are attributed to their enhanced surface area and the presence of surface-bound plant biomolecules [8]. A major advantage of this biosynthesis route is its environmental friendliness, as the use of plant-based extracts minimizes the need for hazardous chemicals, making the process safer and more sustainable. The synthesis of nanoparticles using plant extracts also tends to be faster and more efficient, leading to lower production costs. These factors contribute to the overall feasibility of large-scale production of biogenic nanoparticles, opening doors for their widespread use in pharmaceuticals, medical devices, and diagnostics.

Role of plant parts in nanoparticle synthesis

Plants are natural reservoirs of bioactive molecules, which play a dual role in nanoparticle synthesis: they reduce metal ions and act as stabilizing agents to prevent aggregation. The potential of plant parts, such as leaves, roots, seeds, and bark, to serve as nanofactories for metal nanoparticles has been demonstrated across various studies. For instance, *Taxuswallichiana* (Himalayan yew), a medicinal plant known for its rich bioactive constituents, has been identified as a potent source of secondary metabolites such as alkaloids, flavonoids, and polyphenols, which can mediate the reduction of metal ions and stabilize the resulting nanoparticles.

Recent studies have reported that extracts from the leaves and bark of *Taxuswallichiana* can reduce silver nitrate ($AgNO_3$) to silver nanoparticles (AgNPs) under ambient conditions. The primary mechanisms behind the reduction include electron transfer mediated by phenolic compounds in the plant extract, which act as reducing agents. Additionally, the compounds present in the plant extracts function as capping agents, which help in the stabilization and functionalization of the nanoparticles, ensuring their colloidal stability and preventing aggregation [9]. Silver nanoparticles synthesized from *Taxuswallichiana* have shown exceptional stability in aqueous solutions due to the binding of the plant's phytochemicals to the nanoparticle surface. This phenomenon is key to controlling the size, shape, and dispersion of the nanoparticles, which directly influences their biological activity and suitability for medical applications. Furthermore, the synthesis of nanoparticles from plant parts, as opposed to synthetic methods, also ensures that these nanoparticles carry plant-derived biomolecules on their surface, which may enhance their interaction with biological systems [10].

Bridging traditional knowledge and modern nanotechnology

The traditional use of *Taxuswallichiana* in ethnomedicine for treating flu, fever, and liver-related disorders is well documented, and this historical knowledge can now be integrated with modern nanotechnology to offer innovative therapeutic solutions. This *bridging system* between ethnobotanical practices and nanotechnology forms the core of this review. The plant's ability to synthesize nanoparticles using simple, cost-effective methods aligns with the principles of sustainable and green chemistry, which are essential for modern nanomedicine. By applying traditional botanical knowledge, scientists have been able to identify plant species like *Taxuswallichiana* that contain bioactive compounds suitable for nanoparticle formation. The resulting plant-mediated nanoparticles not only offer an eco-friendly synthesis route but also carry the inherent therapeutic properties of the parent plant. For instance, the antimicrobial, anticancer, and antioxidant properties of silver nanoparticles synthesized from *Taxuswallichiana* have been shown to enhance drug delivery, wound healing, and targeted therapy, thereby bridging the gap between nature and technology [11]. The integration of ethnobotany and nanotechnology offers an exciting frontier in the development of phytopharmaceuticals, where plant-derived nanoparticles can be designed to mimic the biological effects of their parent plants, such as *Taxuswallichiana*. This approach could lead to the discovery of novel bioactive compounds and nanoparticle-based drug delivery systems that are safer and more effective compared to conventional synthetic nanoparticles.

Innovative applications in medicine

The biomedical applications of plant-derived nanoparticles are wide-ranging and multifaceted. The properties of nanoparticles, such as their small size, high surface-to-volume ratio, and ability to functionalize surfaces, make them ideal candidates for use in drug delivery, imaging, diagnostics, and therapeutic interventions. One of the most promising applications is the targeted delivery of anticancer drugs using plant-based nanoparticles. The ability of nanoparticles to pass through biological barriers and specifically target tumor cells makes them invaluable tools in cancer therapy. In addition to cancer treatment, plant-based nanoparticles have demonstrated significant antimicrobial activity, which is beneficial for treating infections caused by resistant strains of bacteria and fungi. The biocompatibility and low toxicity of these nanoparticles make them safe for use in clinical applications, further supporting their role in modern medicine [12]. Furthermore, the use of plant-derived nanoparticles in tissue engineering and regenerative medicine is gaining attention. The inherent biocompatibility and biodegradability of plant-based nanoparticles ensure that they can be safely incorporated into scaffolds and biomaterials, promoting cell growth and tissue regeneration. For example, AgNPs synthesized from *Taxuswallichiana* have shown potential in accelerating wound healing and promoting the regeneration of damaged tissues.

Examples of green synthesis of nanoparticles from plant parts and their biomedical applications

The green synthesis of nanoparticles (NPs) using plant parts has been explored extensively for its therapeutic potential. Below, we present several examples that highlight the versatility and effectiveness of plant-derived nanoparticles in various biomedical applications:

a) *Taxuswallichiana*: *Silver nanoparticles for antibacterial and anticancer properties*

Taxuswallichiana, known for its medicinal uses, particularly in high-altitude regions, has been successfully used for the green synthesis of silver nanoparticles (AgNPs). These AgNPs demonstrated potent antibacterial activity against *E. coli* and *S. aureus* and exhibited significant anticancer potential by inhibiting the proliferation of MCF-7 cancer cells. The study by Singh *et al.* [13] highlighted the dual therapeutic potential of AgNPs synthesized from *Taxuswallichiana*, establishing their applicability in both antimicrobial and anticancer treatments.

b) *Coriandrumsativum*: *Silver nanoparticles for antibacterial, antifungal, and anticancer activities*

In a different study, *Coriandrumsativum*(coriander) extract was used for the green synthesis of AgNPs. These

nanoparticles exhibited broad-spectrum antimicrobial properties, showing effectiveness against both bacterial and fungal pathogens. In addition to antimicrobial activity, the AgNPs demonstrated selective cytotoxicity against cancer cell lines, making them promising candidates for targeted cancer therapy. Jain *et al*. [14] noted that the synthesized nanoparticles showed enhanced therapeutic potential due to their ability to selectively target cancerous cells while sparing healthy tissues.

c) *Azadirachtaindica*: *Gold nanoparticles for cancer treatment and drug delivery*

The green synthesis of gold nanoparticles (AuNPs) using *Azadirachtaindica* (neem) extract has shown significant promise in the field of cancer therapy and drug delivery. Gold nanoparticles derived from neem were loaded with anticancer drugs and tested against cervical cancer cells. The results indicated enhanced drug delivery and targeted cancer treatment, with reduced toxicity to healthy cells. This approach exemplifies the potential of plant-derived AuNPs as efficient drug carriers in cancer therapies [15].

d) *Allium sativum*: *Copper nanoparticles for antimicrobial applications*

Allium sativum(garlic) has been widely used for its medicinal properties, and researchers have utilized it for the green synthesis of copper nanoparticles (CuNPs). The resulting CuNPs displayed significant antibacterial and antifungal properties, particularly against pathogens such as Candida albicans and Staphylococcus aureus. These CuNPs have the potential to be used in the treatment of infections, especially in the face of growing antimicrobial resistance. Ruparelia *et al*. [16] demonstrated that garlic-derived CuNPs could enhance the efficacy of traditional antibiotics, providing an alternative approach to combating resistant infections. These examples illustrate the broad applications of plant-based nanoparticles in medicine, ranging from antibacterial and antifungal treatments to anticancer drug delivery systems. The green synthesis approach not only offers an environmentally friendly method but also ensures the production of biocompatible and effective nanoparticles for a variety of therapeutic purposes.

Future prospects of green synthesis of nanoparticles in medicine

The green synthesis of nanoparticles using plant parts is a promising and rapidly advancing field in nanobiotechnology. With the growing emphasis on sustainability and environmental considerations, plant-mediated synthesis offers a safe, cost-effective, and eco-friendly alternative to traditional methods that often rely on toxic chemicals and high-energy processes. As research progresses, there is increasing potential to expand the applications of plant-derived nanoparticles in various biomedical fields, particularly in drug delivery, cancer therapy, wound healing, and antimicrobial treatments. Future studies are expected to focus on optimizing the synthesis processes for greater control over nanoparticle size, shape, and surface properties, all of which play a critical role in their biological activities and therapeutic efficacy. Moreover, the integration of nanomedicine with personalized healthcare will open new avenues for the design of tailored therapies. The use of plant-based nanoparticles to enhance the bioavailability of drugs, minimize side effects, and achieve targeted delivery to specific tissues or cells represents a major leap forward in therapeutic strategies. In addition, with growing concerns regarding antimicrobial resistance, the development of nanoparticle-based treatments for infections could become a crucial part of modern medicine. The potential for multi-functional nanoparticles that combine antimicrobial and anticancer properties is a promising direction for future research. For future advancements, further exploration into the environmental impact and biocompatibility of plant-derived nanoparticles will be essential. Detailed in vivo studies, clinical trials, and regulatory approvals will play a key role in translating laboratory successes into practical, real-world applications. In summary, the future of plant-mediated nanoparticle synthesis holds immense promise for revolutionizing modern medicine, offering sustainable solutions for disease prevention and treatment while aligning with global efforts toward greener, safer technologies.

CONCLUSION

The green synthesis of nanoparticles using plant parts represents a revolutionary approach in the field of nanobiotechnology, aligning with the growing demand for environmentally friendly and sustainable technologies in medicine. Plant-derived nanoparticles have demonstrated considerable potential in various biomedical applications, including antimicrobial, anticancer, and drug delivery systems. The ability to leverage the natural properties of plant extracts for nanoparticle synthesis not only provides a cost-effective alternative to conventional chemical methods but also ensures biocompatibility and minimizes toxicity, making them ideal candidates for therapeutic use. Throughout this review, we have highlighted the versatility of plant-mediated nanoparticles, with examples from a range of plant species such as *Taxuswallichiana*, *Coriandrumsativum*, *Azadirachtaindica*, and *Allium sativum*. These case studies underscore the promising potential of plant-based nanomaterials in addressing current challenges in medicine, particularly in the areas of infection control, cancer therapy, and drug delivery. While the green synthesis approach has proven effective in laboratory studies, further research is needed to optimize the synthesis processes, standardize methodologies, and explore the long-term effects and safety of these nanoparticles in clinical settings. The future of plant-mediated nanoparticle synthesis holds immense promise, with the potential to revolutionize medical treatments by combining the efficacy of nanotechnology with the sustainability of plant resources. However, robust clinical trials and regulatory approvals will be essential to fully realize the therapeutic potential of plant-derived nanoparticles in real-world medical applications. In conclusion, the integration of plant-based green synthesis into modern medicine not only offers a sustainable and effective approach to the development of novel therapeutic agents but also paves the way for the next generation of nanomedicines that are both biocompatible and environmentally responsible.

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