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Green Nanotechnology: Role of Medicinal Plants in the Eco-Friendly Synthesis of Functional Nanoparticles

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ABSTRACT

Green-synthesized nanoparticles (GSNPs) are green, sustainable, and biocompatible nanomaterials that combine the concepts of nanotechnology and green chemistry. Plant-based bioactive compounds are used to produce nanoparticles because they reduce toxic reagents and enhance environmental safety. The review is a broad discussion of the biological synthesis-based processes with emphasis on the role of phytochemicals, including flavonoids, terpenoids, and phenolics, in the reduction, stabilization, and capping of nanoparticles. In addition, it talks about the criteria used to select medicinal plants, focusing on the diversity of bioactive compounds, availability, sustainability, and the traditional therapeutic worth of the medicinal plants. Another aspect that is highlighted in the paper is the structure-function relationships of phytochemicals and how they affect nanoparticle size, morphology, and stability. The current developments in comprehending the biomedical, antimicrobial, and therapeutic uses of GSNPs are discussed, and their possible limitations and future opportunities are examined. Overall, the above review highlights the potential of green-synthesized nanoparticles as environmentally-friendly, cost-efficient and all-purpose nanoparticles, which can be utilized across medicine, agriculture, and environmental remediation.

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Introduction

Nanotechnology is now being developed as a multidisciplinary branch that combines ideas in chemistry, biology, physics, and materials science to produce nanoscale materials exhibiting restricted properties. Nanoparticles (NPs) are materials with a size between 1-100 nm with unusual physicochemical and biological properties, such as a high surface area and high reactivity, and tunable optical and electrical properties. These characteristics allow their multiple use in the field of medicine, agriculture, energy, and environmental cleanup (Chauhan et al., 2020).

Traditional ways of producing nanoparticles, like physical and chemical processes, usually use dangerous reagents, high energy, and toxic byproducts and endanger people and the environment (Agarwal et al., 2017). A solution to these issues has been proposed in the creation of a green synthesis, which is sustainable, economical, and environmentally friendly. This method adopts the use of biological organisms like plants, bacteria, fungi, and algae in the production of nanoparticles under mild reaction conditions (Iravani, 2011).

Plants, in particular, are viewed as an especially promising biological system to use in the synthesis of nanoparticles, since they have a highly abundant source of bioactive biomolecules, such as flavonoids, terpenoids, alkaloids, phenolics, and proteins that are natural reducing or stabilizing agents (Mittal et al., 2013). The phytochemicals that are contained in plants not only help in lowering metal ions, but they also serve to stabilize the synthesized nanoparticles, to avoid the aggregation of the nanoparticles. Besides, plant-mediated nanoparticles are more biocompatible and have a greater therapeutic potential, combining the pharmacological effects of medicinal plants with the benefits of nanotechnology (Kumar et al., 2019).

Combining the notion of nanotechnology with those of green chemistry, therefore, offers a good platform on which to emerge with promising functional nanomaterials that are safe, efficient and sustainable In this review, the author has discussed the processes involved in plant-mediated syntheses of nanoparticles, the activity of various phytochemicals and the selection of an appropriate medicinal plant and how phytochemical structure relates to the activity of nanoparticles. Moreover, it brings into focus the biomedical applications, existing problems and future of the green synthesized nanoparticles.

Mechanisms of Nanoparticle Formation

Plant extracts have complex yet efficacious biosynthesis of nanoparticles, which entail the reduction of metallic ions by diverse phytochemical components. Bioactive compounds that are abundant in medicinal plants can act as natural reducing, capping and stabilizing agents; transforming metal ions into stable nanoparticles in mild and eco-friendly conditions. The entire process is based on the nature and concentration of the phytochemicals, the metal precursor employed and environmental parameters like pH, temperature and reaction time.

Types of Phytochemicals

Phytochemicals have also been used in the fundamental processes of the green

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synthesis of nanoparticles in the reduction and stabilization reactions. Flavonoids are also known to be good antioxidants as well as reducing and stabilizing agents in the synthesis of nanoparticles. They give out electrons to the metal ions, which makes it easier to reduce them to nanoparticles. The terpenoids are involved in lowering metal salts to nanoparticles and also in stabilizing them so that they do not form aggregates. The phenolic compounds also present functional groups that are capable of being present and interacting with the metal ions, therefore contributing to the formation and stability of the nanoparticles. Their formation and heterogeneity to a greater extent determine the morphology, size, and uniformity of the formed nanoparticles.

Mechanisms of Nanoparticle Formation

The phytochemicals found in the herbs are natural reducer agents and convert the metal ions into nanoparticles. They can also be applied to stabilization in the capping of the nanoparticles and avoiding agglomeration and equal distribution of the particles (Ilavenil et al., 2025; Singh et al., 2023). The connection of phytochemicals and metal ions in most cases results in the creation of nanostructures that have their own physicochemical characteristics. As an example, phenolic and protein help in complexation and further stabilization processes and lead to relatively longer life of nanoparticles, as well as better functional possibilities.

Structure–Function Relationships

The structure of phytochemicals has a direct relationship with the reactivity of metal ions with phytochemicals. Hydroxyl and carbonyl functional groups are functional groups of an important role in metal ion reduction and stabilization of nanoparticles. Moreover, such functional groups of space and density influence the size, morphology, and stability of the products of the produced nanoparticles. The listed points prove the importance of the molecular structure of phytochemicals in regulating the production of nanoparticles and their further characteristics (Singh et al., 2023; Jeevanandam et al., 2022).

Selection Criteria for Medicinal Plants

The efficiency and stability of the nanomaterials as well as the biological activity is dependent on the appropriate selection of medicinal plants to be used for the production of nanoparticles. This choice is determined by a number of factors such as bioactive chemical makeup, accessibility, sustainability, as well traditional methods of therapeutic applications.

Bioactive Compound Profile

Plant materials with high concentration of bioactive compounds such as flavonoids, terpenoids and phenolics are the most sought ones in the synthesis of nanoparticles. These phytochemicals are good reducing, capping and stabilising agents to induce a controlled formation of nanoparticles. The concentration and the diversity of these bioactive molecules are directly connected with the efficiency and the repeatability of the synthesis process which, in the end, will influence the physicochemical characteristics of the nanoparticles (Alharbi et al., 2022).

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Availability and Sustainability Considerations

For green synthesis to be a sustainable and environment friendly process, the plants or plants of choice should be sustainable for harvesting and easily available. The facilities that grow or grow in a large number easily are good, as they ensure that the use of plants is economically feasible as well as environmentally friendly. Sustainable harvesting also reduces the ecological footprint of synthesis process and the process is also governed by the principles of green chemistry (Jasemi et al., 2020).

Traditional Medicinal Uses and Potential Synergies

The use of medicinal plants which are traditionally used for therapeutic purpose is of special advantage for the synthesis of nanoparticles. The nanoparticles which are present in such plants tend to have naturally biologic activities, which indicate the pharmacological applications of the parent plant. The traditional medicine and the nanotechnology are synergistic which strengthens the therapeutic ability of the nanoparticles including antimicrobial, antioxidant and anticancer ability (Arya et al., 2022; Giordano et al., 2021).

The intrinsic pharmacological significance of the nanoparticles of medicinal plants used in synthesizing nanoparticles, other than offering a sustainable and environmental-friendly means of manufacturing nanomaterials, also imparts intrinsic pharmacological importance of the same to the nanoparticles. This could present an enormous possibility of the use of this measurement in a number of medical, agricultural and environmental remediation applications to lead to the production of the next generation of nanomaterials that are both functional and biocompatible.

Biomedical and Therapeutic Applications of Green-Synthesized Nanoparticles

The special physicochemical characteristics, biocompatibility and innate bioactivity have led to the high potential of green-synthesized nanoparticles extracted using medicinal plants in biomedical applications. These are antimicrobial therapy, anticancer therapy, drug delivery, theranostics and tissue engineering.

Antimicrobial and Anticancer Activities

Nanoparticles using plant-mediated green synthesis have strong antimicrobial effects and are effective against many different pathogens (pathogenic bacteria, fungi, including resistant strains). Their mechanism of action may include the production of reactive oxygen species (ROS), the attack on the cell walls of the microbial species and the inhibition of metabolic pathways, which add up to antimicrobial inhibition or death of the microbial species (Singh and Nalwa, 2011).

In cancer treatment, important treatment is done by nanoparticles like gold and silver in targeted drug delivery and treatment upgrade. The targeted delivery of anticancer agents to the tumor locations is also facilitated by these nanoparticles, which will reduce homogeneous toxicity and increase the impact of the drug. These nanoparticles have a small size, which enhances their uptake into the cells and enables them to perform a site-specific therapeutic action due to their large surface area and surface functionalization capabilities (El-Meligy et al., 2024).

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Drug Delivery Systems and Theranostics

Nanoparticles manufactured through green technology are part of the development of advanced vehicles with specific drug delivery in an organized manner. The therapeutic molecules to be delivered then, can be carried to the target site, and the off-target effects can be eliminated and minimized due to the surface modification and functionalization of these nanoparticles (Siddique and Chow, 2020; Lohcharoenkal et al., 2014).

The Theranostics is applied in the form of one application consisting both of therapy and diagnostics. With nanoparticles, it is possible to have a mixture of drug delivery and real-time imaging, which allows clinicians to monitor the response to drug treatment and change her drug delivery approaches. This type of dual functionality is especially useful in the processes of cancer control and precision medicine (Siddique and Chow, 2020).

Tissue Engineering and Regenerative Medicine

Nanoparticles make a contribution to tissue engineering as a scaffolding material in order to support cell adherence, proliferation and differentiation. Their addition in biomaterials enhances their mechanical and biological properties of scaffolds, which helps regenerating/repairing tissues. These applications range in application to wound healing, bone regeneration and organ engineering, as it shows the versatility of the plant-derived nanoparticles in regenerative medicine (Siddique and Chow, 2020).

Environmental Applications of Green-Synthesized Nanoparticles

Green-synthesized nanoparticles have shown an increasing use in environmental remediation applications due to their huge surface areas, activity and environmental friendly synthesis processes. Their applications are in water purification, the soil remediation industry, agricultural enhancement and biosensing in environmental monitoring.

Water Purification and Pollutant Degradation

Nanoparticles improve the cleaning up of water with contaminants, including heavy metals, dyes & organic pollutants. The large surface to volume too predisposes them towards adsorption process whereas the catalytic activity leads to decomposition of hazardous substances (Venkateshaiah et al., 2022; Khin et al., 2012).

Zero-valent iron nanoparticles (nZVI), for example, have been successfully used for the detoxification of chlorinated organic compounds and thus passed the potential for industrial scale wastewater treatment (Monga et al., 2020). The green synthesis of such nanoparticles ensures they have a minimal effect on the environment while they are being produced, hence they are sustainable alternatives to the traditional chemical remediation techniques.

Soil Remediation and Agricultural Applications

Plant-mediated nanoparticles support the soil life while they degrade toxic substances as well as enhancing the soil nutrient availability. Additionally, they find use in nano

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enabled fertilizers, which aid in the effectiveness of nutrient uptake and prevent the overuse of chemicals. Such applications not only improve the productivity of the crop but also reduces environmental pollution by the usage of fertilizers in traditional methods (Das et al., 2019).

Biosensors for Environmental Monitoring

Nanoparticle-enabled biosensors are superior to the current biosensors in terms of sensitivity and responsiveness to detection of environmental pollutants. Their ability to detect low levels of contaminants, such as heavy metals or organic toxins, can provide opportunity to monitor the environment in real-time and simple to conduct, rapid intervention measures (Andreescu et al., 2009).

By the combination of high reactivity and environment benign synthesis, the green-synthesized nanoparticles offer versatile solutions for sustainable environment management and monitoring.

Industrial and Technological Applications of Green-Synthesized Nanoparticles

The uses of the nanoparticle synthesized in green has shown amazing acceptance in many of the industries and technological applications and especially for catalysis and energy conversion applications, electronics/opto-electronics and smart materials. They have a peculiar physicochemical behavior, their chemistry and functionality is ecology friendly, being this one of the points of utmost value by industrial uses of the present century.

Catalysis and Energy Conversion

Nanoparticles are also taking the centre stage in the improvement of the catalytic processes since they have a high surface area and reactivity. They are faster chemical reactions that reduce energy requirements and efficiency, and favor green industrial processes. As an example, the electrosynthesis methods with nanoparticles have been embraced to minimize the level of carbon emissions in the petrochemical sector as compared to conventional thermochemical approaches (Xia et al., 2022).

The nanoparticles are important products in high-tech batteries and fuel cells in energy applications. Catalytic activity in electrochemical reactions can be improved by them and contributes to the growth of energy storage and conversion as a part of the solution to the creation of sustainable energy systems with low carbon levels (Xia et al., 2022).

Electronics and Optoelectronics

Nanoparticles contribute to the improved activity of electronic and optoelectronic devices because of their tunable electronic and optical properties. They are used in advanced sensors for industrial and environmental sensors that provide better sensitivity and high response time (Massaro, 2023).

Integration with Industry 5.0 concepts regarding the application of AI-powered analytics in conjunction with nanoparticle-based sensors to optimise manufacturing processes, and in doing so, to enable adaptive, self-learning systems that provide improved efficiency and reliability of the manufacturing process (Massaro, 2023).

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Smart Materials and Coatings

Nanoparticles are used in smart materials and coatings that are sensitive to dynamic environmental stimuli. Some of the applications include self-healing surfaces, protective coatings, and materials with increased durability. Additive manufacturing (3D printing) Material benefits from nanoparticles incorporation, it is allows the realise of complex, customizable components with a minimum of waste, and to comply with sustainable manufacturing practices (Fidan et al., 2024).

The innovations can be encountered in areas like the automatics, aerospace and electronics industries, which have revealed the transformative nature of the green synthesis nanoparticles in the current industrial and technological developments.

Challenges and Future Perspectives

Nonetheless, the issue of green synthesis of nanoparticles has its own problems, even in spite of significant progress in the area. To overcome these limitations, it is essential to explore industrial applications and as many environmental and biomedical advantages of these nanoparticles as possible.

Current Limitations

Scalability and Reproducibility

The large scale in the process of green synthesis is a bigger challenge as far as it is quite difficult to do the same in the lab and then the same on an industrial scale. Diversity of the biological sources, like the difference in the concentration of phytochemicals, may lead to variation in the size, shape, and functions of the nanoparticles. Limestone cannot be used in large-scale applications (Zaragosa et al., 2024).

Mechanistic Understanding

A lack of mechanistic knowledge of plant-mediated manufacturing of nanoparticles prevents optimization and process control. Phytochemical interactions with metal ions can be elucidated in depth in order to reliably engineer nanoparticles for particular applications (Tran et al., 2024; El-Seedi et al., 2024).

Standardization and Quality Control

Lack of standardized protocols and variability from batch to batch a challenge in the quality control scope. Establishing stringent requirements of characterization and synthesis referred to reproducible role playing as green-synthesized nanoparticles for the integrated specification in the mainstream site applications within biomedical and industrial practice is one facet to confirm the habitability of requirements of the standardization of the technologies (Fahim et al., 2024).

Emerging Trends

Integration with Other Green Technologies

Emerging approaches involve waste-derived materials as raw materials, the principles of the circular economy and maximizing the efficiency of resources. Such approaches

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are in place to increase sustainability and economic viability in the production of nanoparticles (Abdelbasir et al., 2020).

Artificial Intelligence (AI) in Nanoparticle Design

AI and machine learning provide powerful means for optimization of synthesis conditions, prediction of the properties of nanoparticles and for reproducibility. Using complex experimental datasets, AI can be used to accelerate the discovery and scale-up of green-synthesized nanoparticles (Chandrasekar et al., 2025).

Circular Economy Approaches

Circular economy models are used to emphasize the reuse of waste and materials. These principles also have a lesser effect on the environment when applied in the production of nanoparticles, which helps to establish a sustainable environment and helps to achieve world sustainability goals (Michailidu et al., 2024).

Future Research Directions

In the future, the study of green synthesis of nanoparticles will reveal a number of new sources, enhance the functionality of the nanoparticles, and resolve safety and regulatory problems. These directions are both biomedical and environmental in nature, with sustainable practices being encouraged.

Exploring New Medicinal Plant Sources

Diverse Phytochemical Reservoirs

Given that phytochemicals are natural reducing and stabilising agents, medicinal plants provide an abundant source of phytochemicals. These substances are inclined to give the nanoparticles certain physicochemical characteristics that enhance their bioactivity and therapeutic characteristics. The exploration of the underutilized or endemic plant species has a chance of revealing the new nanoparticles that have superior pharmacological character and extended application opportunities (Ahmed et al. 2019; Alharbi et al. 2022).

Enhancing Functionality and Targeting Capabilities

Targeted Drug Delivery

Further applications are directed towards the enhancement of nanoparticle targeting based on surface modification and functionalization. Delivery of nanoparticles to specific cells, e.g., cancerous tissues, can be facilitated by conjugation of nanoparticles to ligands, antibodies or other targeting moieties, thus reducing off-target effects and minimizing the required treatment. Gold nanoparticles that were mediated by plants, such as demonstrated good outcomes in targeted cancer therapy that is targeted (Nisha et al., 2024).

Multifunctional Coatings

Another important trend is the development of multifunctional nanoparticles. These can have anticancer and antimicrobial as well as antioxidant activity, as well as the capacity to deliver several drugs or diagnostic agents at the same time. The promotion in this respect will enhance the diversity of green-synthesized nanoparticles in medicine and the environment (Kartini et al., 2020).

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Addressing Safety and Regulatory Concerns

Biosafety and Biocompatibility

A major issue is the safety of the green-synthesized nanoparticles. There are systematic studies required in the field of cytotoxicity, biodistribution, as well as long-term effects. Unified quality safety assessment standards will minimize the regulatory approval barriers and safe incorporation into clinical and industrial applications (Alharbi et al., 2022).

Regulatory Frameworks

Robust regulation frameworks are necessary in order to homogenize the methods of green synthesis and the quality. Guidelines need to cover the unique characteristics, production methods and the application of the green synthesized nanoparticles to ensure their safe and effective use in the biomedical, environmental and industrial sectors (Dagmawy, [year]).

Conclusion

Nanoparticles synthesized green are a sustainable and multi-purpose approach to nanotechnology and the integration of the principles of green chemistry and biomimetic strategies, and environmentally friendly materials. The use of medicinal plants plays a crucial role in the quality of bioactive compounds that enable the formation of nanoparticles with improved stability, pharmacological and biocompatibility. Not only does the application of the plant-derived phytochemicals reduce the number of toxic chemicals that are applied, but they also provide an inbuilt biological functionality which opens applications in medicine, environmental remediation and agriculture.

The improved synthesis methods have used aqueous methods of extraction, microwave-assisted and sonochemical methods in addition to a strict protocol of characterization and has lead to an improved control in size, morphology and surface characteristics of the nanoparticles. A combination of these developments and standardized quality control of the technology enable reproducibility and scalability, which are required in the industrial and clinical applications of translation.

Although these advances have been made, the challenges that remain are the lack of mechanistic knowledge, biological variability and regulatory problems. The prospective research on the unexamined medicinal plants, the design and targeted delivery of the nanoparticles, the safe and effective analysis will play an important role in the development of green nanotechnology. Through these hindrances the green synthesized nanoparticles can play a role in sustainable development, novel therapeutics and sustainable industrial ICs.

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