

Original Article

PLANT-BASED GREEN NANOTECHNOLOGY: ADVANCES IN THE BIOSYNTHESIS, CHARACTERIZATION, AND BIOLOGICAL APPLICATIONS OF NANOMATERIALS

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ABSTRACT

Nanotechnology has developed very rapidly and has had a great impact on a number of sciences, in particular biomedicine, agriculture and environmental remediation. The production of nanomaterials by traditional techniques relies on physical and chemical procedures that are efficient but use toxic reducing agents, produce toxic by-products and need large amount of energy. Over the last few years, plant-based green nanotechnology has been identified as a revolutionary, eco-friendly and sustainable alternative to these traditional techniques. Plant extracts including flavonoids, polyphenols, terpenoids, and alkaloids exhibit an extensive phytochemical diversity, which enables scientists to efficiently reduce metal ions and stabilize the generated nanoparticles simultaneously through an environmentally friendly process. This peer-reviewed article reviews comprehensively the recent progress in the biosynthesis of plant-mediated nanomaterials, especially metallic and metal oxide nanoparticles including silver, gold, copper and zinc oxide. It also gives detailed information on the essential techniques used to characterize nanoparticles in terms of their shape, size and structure such as UV-Vis, FTIR, XRD and SEM. Note that this review extensively discusses the biological uses of these biogenic nanoparticles with special focus on their potential antimicrobial, anticancer, antioxidant and targeted drug delivery capabilities. This paper reveals the revolutionary potential of plant-based green nanotechnology in modern science by integrating fundamental mechanisms and practical applications and addressing the current challenges in scalability and standardization.

Keywords: Green Nanotechnology, Biosynthesis, Nanomaterials, Phytochemistry, Characterization, Biological Applications, Nanomedicine

INTRODUCTION

Nanotechnology is an interdisciplinary science. It is concerned with the synthesis, characterization and application of materials at the nano scale, usually in the range 1 to 100 nanometers. Materials at this size have very different physicochemical properties compared to bulk materials such as higher surface area to volume ratios, increased reactivity and unique optical and magnetic properties [Samuel et al. \(2022\)](#). These novel properties have motivated lots of research interest on the applications of nanomaterials in bio-medicine, electronics, agriculture and environmental engineering.

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In a broad sense, the synthesis of nanomaterials is categorized into top-down and bottom-up approaches. The top-down approach is a mechanical degradation of bulk materials into nano-sized particles using methods such as milling, lithography and laser ablation. The bottom-up approach, however, is based on the construction of nanoparticles from atoms or molecules by chemical reduction, sol-gel processes or vapor deposition. Bottom-up chemical approaches can be used to prepare nanoparticles and are very efficient, allowing the synthesis of nanoparticles with a tunable size. But mostly they use toxic chemicals as reducing agents like sodium borohydride or hydrazine hydrate. Furthermore, traditional methods generate toxic byproducts that are damaging to the environment and biology and limit their in vivo use for clinical and biomedical purposes.

These pressing environmental and safety issues have accelerated the emergence of green nanotechnology as a sustainable, biocompatible and cost-effective alternative. The green synthesis is performed rigorously in accordance with the principles of green chemistry such as the use of eco-friendly solvents, non-toxic reducing agents and energy-efficient processes [Mukherjee et al. \(2021\)](#). In this sense, biological systems such as bacteria, fungi, yeast, algae and plants can be regarded as natural “nanofactories”. The plant mediated synthesis or the phytosynthesis has gained an unparalleled attention because it completely avoids the biohazards associated with the microbial cultures, avoids the complicated processes of maintaining the cell cultures and provides a rapid one step protocol for the fabrication of the nanoparticles [Morgan and Aboshanab \(2024\)](#).

Leaves, stems, roots, flowers and fruits of the plant produce extracts very rich in bioactive phytochemicals. These primary and secondary metabolites include polyphenols, flavonoids, alkaloids, terpenoids and proteins which act as powerful reducing agents to reduce the metal ions to zero-valent nanoclusters and as stabilizing capping agents to prevent their agglomeration [Dash et al. \(2021\)](#). The biogenic nanoparticles synthesized exhibited excellent biocompatibility, high stability and high biological activity and can be considered as promising candidates for advanced therapeutic applications.

The review article discusses the complexity of the mechanisms of green nanotechnology based on plants. In this work, we critically review the different classes of biogenic nanomaterials and analyze the analytical techniques for their characterization, emphasizing their significant impact on biological applications with special emphasis on their antimicrobial, anticancer and nano pharmacological potential.

MECHANISM OF PLANT-BASED BIOSYNTHESIS

Preparation of metallic nanoparticles from plant extracts has mainly been achieved by reduction-oxidation (redox) process. The addition of a metal precursor salt (e.g. silver nitrate or auric acid) to an aqueous plant extract results in the bioreduction of the metal cations in solution to a stable zero-valent metallic state. This change is actively induced by the complex of phytochemicals found in the botanical extract.

Phytochemicals are broadly classified based on their chemical structure and each class has a unique mechanistic role in the nucleation and stabilization of nanoparticles. Polyphenols and phenolic acids (gallic, caffeic and ellagic acids) are among the most potent reducing agents, since they can donate electrons very well. The redox potential of hydroxyl and carboxyl groups is proportional to the number and position of the groups. In synthesis these hydroxyl groups are oxidized to quinones, at the same time reducing the metal ions, and initiating the nucleation of the metal atoms.

Flavonoids are another important group of biomolecules in green synthesis. They are a major subgroup of polyphenols (e.g. quercetin, luteolin and rutin). The unique carbon framework of flavonoids is renowned for superb metal chelation properties. The flavonoids are good reducers of metal cations with electron donation and hydrogen abstraction (often assisted by keto-enol tautomerism). Mechanistic models suggest that flavonoids form stable intermediate complexes with metal ions before oxidation and are retained on the surface of the newly formed nanoparticle as an efficient capping agent preventing aggregation.

Terpenoids are a large and structurally diverse group of secondary metabolites built from isoprene units. The extracts rich in terpenoids contain different functional groups, e.g. aldehydes, alcohols and carboxylic acids, which are very active in redox reactions. In particular the oxidation of terpenoid alcohol groups to carbonyl derivatives is often coupled to electron transfer required for reduction of metallic ions. Moreover, the intrinsically bulky and highly hydrophobic nature of terpenoids offers superb sterics hindrance around the nucleating particles, and consequently, acts as highly efficient steric stabilizers that define the final morphological profile of the nanomaterials.

Plant-derived amino acids, alkaloids and proteins are also critical for stabilizing the nanoparticles. Amino acids with special types of side chains (thiol group in cysteine or amine groups etc.) have huge binding affinity toward metallic surfaces. They form intricate organic coronas around the nanoparticles, protecting them from the surrounding aqueous environment. This avoids flocculation and significantly improves the biocompatibility of the obtained nanostructures.

Figure 1

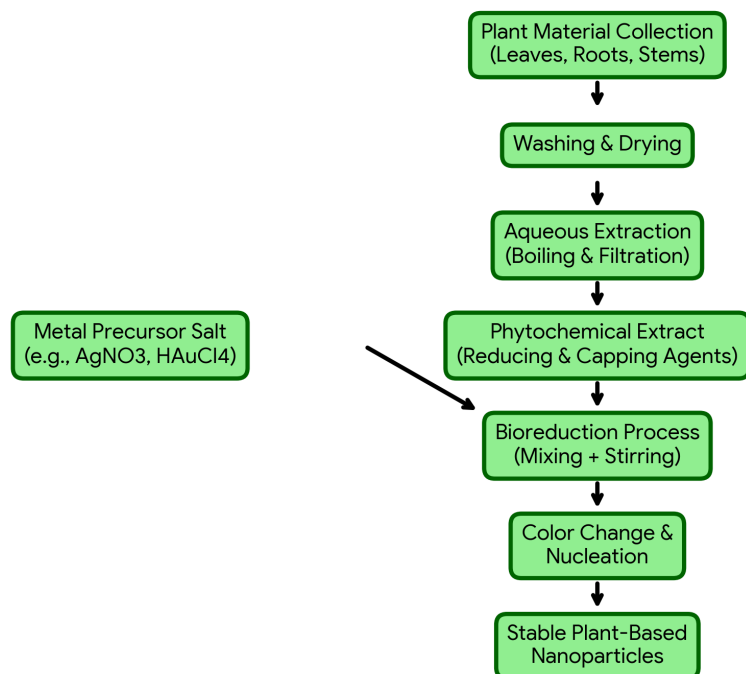


Figure 1 Schematic Workflow of Plant-Mediated Green Synthesis

TYPES OF BIOGENIC NANOMATERIALS SYNTHESIZED

Different plant products can be used for the preparation of metal and metal oxide nanoparticles. The physicochemical properties of these nanoparticles can be modified by changing parameters like temperature, pH of the reaction mixture, extraction parameters and stoichiometric ratio of metal salt and plant extract.

Biogenic silver nanoparticles (AgNPs): These are the most studied nanomaterials in green nanotechnology due to their great potential to kill a broad spectrum of microbes. The plant mediated biosynthesis of AgNPs is very rapid and can be easily monitored by the change in color of the reaction mixture from light yellow to dark colloidal brown by the excitation of surface plasmon resonance (SPR). The root extract of *Stephania abyssinica* was efficiently used for the reduction of silver nitrate into stable AgNPs which were highly efficient in killing both Gram positive and Gram-negative bacteria for example (Gebenehu, n.d.). Similarly, Santhosh (n.d.) has reviewed AgNPs synthesized from different plant sources as multi-functional biosynthesis that can inhibit biological processes and promote plant growth.

Gold nanoparticles (AuNPs): These are of great importance in the biomedical field for their unique optical properties and non-cytotoxicity. This makes them useful for targeted delivery of drugs and also for the diagnosis of cancer. Plant extracts and AuNPs have been reported to possess excellent anticancer, antimicrobial and catalytic activities [Dash et al. \(2021\)](#). The process of producing pure gold from chloroauric acid (HAuCl₄) is called bioreduction. They also make gold nanoparticles of different shapes such as spheres, triangles and hexagons. [Ahmad et al. \(2024\)](#) prepared highly stable AuNPs using extract of *Aconitum violaceum*. This supports the hypothesis that plant chemicals may be used as useful capping and reducing agents for the synthesis of nanostructures homogeneously distributed and with huge therapeutic potential.

Biogenic ZnO: NPs are very useful metal oxide nanomaterials due to their high photo catalysis, UV filtering and anti-microbial properties. The green synthesis of ZnO nanoparticles is generally done by reduction of zinc acetate or zinc nitrate with the help of phytocompounds and heating at low temperature to make the structures very crystalline. [Fouda et al. \(2023\)](#) synthesized ZnO nanoparticles by using liquid extract of *Punica granatum*. The prepared nanoparticles also showed excellent killing of bacteria including dangerous bacteria such as *Pseudomonas aeruginosa* and *Staphylococcus aureus*. They degrade pollutants in the environment in different ways.

Cu/CuO NPs: copper and copper oxide nanoparticles. Copper based nanoparticles (NPs) are an attractive low-cost alternative to noble metals. They don't like fungus, bacteria and algae. Kothari in 2023 reported a rapid, inexpensive and biologically active route for synthesis of chemicals using biosynthesis of stable copper nanoparticles from cinnamon tree extract. [Antonio-Pérez et al. \(2023\)](#)

contributed to the list of medicinal plants for the synthesis of CuNPs which are very effective against free radicals, can be used for the treatment of advanced metabolic diseases and for the development of cardioprotective medicines.

Table 1

Table 1 Key Plant Sources, Synthesized Nanoparticles, and Applications			
Plant Extract	Nanoparticle	Phytochemical Role	Biological Application
Stephania abyssinica	Silver (Ag)	Reducing & stabilizing agent	Antimicrobial against E. coli & S. aureus
Aconitum violaceum	Gold (Au)	Alkaloids & flavonoids mediation	Antibacterial, antioxidant, photocatalysis
Punica granatum	Zinc Oxide (ZnO)	Polyphenol reduction	Antimicrobial & catalytic dye degradation
Cinnamon bark	Copper (Cu)	Tannins & glycosides capping	Antioxidant and biological inhibition
Algae species	Metal NPs	Metabolite bio-reduction	Cytotoxicity reduction & environmental remediation

CHARACTERIZATION TECHNIQUES

A series of advanced analytical characterization techniques are required for the correct identification of the physiochemical properties, structural integrity and biological effectiveness of plant-made nanomaterials. The three methods provide complementary information on size, shape and surface functionality of biogenic nanoparticles.

UV-Visible Spectroscopy (UV-Vis): UV-Vis spectroscopy is the most widely used technique to quickly demonstrate the formation of nanoparticles in real time. Metallic nanoparticles, especially gold and silver, have a characteristic optical effect called Surface Plasmon Resonance (SPR). This is a process of coherent movement of a group of free electrons in the conduction band by electromagnetic energy. The surface plasmon resonance (SPR) peak for silver nanoparticles is usually around 400 to 450 nm. Gold nanoparticles have SPR bands ranging from 500 to 550 nm. The exact size, shape and distribution of the nanoparticle corresponds directly with its wavelength, peak intensity and spectral bandwidth.

Fourier Transform Infrared Spectroscopy (FTIR): FTIR analysis is very important in green nanotechnology for identification of the exact biological groups involved in the reduction and later capping of nanoparticles. The FTIR method is based on the measurement of the amount of infrared radiation absorbed by the vibrational frequencies of the plant extract before and after the synthesis for different chemical bonds. Changes in specific peaks such as broad O-H stretch of phenolic compounds, disappearance or shifting of C=O stretch of flavanone carbonyl groups indicate that these biological components are actively participated and strongly bounded to the surface of nanoparticles. This is evidence of the effectiveness of the process of biomolecular stabilization.

X-Ray Diffraction (XRD): X-ray diffraction is a nondestructive method to identify the precise crystallographic structure, phase composition and inherent crystalline purity of synthesized nanomaterials. Bragg's Law explains how X-rays refract and scatter when they hit a solid nanoparticle. Intense (111) diffraction of face centered cubic silver and other characteristic diffraction peaks can be used to demonstrate that the particles are made of elements. The average crystallite domain size can also be obtained from the width of the dominant diffraction peaks using the Debye-Scherrer equation.

Electron Microscopy (SEM and TEM): Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) are used to study the architectural topography, morphological shapes and accurate physical size distribution of the nanoparticles. SEM employs a focused electron beam to scan the sample and generate high resolution three-dimensional topographic images of the groups of nanoparticles and surface textures. A TEM, however, passes electrons through a very thin sample matrix and the images have a resolution that is orders of magnitude higher. Very good to show the crystalline internal lattice fringes is the TEM. The changes in the shapes of nanoparticles such as spherical, rod-like or triangular can be clearly seen.

Zeta Potential & Dynamic Light Scattering (DLS): DLS measures the time dependent fluctuations in light scattering to determine the precise hydrodynamic diameter and size distribution profile of nanoparticles fully suspended in water. Zeta Potential is also a measure of the electrostatic strength of the electric charge on the shear plane of the nanoparticle. A high zeta potential (e.g. $> \pm 30$ mV) indicates a strong electrostatic repulsion between particles in close proximity to each other. This means that the particles are very stable and they will not stick together or agglomerate in the biological fluids.

BIOLOGICAL APPLICATIONS

The goal of green nanotechnology is to translate plant-mediated nanomaterials from the laboratory bench to clinical and commercial biological applications. Biogenic nanoparticles are inherently superior in their biological properties compared to chemically synthesized ones due to the capping with bioactive plant metabolites.

Antimicrobial & Antifungal Properties: One of the most reported applications of biogenic metallic nanoparticles is their excellent performance as broad-spectrum biocidal agents against highly resistant bacterial and fungal strains. Sure, the antimicrobial mechanism is multifactorial. The nanoparticles mainly release cytotoxic metallic ions (i.e. Ag⁺ or Zn²⁺) that electrostatically bind to the negatively charged microbial cell walls. This binding causes a violent disruption of membrane permeability leading to irreversible loss of important intracellular constituents. Generation of highly reactive Reactive Oxygen Species (ROS) such as hydroxyl radicals and superoxide anions also causes catastrophic oxidative stress in the microbial cell leading to destruction of DNA, denaturation of proteins and finally the cell death by apoptosis. For instance, the green synthesized ZnO NPs exhibited such ROS-dependent killing effect against resistant strains such as *Pseudomonas aeruginosa* [Fouda et al. \(2023\)](#).

Anti-Cancer Drug Delivery and Therapeutics: Plants synthesized gold and silver nanoparticles are emerging as the potential tools in today's oncology. Due to their ultra-small size, biocompatibility and high surface area, these nanoparticles are able to penetrate the highly permeable tumor vasculature via the enhanced permeability and retention (EPR) effect. They can be actively conjugated to particular ligands for cancer targeting, to chemotherapeutic agents or to particular antibodies. In many cases, the biogenic capping agents themselves have inherent anti-proliferative properties which in synergy with the core metallic nanoparticle induce targeted apoptosis in malignant cancer cells without lethal cytotoxicity in healthy, surrounding tissues. [Dash et al. \(2021\)](#) demonstrated that biogenic gold nanoparticles are highly effective for direct anticancer applications and as advanced nanomedicine delivery systems.

Anti-inflammatory and anti-oxidant activities: Many human diseases such as neurodegeneration and arthritis are caused by oxidative stress and chronic biological inflammation. Biogenic nanomaterials (especially those synthesized from antioxidant-rich extracts such as phenolics and flavonoids) are highly capable of scavenging radicals. The biological capped nanoparticles could neutralize the highly unstable free radical, greatly reduce oxidative damage to cells. Moreover, green nanoparticles have good anti-inflammatory property as reported by [Samuel et al. \(2022\)](#), where they can specifically control macrophage phenotype, efficiently suppress pro-inflammatory cytokines, and speed up tissue healing.

Agriculture & Environmental Rehabilitation: Biological nanomaterials are beyond direct human health and they are transforming agricultural science. They are carefully engineered into nano-fertilizers and nano-pesticides, leading to a substantial improvement of plant nutrient uptake, systematic stimulation of seed germination, and protection of crops against virulent fungal pathogens in negligible ecological footprints. Moreover, the biogenic nanoparticles (in particular ZnO and TiO₂) possess excellent photocatalytic properties and are extensively utilized in total environmental remediation. They possess great potential to degrade highly toxic industrial dyes rapidly, to remove heavy metal contaminants from wastewater and to break down agricultural chemical runoffs.

Figure 2

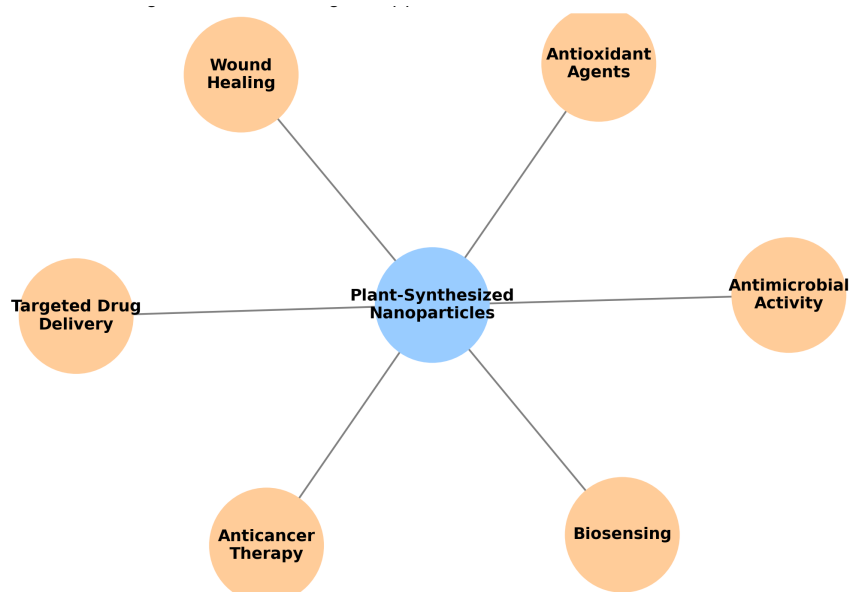


Figure 2 Broad Biological Applications of Green Nanomaterials

CHALLENGES AND FUTURE PERSPECTIVES

The phenomenal scientific leaps made by plant-based green nanotechnology are met with rigorous systemic challenges that heavily impede its swift transition into commercial scalability and global clinical utilization. The chief difficulty is biological

standardization. Plant extracts are naturally complex and variable, and their exact phytochemical composition depends largely on the plant's geographical location, season of harvest, and exact soil conditions. This extreme variability makes it very difficult to reproduce nanoparticle synthesis, giving rise to dramatically different nanoparticle sizes, different morphologies and wildly varying bioactivities between different batches.

Another daunting challenge is scaling up the biogenic synthesis process from small laboratory volumes to large industrial production. Extreme precision and continuous optimization of reaction thermodynamics are required to achieve tight control over the exact monodispersed and long-term stability of nanoparticles in multi-liter reactor scales. Moreover, a large, longitudinal study of the precise bio-kinetics, long-term cellular toxicity and environmental bio-accumulation of these green nanomaterials is absolutely imperative. Massively upscale comprehensive in vivo clinical trials are indispensable to delineate absolute safety profiles of these biogenic nano-agents prior to full approval for human medical applications by global regulatory agencies (e.g., FDA).

Future perspectives strongly require the full integration of artificial intelligence and advanced machine learning algorithms for optimization of green synthesis protocols. By mathematically modeling the precise biomolecular interactions between specific plant metabolites and inorganic metal precursors, scientists will eventually be able to custom design bespoke biogenic nanoparticles tailored for hyper-specific disease targeting, advanced environmental remediation and next-generation smart materials.

CONCLUSION

To summarize, plant-based green nanotechnology is indeed one of the most promising, sustainable and highly innovative frontiers of modern materials science. Scientists have elegantly utilized the rich and diverse phytochemical reservoirs inherent in plants to completely revolutionize the synthesis of highly stable, robust, and biologically active nanomaterials, perfectly circumventing the severe toxicological hazards strictly associated with conventional chemical fabrication methodologies.

Biogenic nanoparticles have demonstrated their absolute superiority as advanced functional materials by rigorous structural characterizations and phenomenal real-world demonstrations of antimicrobial, anticancer and environmental capabilities. Despite the severe limitations of total standardization and global industrial scalability, the present development of nano-biotechnology almost certainly guarantees that green-synthesized nanomaterials will revolutionize biomedicine, sustainable agriculture and advanced ecological engineering.

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