

Green Synthesis of Silver Nanoparticles Using Plant Extracts: A Sustainable Approach for Environmental Applications

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Abstract

The hunt for sustainable alternatives has been fuelled by the indiscriminate use of dangerous chemical reagents and energy-intensive physical processes in conventional nanoparticle manufacturing. Utilising phytochemicals including flavonoids, terpenoids, polyphenols, and alkaloids as natural reducing and capping agents, green production of silver nanoparticles (AgNPs) using plant extracts has become a straightforward, inexpensive, and environmentally safe method. The current knowledge of plant-mediated AgNP synthesis, the reaction parameters that control particle size, shape, and stability, and the analytical methods used to characterise them such as UV-visible spectroscopy, Fourier-transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), and electron microscopy (SEM/TEM) are all compiled in this review. Environmental applications, such as photocatalytic degradation of synthetic dyes, elimination and colorimetric detection of hazardous heavy metal ions, antimicrobial disinfection of contaminated water, and prospects in agricultural pest and pathogen management, are given special attention. The benefits of biogenic AgNPs over their chemically synthesised counterparts are examined, along with the ongoing issues of long-term ecotoxicological safety, standardisation, and reproducibility. The review concludes that, if synthesis protocols are optimised and toxicological profiles are thoroughly established prior to large-scale deployment, plant-mediated green synthesis represents a scalable and scientifically sound path toward sustainable nanotechnology for environmental remediation.

Keywords: *green synthesis; silver nanoparticles; plant extract; environmental remediation; photocatalysis; heavy metal removal; sustainability*

1. Introduction

Materials science has undergone a revolution thanks to nanotechnology, which has made it possible to create particles with sizes between 1 and 100 nanometres. At this scale, materials exhibit size- and shape-dependent optical, electrical, catalytic, and antimicrobial properties that are significantly different from those found in bulk. Because of their strong surface plasmon resonance, high surface-area-to-volume ratio, broad-spectrum antimicrobial action, and catalytic

versatility all of which support applications in medicine, agriculture, textiles, sensing, and environmental remediation silver nanoparticles (AgNPs) have garnered disproportionate scientific attention among the various metallic nanomaterials studied.

Physical techniques (such as laser ablation, heat evaporation, and sputtering) and chemical techniques (such as chemical reduction using sodium borohydride or citrate, electrochemical synthesis) are the two main categories of traditional strategies to AgNP production. Although these methods are successful in regulating particle size, they usually need large energy inputs, complex equipment, and hazardous reducing or capping chemicals whose residues remain on the surface of the nanoparticles and in the surrounding wastewater. The acceptability of chemically synthesised AgNPs for uses like water purification and wound care that are meant to directly interact with ecosystems or human health has been restricted due to the ensuing environmental and biological toxicity issues.

As a result, green synthesis also known as biogenic or biological synthesis has become a desirable alternative paradigm. It replaces hazardous chemical reagents with biological resources, most commonly plant extracts, but also bacteria, fungi, algae, and yeast, which supply the reducing and stabilizing biomolecules necessary to convert silver ions (Ag^+) from a soluble salt precursor, typically silver nitrate (AgNO_3), into stable, zero-valent silver nanoparticles (Ag^0). Plant-mediated synthesis is generally preferred over microbial routes because it avoids the need for aseptic culture maintenance, proceeds more rapidly, and can be performed at ambient temperature and pressure using inexpensive, widely available plant material such as leaves, fruit peels, seeds, roots, and flowers. Plant extracts' extensive phytochemical composition which includes flavonoids, terpenoids, phenolic acids, alkaloids, tannins, saponins, and ascorbic acid is responsible for their capacity to reduce. These molecules provide a dual reducing-capping role that is essential to the green synthesis mechanism: they give electrons to reduce Ag^+ to Ag^0 while also adhering to the surface of the nanoparticle to prevent agglomeration. The resultant AgNPs exhibit a broad range of sizes, shapes, and surface functions due to variations in the phytochemical profile among plant species, tissue types, and extraction conditions, providing a tunable platform for application-specific optimisation.

The existing literature on plant-mediated green synthesis of AgNPs is summarised in this review, with a focus on environmental applications. A thorough explanation of applications in dye degradation, heavy metal detection and removal, and water disinfection follows a description of

the synthesis mechanism, important reaction parameters, and conventional characterisation techniques. A critical evaluation of the benefits, drawbacks, and future research paths required to convert laboratory-scale green synthesis into scalable, ecologically conscious technology concludes the review.

2. Mechanism of Plant-Mediated Green Synthesis

Three steps make up the general process for plant-mediated AgNP synthesis: (i) preparation of the plant extract, usually by boiling or macerating fresh or dried plant material in distilled water or a mild solvent followed by filtration to remove particulate debris; (ii) reaction of the extract with an aqueous solution of silver nitrate under controlled conditions of temperature, pH, and reaction time; and (iii) confirmation of nanoparticle formation, typically indicated by a visible colour change of the reaction mixture from pale yellow to reddish-brown due to excitation of the surface plasmon resonance band of metallic silver.

Mechanistically, the process is thought to start with an activation phase when phytochemicals that donate electrons convert Ag^+ ions to Ag^0 atoms. After that, these atoms undergo nucleation to create tiny clusters, which then expand through the aggregation of nearby nuclei (a growth phase) until thermodynamically stable nanoparticles are created. Through hydroxyl, carbonyl, and amine functional groups, capping biomolecules concurrently attach to the surface of nanoparticles, preventing further development, adding colloidal stability, and lessening the likelihood of particles to agglomerate. The identical synthesis technique used to different plant species usually produce AgNPs with significantly varied size and form since reduction and capping happen simultaneously and are determined by the particular phytochemical cocktail contained in a given plant extract.

3. Factors Influencing Nanoparticle Formation

Optimising a number of reaction parameters is essential to repeatable green synthesis since it has been consistently demonstrated that these factors affect the size, shape, yield, and stability of biosynthesised AgNPs.

3.1 Concentration of Plant Extract and Metal Precursor

Since more reducing biomolecules are available to quickly lower the available Ag^+ pool, increasing the extract-to-precursor ratio often enhances the pace of nucleation and frequently produces a greater number of smaller nanoparticles. On the other hand, if there are too few capping molecules compared to the number of nuclei generated, an excessive concentration of extract may sometimes encourage agglomeration.

3.2 Reaction Temperature

While lower temperatures promote slower particle development and relatively bigger nanoparticles, higher reaction temperatures usually speed up the reduction process, promoting fast nucleation and the production of smaller, more evenly sized particles.

3.3 pH of the solution

The plant extract's functional groups ionisation state and, consequently, their reduction effectiveness are influenced by the pH of the reaction liquid. While acidic circumstances tend to impede reduction and encourage bigger or irregularly shaped particles, alkaline environments often increase the availability of hydroxyl groups for silver ion reduction, frequently producing smaller, more spherical nanoparticles.

3.4 Reaction Time

Up to a saturation point, where further silver ion reduction stops because the precursor is depleted, nanoparticle size and yield typically increase with reaction time; extended incubation beyond this point might encourage Ostwald ripening and particle aggregation.

3.5 Plant Species and Plant Part

The single most important factor influencing the morphology and bioactivity of the resulting AgNPs is the different concentrations and combinations of phytochemicals found in different plant tissues (leaf, seed, fruit peel, root, flower). This explains the significant variation in reported particle characteristics even for ostensibly similar synthesis protocols.

4. Characterization Techniques

In order to verify nanoparticle production and clarify physicochemical characteristics pertinent to downstream applications, a standard characterisation battery is employed throughout the literature.

4.1 UV-Visible Spectroscopy

The first and most common confirmation of nanoparticle formation is the appearance of a distinctive surface plasmon resonance absorption band, usually between 400 and 450 nm for spherical AgNPs; the location and width of this peak provide initial information on particle size distribution and aggregation state.

4.2 Fourier-Transform Infrared Spectroscopy (FTIR)

By comparing the vibrational spectra of the synthesised nanoparticles and the raw plant extract, FTIR analysis can identify the functional groups of phytochemicals that cause surface capping and

silver ion reduction. This process typically reveals shifts related to hydroxyl, carbonyl, and amine groups.

4.3 X-ray Diffraction (XRD)

By using the Scherrer equation to estimate the average crystallite size based on the width of the characteristic Bragg reflections, XRD verifies the crystalline, face-centered cubic structure typical of metallic silver.

4.4 Electron Microscopy (SEM and TEM)

While energy-dispersive X-ray spectroscopy (EDS/EDX) is frequently used in conjunction with electron microscopy to confirm elemental silver composition, scanning and transmission electron microscopy (TEM) offer direct visualisation of nanoparticle size, shape, and dispersion state. TEM offers higher resolution suitable for measuring particles below 20 nanometres.

4.5 Dynamic Light Scattering and Zeta Potential

Zeta potential measurement measures surface charge and colloidal stability; values greater than about -30 mV typically indicate good electrostatic stabilisation against aggregation. Dynamic light scattering (DLS) provides the hydrodynamic size distribution of nanoparticles in colloidal suspension.

5. Environmental Applications

Utilising their catalytic, redox, and antibacterial qualities, biogenic AgNPs made from plant extracts have been thoroughly tested for a variety of environmental remediation applications.

5.1 Photocatalytic and Catalytic Degradation of Synthetic Dyes

The permanence and toxicity of synthetic dyes including methylene blue, methyl orange, rhodamine B, crystal violet, and Congo red make industrial effluents from the textile, paper, and dye production industries a significant cause of water pollution. Significant catalytic activity has been shown by plant-mediated AgNPs in the reductive degradation of such dyes, usually in the presence of a reducing agent like sodium borohydride or by photocatalysis powered by solar light. By facilitating electron transfer from the reductant to the dye molecule, the nanoparticle surface typically functions as an electron-relay system. This lowers the activation energy of degradation and speeds up the breakdown of the chromophoric azo or aromatic ring structures into less toxic byproducts. Depending on catalyst loading, dye concentration, and light conditions, reported degradation efficiencies for plant-synthesised AgNPs commonly surpass 75–90% during reaction periods ranging from a few minutes to about an hour.

5.2 Detection and Removal of Toxic Heavy Metal Ions

Due to the non-biodegradable and bioaccumulative nature of metals including lead, cadmium, chromium, mercury, and copper, heavy metal poisoning of water bodies resulting from mining, electroplating, and industrial discharge poses serious dangers to ecosystems and human health. AgNPs derived from plants have been used as active remediation agents that adsorb or catalytically change toxic metal species into less mobile or less toxic forms, as well as colorimetric sensors that use metal-ion-induced changes in surface plasmon resonance to enable spectrophotometric or naked-eye detection of ions such as Cu^{2+} , Ni^{2+} , $\text{Cr}^{3+}/\text{Cr}^{6+}$, and $\text{Fe}^{2+}/\text{Fe}^{3+}$. In comparison to bare or chemically capped nanoparticles, the phytochemical capping layer around biogenic AgNPs, which is rich in functional groups that provide oxygen and nitrogen, increases affinity for metal ion chelation.

5.3 Antimicrobial Water Disinfection

AgNPs are used in point-of-use water disinfection systems and antimicrobial filtration membranes because of their well-established antibacterial and antifungal activity, which results from disruption of microbial cell membranes, production of reactive oxygen species, and interference with intracellular enzymatic and genetic machinery. Strong inhibitory activity against multidrug-resistant bacterial strains and common waterborne pathogens like *Escherichia coli* and *Staphylococcus aureus* has been demonstrated by plant-synthesized AgNPs, providing a biocompatible substitute for chlorine-based disinfection with less production of hazardous disinfection byproducts.

5.4 Agricultural and Soil Remediation Applications

Beyond aquatic remediation, plant-mediated AgNPs have been investigated as environmentally safe nano-pesticides and nano-fungicides that can reduce the impact of phytopathogens on crop yield and control plant pathogens with less off-target toxicity than traditional agrochemicals. However, as excessive or uncontrolled application of AgNPs can potentially constitute an ecotoxicological danger to soil microbiota and beneficial insects, care must be taken to assess nanoparticle accumulation in soil and absorption by non-target species.

6. Advantages of Plant-Mediated Green Synthesis

A naturally occurring capping layer of biomolecules that can improve biocompatibility for applications involving direct environmental or biological contact; (i) elimination or significant reduction of toxic reducing and capping agents, lowering the environmental and biological hazard

associated with nanoparticle residues; (ii) use of cheap, renewable, and widely available plant biomass, which lowers production cost; (iii) ambient reaction conditions that avoid high energy consumption; and (v) the potential to tune nanoparticle properties simply by changing plant species, plant part, or extraction method, without the need for specialised surfactants or stabilisers.

7. Challenges and Limitations

Notwithstanding these benefits, a number of obstacles still prevent plant-mediated AgNP synthesis from being widely used in industry. Reproducibility is challenging to ensure at scale due to batch-to-batch variability in phytochemical composition, which results from variations in plant growing circumstances, geographic origin, harvest season, and extraction process. Compared to chemical synthesis, where reaction stoichiometry may be precisely regulated, precise control over nanoparticle size and form is still more difficult. Additionally, the ecotoxicological profile of biogenic AgNPs themselves, including their potential for bioaccumulation and interaction with non-target aquatic and soil organisms, requires more thorough and standardised long-term assessment before large-scale environmental deployment can be deemed completely safe, even though green synthesis reduces the use of overtly toxic chemicals.

8. Conclusion and Future Perspectives

An increasingly well-established and scientifically sound alternative to traditional physical and chemical nanoparticle creation methods is the green synthesis of silver nanoparticles using plant extracts. This method significantly lessens the environmental and toxicological burden associated with the production of nanoparticles by using naturally occurring phytochemicals as reducing and capping agents. It also produces materials that have been shown to be useful in dye degradation, heavy metal sensing and removal, antimicrobial water disinfection, and sustainable agriculture. Standardised synthesis procedures to increase reproducibility, systematic structure-activity studies connecting particular phytochemical profiles to nanoparticle performance, thorough life-cycle and ecotoxicological assessment, and pilot-scale process engineering to close the gap between lab research and field-deployable technology are all necessary to fully realise the potential of plant-mediated AgNPs for large-scale environmental remediation. Plant-mediated green synthesis is well-positioned to become a key component of sustainable nanotechnology for environmental protection with ongoing multidisciplinary research encompassing phytochemistry, materials science, and environmental engineering.

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