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GREEN ROUTES TO SILVER NANOPARTICLES: SUSTAINABLE SYNTHESIS AND EMERGING APPLICATIONS

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ABSTRACT

Green nanotechnology has gained significant attention due to the growing need for environmentally benign and sustainable synthesis routes. This review highlights plant-mediated synthesis of silver nanoparticles (AgNPs) as an effective alternative to conventional chemical methods that rely on toxic reagents. In this approach, bioactive compounds present in plant extracts act simultaneously as reducing and stabilizing agents, enabling the formation of silver nanoparticles under mild and eco-friendly conditions. The successful synthesis of AgNPs is initially indicated by a distinct visible colour change and further confirmed using UV–Visible spectroscopy. Comprehensive characterization of the biosynthesized nanoparticles is carried out using Fourier Transform Infrared Spectroscopy (FTIR), X-ray Diffraction (XRD), Scanning and Transmission Electron Microscopy (SEM/TEM), and particle size analysis to assess their functional groups, crystalline structure, morphology, and size distribution.

The results reported in various studies demonstrate that plant-derived AgNPs possess good stability, well-defined morphology, and a high surface-to-volume ratio, which are desirable features for catalytic applications. The catalytic performance of these nanoparticles has been evaluated in selected organic name reactions, where they exhibit enhanced reaction rates, higher product yields, and the ability to operate under mild reaction conditions. These advantages underline the effectiveness of biosynthesized AgNPs as green catalysts. Overall, this review emphasizes the potential of plant-based silver nanoparticles in promoting sustainable and environmentally friendly organic transformations, thereby contributing to the advancement of green chemistry and sustainable catalytic processes.

Keywords: *Nanotechnology, Green Synthesis, Plant mediated synthesis, Silver nanoparticles, Applications.*

INTRODUCTION

Nanotechnology is a rapidly advancing branch of science and technology that involves the study, design, and application of materials at the nanoscale, typically in the range of 1–100 nanometers (nm)[1]. At this scale, materials exhibit unique physicochemical properties that differ significantly from their bulk forms, such as increased surface-to-volume ratio, enhanced reactivity, and adjustable optical and biological characteristics. These distinctive features enable precise manipulation of matter at the atomic and molecular levels, leading to the development of innovative materials with improved mechanical, chemical, and functional properties. As a result, nanotechnology has found widespread applications in diverse fields including medicine, agriculture, electronics, energy, and environmental remediation[2].

Among various nanomaterials, silver nanoparticles (AgNPs) have attracted considerable scientific and industrial interest owing to their exceptional antimicrobial, antioxidant, catalytic, and optical properties[3]. Traditionally, AgNPs are synthesized using physical and chemical methods such as thermal decomposition, chemical reduction, and photochemical techniques. However, these conventional approaches often require high energy input and involve toxic reducing agents and stabilizers, which pose serious risks to both the environment and human health[4]. These concerns have driven the search for safer, cleaner, and more sustainable synthesis routes.

Green chemistry provides a sustainable framework to address these challenges. It is defined as "the design of chemical products and processes that reduce or eliminate the use and generation of hazardous substances"[5]. The principles of green chemistry emphasize waste prevention, energy efficiency, and the use of renewable resources, making it highly compatible with modern nanomaterial synthesis. The incorporation of green chemistry principles into nanotechnology has led to the emergence of environmentally benign nanoparticle synthesis strategies.

Green synthesis of nanoparticles represents a practical application of green chemistry, where biological systems such as plants, microorganisms, and biomolecules are employed as reducing and capping agents[6]. Among these, plant-mediated synthesis has gained particular attention due to its simplicity, cost-effectiveness, scalability, and eco-friendly nature. This approach avoids the use of harmful chemicals and instead relies on plant extracts rich in naturally occurring phytochemicals.

Plant-mediated synthesis of silver nanoparticles utilizes extracts from various plant parts, including leaves, bark, roots, fruits, and seeds, which contain bioactive compounds such as flavonoids, phenolics, terpenoids, alkaloids, and proteins[7]. These phytochemicals act simultaneously as reducing agents, converting silver ions (Ag^+) into metallic silver (Ag^0), and as stabilizing agents, preventing nanoparticle aggregation. Several plant species, including Azadirachta indica, Moringa oleifera, Terminalia chebula, Syzygium cumini, Ocimum sanctum, Camellia sinensis, and Aloe vera, have been successfully employed for the eco-friendly synthesis of AgNPs[8–11]. The resulting nanoparticles are often described as eco-benign due to their reduced toxicity and enhanced biological compatibility.

Therefore, green routes to silver nanoparticles not only minimize environmental and health hazards associated with conventional synthesis methods but also support sustainable development goals. This review focuses on recent advances in plant-mediated green synthesis of AgNPs, the role of phytochemicals in nanoparticle formation, and the emerging applications of these sustainably synthesized nanomaterials.

METHODOLOGY: ROUTES FOR THE SYNTHESIS OF SILVER NANOPARTICLES:

Silver nanoparticles (AgNPs) can be synthesized through a wide range of approaches that differ in complexity, environmental impact, cost, and control over particle characteristics. In this review, various reported synthesis methodologies are systematically analyzed and categorized into physical, chemical, biological (green), radiation-based, and template-assisted routes, with special emphasis on plant-mediated green synthesis due to its sustainability and scalability.

Overview of Available Synthesis Methods:

The commonly reported methods for the preparation of silver nanoparticles include:

- **Physical methods**, such as evaporation–condensation and laser ablation, which avoid chemical reagents but require high energy input and specialized equipment.
- **Chemical methods**, which rely on chemical reducing agents and stabilizers and are favored for their rapid reaction rates and precise control over nanoparticle size and morphology.
- **Biological (green) methods**, utilizing plant extracts, microorganisms, or biomolecules as reducing and capping agents.
- **Radiation-based methods**, where gamma rays, UV, or microwave radiation initiate reduction of silver ions.
- **Template-assisted methods**, which employ polymers, surfactants, or solid matrices to regulate nanoparticle growth.

Among these, **chemical methods** are frequently selected when uniform particle size and fast synthesis are required; however, concerns regarding toxicity and environmental burden have shifted attention toward **biological green routes**.

PLANT-MEDIATED GREEN SYNTHESIS OF SILVER NANOPARTICLES:

Selection of Plant Materials:

Plant-mediated synthesis is one of the most widely explored green approaches for AgNP preparation. Various plant parts—including **leaves, stems, roots, bark, flowers, fruits, and seeds**—have been successfully employed. The effectiveness of a plant extract largely depends on the presence of bioactive phytochemicals such as **flavonoids, polyphenols, terpenoids, alkaloids, proteins, saponins, and carbohydrates**, which function as both reducing and stabilizing agents.

Commonly reported plants include Azadirachta indica (Neem), Ocimum sanctum (Tulsi), Aloe vera, and Camellia sinensis (tea leaves), owing to their rich phytochemical profiles.

Plant-Based Extraction and Synthesis Strategies:

1. Aqueous Plant Extract Method:
In this widely adopted approach, selected plant parts are thoroughly washed, shade-dried, and boiled or refluxed in distilled water to obtain an aqueous extract. Upon mixing with aqueous silver nitrate ($AgNO_3$), the phytochemicals present in the extract reduce Ag^+ ions to metallic Ag^0 while simultaneously capping the formed nanoparticles. Dhar et al. demonstrated successful synthesis and stabilization of AgNPs using Phyllanthus emblica fruit extract, highlighting the role of plant biomolecules in controlled nanoparticle formation[12].

2. Microwave-Assisted Plant Extract Method:
Microwave irradiation has been introduced to enhance reaction kinetics and improve nanoparticle uniformity. In this method, the plant extract–$AgNO_3$ mixture is exposed to microwave energy, which accelerates reduction by rapid and uniform heating. Singh et al. reported that microwave-assisted green synthesis significantly reduced reaction time and produced more uniform AgNPs compared to conventional passive methods[13].

3. Hot Plate / Heating-Assisted Synthesis:
Controlled heating of the plant extract–silver salt mixture (typically 60–100°C) is used to accelerate reduction and influence nanoparticle size and shape. Amjid Khan et al. synthesized AgNPs using Withania coagulans leaf extract[14] by heating the reaction mixture at 60°C for four hours, demonstrating enhanced reduction kinetics and controlled silver nuclei growth.

4. Ultrasonication-Assisted Extraction:
Ultrasonication improves the extraction efficiency of phytochemicals by disrupting plant cell walls and increasing mass transfer. The sonicated extract, when combined with $AgNO_3$, exhibits faster reaction rates and improved nanoparticle yield. Babu Sumi Maria et al. compared open heating, reflux, and ultrasonication for extracting Zizyphus xylopyrus bark and showed that extraction methodology significantly influences phytochemical availability and AgNP synthesis efficiency[15].

5. Cold Extraction (Room-Temperature Synthesis):
To preserve thermolabile phytochemicals, cold extraction methods involve maceration of plant material in water at room temperature without external heating. Wickramarachchi et al. demonstrated that AgNPs synthesized under ambient conditions retained active phytochemicals and achieved effective reduction and stabilization without thermal degradation[16].

6. pH-Tuned Green Synthesis:
The pH of the reaction medium plays a critical role in determining nanoparticle size, morphology, and stability. Variations in pH alter the ionization state and reactivity of phytochemicals. Chhangte Vanlalveni et al. reported that alkaline and acidic environments significantly modify reduction capacity and capping behavior, enabling tunable synthesis of AgNPs[17].

7. Sunlight-Assisted Phytochemical Reduction:
Sunlight exposure provides a sustainable energy source for initiating rapid reduction of silver ions. In this method, plant extract–$AgNO_3$ mixtures are exposed to natural sunlight, eliminating the need for chemical reducers or heating. Vanlalveni et al. highlighted the efficiency of light-triggered green synthesis[17], while Gloria N. Aningo et al. demonstrated sunlight-assisted AgNP formation using Musa acuminata peel extract with enhanced antimicrobial activity[18].

8. Influence of Different Plant Parts:
Different plant parts possess distinct phytochemical compositions, which influence nanoparticle properties. Sajib Aninda Dhar et al. employed Phyllanthus emblica fruit extract for controlled AgNP synthesis[12], whereas Priya Banerjee et al. used leaf extracts of Musa balbisiana, Azadirachta indica, and Ocimum tenuiflorum, highlighting the role of plant diversity in sustainable synthesis[19].

9. Combined Extraction Techniques:
Hybrid extraction strategies, such as reflux combined with ultrasonication, are used to maximize phytochemical recovery and improve nanoparticle synthesis efficiency. Such integrated methods were effectively demonstrated by Babu Sumi Maria et al. using Zizyphus xylopyrus bark extracts[15].

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Mechanistic Insight into Plant-Mediated AgNP Formation:

In plant-mediated green synthesis, silver nitrate dissociates in aqueous media to release Ag^+ ions. Phytochemicals such as flavonoids, phenolics, terpenoids, and proteins donate electrons to reduce Ag^+ to metallic Ag^0. The reduced silver atoms nucleate rapidly, followed by controlled growth and stabilization through adsorption of biomolecules on the nanoparticle surface. These biomolecules act as natural capping agents, preventing agglomeration and imparting stability[16, 20].

The exact mechanism varies depending on plant species, extract composition, concentration, pH, temperature, and exposure conditions. Shahzadi et al. (2025) emphasized that simultaneous reduction and capping govern nanoparticle stability and functional performance [6]. Recent studies using diverse medicinal plants such as Cinchona species[21], Capsicum chinense[22], Astragalus fasciculifolius (Anzaroot)[23], Blumea oxyodonta[24], Eugenia roxburghii[25], Curcuma longa, and others demonstrate that phytochemical-driven AgNP synthesis not only ensures environmental safety but also enhances biological activities including antibacterial, antifungal, antioxidant, anti-inflammatory, anticancer, and antibiofilm properties[19–28].

CONCLUSION

Green routes for the synthesis of silver nanoparticles have emerged as a sustainable and environmentally responsible alternative to conventional physical and chemical methods. Among the various green approaches, plant-based methodologies stand out due to their simplicity, cost-effectiveness, and eco-friendly nature. The rich diversity of phytochemicals such as phenolics, flavonoids, terpenoids, and alkaloids present in plant extracts plays a crucial role as natural reducing, stabilizing, and capping agents, eliminating the need for toxic reagents and harsh reaction conditions.

Plant-mediated synthesis offers remarkable versatility, as the physicochemical properties of AgNPs can be effectively tuned by adjusting parameters such as extract concentration, pH, temperature, reaction time, energy input, and extraction techniques. These controllable factors enable precise regulation of nanoparticle size, shape, surface characteristics, and dispersion, which in turn directly influence their biological activity and functional performance. Such flexibility makes plant-based routes particularly attractive for tailoring AgNPs for specific applications.

Furthermore, AgNPs synthesized via green routes demonstrate enhanced biocompatibility and broad-spectrum biological activities, including antimicrobial, antioxidant, anticancer, and catalytic properties, supporting their growing use in biomedical, environmental, and industrial fields. Despite significant progress, challenges related to large-scale production, batch-to-batch reproducibility, and mechanistic understanding of phytochemical–metal interactions still need to be addressed.

Overall, plant-based green synthesis represents a promising and sustainable pathway for the production of silver nanoparticles. Continued research focused on standardization, scale-up strategies, and application-oriented optimization will further strengthen the role of green AgNPs in advancing nanotechnology while aligning with principles of environmental sustainability and green chemistry.

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