Review Article

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A Review of Green Synthesis of Silver Nanoparticles Using Plant Extracts: Mechanisms, Characterization, Comparative Analysis, Challenges, and Emerging Biomedical and Environmental Applications

P. Veerakumari[1], A. Venkateswara Rao[1*], S. Prasanthi[2], P. Ramakrishna[3], E. Rajesh[4], Komali Challa[5], B. Vikram Babu[6] and M. Brahmayya[7]

[1]Department of Physics, Koneru Lakshmaiah Education Foundation, Guntur, AP, India
[2]Department of Chemistry, Adikavi Nannaya University, Tadepalligudem, AP, India
[3]Department of Physics, Vivekananda Degree College, S Kota, Vizianagaram, AP, India
[4]Department of Physics, Aditya University, Surampalem, AP, India
[5]Department of Engineering Physics, Andhra University, Visakhapatnam, AP, India
[6]Department of Physics, Andhra University, Visakhapatnam, AP, India
[7]Department of Chemistry, VNR Vignana Jyothi Institute of Engineering and Technology, Nizampet, Hyderabad, TG, India
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*avrtoavr@gmail.com

ABSTRACT

Silver nanoparticle (AgNP) production has attracted considerable interest due to its remarkable physicochemical properties and wide-ranging applications in catalysis, healthcare, and environmental science. Among various synthesis strategies, green synthesis using plant extracts has emerged as an efficient, economical, and environmentally friendly alternative to conventional chemical and physical methods. This approach uses abundant plant phytochemicals, including terpenoids, alkaloids, phenolics, and flavonoids, which act as natural reducing, stabilizing, and capping agents during nanoparticle formation. Recent advances have improved control over nanoparticle shape, size, and stability by optimizing parameters such as temperature, reaction time, pH, and extract concentration. This review critically synthesizes recent literature on the plant-mediated green synthesis of AgNPs by comparing different plant extracts, synthesis strategies, characterization techniques, and application outcomes. It also identifies current research challenges, knowledge gaps, and future directions for developing sustainable and scalable silver nanoparticle technologies. Comparative studies using different plant extracts reveal significant variations in reduction efficiency, particle size distribution, and application-specific performance. Green-synthesized AgNPs demonstrate strong antioxidant, antimicrobial, catalytic, and sensing capabilities, making them promising for biological applications, wastewater treatment, and pollutant degradation. Overall, the review highlights recent progress in plant-mediated AgNP synthesis, underlying green synthesis mechanisms, the essential role of phytochemicals, and the functional relevance of AgNPs, supported by selected reference studies and comparative assessments of synthesis outcomes.

Keywords: Plant extracts; Silver nanoparticles; Green synthesis; Phytochemicals; Antimicrobial activity; Eco-friendly nanotechnology.

1. INTRODUCTION

Recent research has shown that plant-mediated synthesis of silver nanoparticles has evolved from a simple, eco-friendly alternative into a versatile, sustainable nanotechnology platform with broad biomedical and environmental applications. Studies by Chung *et al.* (2016), Khan and Javed (2021), and Wirwis and Sadowski (2023) reported that plant species selection and phytochemical composition significantly influence nanoparticle size, morphology, crystallinity, stability, and biological activity. Comparative investigations have further shown that optimizing synthesis parameters, including pH, temperature, silver precursor concentration, extract dosage, and reaction time, is crucial for controlling nanoparticle formation and functional performance (Dutta *et al.* 2020; Mickky *et al.* 2024; Balaji *et al.* 2025). Moreover, several recent reviews highlight substantial advances in green synthesis methodologies, characterization techniques, multifunctional applications, toxicity assessment, and sustainable large-scale production, while identifying challenges in reproducibility and commercialization. Nevertheless, comprehensive comparative evaluations integrating synthesis mechanisms, reaction parameters, characterization methods, and application-specific performance across diverse plant sources remain limited. Therefore, this review critically synthesizes the current literature to bridge these gaps and provide an updated perspective on recent progress, existing challenges, and future opportunities in plant-mediated green synthesis of silver nanoparticles.

2. MECHANISM OF GREEN SYNTHESIS

2.1 Role of Phytochemicals

Ag^+ ions are converted to metallic silver (Ag^0) by bioactive chemicals found in plant extracts, which also stabilize the resulting nanoparticles (Makarov *et al.* 2014). Phenolic acids, flavonoids, terpenoids, saponins, and reducing sugars are examples of common phytochemicals. These compounds facilitate the reduction of silver ions by donating electrons.

Green synthesis using plants and plant extracts has gained popularity because it is a rapid, environmentally friendly, non-pathogenic, single-step, and economical approach. Green synthesis using plants and plant extracts is generally faster than synthesis using other microorganisms, such as fungi and bacteria. Consequently, the use of plant extracts in green synthesis has attracted considerable research interest in recent years (Amit *et al.* 2013). Studies show that, depending on the plant extract, metal nanoparticles (NPs) can form rapidly in the metal salt solution at ambient temperature. Once the plant extract is selected, temperature, pH, metal salt, and extract concentration are the primary variables that influence the process. Beyond the formation conditions, the most important factor is the plant from which the extract is obtained. Plant extracts can reduce Ag^+ ions and enhance nanoparticle stability through numerous active compounds, making them a valuable approach for producing NPs. Stems, leaves, bark, shoots, seeds, flowers, and their derivatives have all been successfully used to produce nanoparticles (Nadiyah *et al.* 2021), as shown in Fig. 1. As shown in Table 1, various plant sources have been successfully employed for the green synthesis of silver nanoparticles, exhibiting differences in phytochemical composition, nanoparticle characteristics, and potential applications.

The mechanistic steps involved are as follows:

- *Activation*, in which Ag^+ is converted to Ag^0 by phytochemicals;
- *Growth*, involving the nucleation and coalescence of Ag^0 atoms to form small clusters; and
- *Stabilization*, in which phytochemicals are adsorbed onto the nanoparticle surface, preventing aggregation (Noor *et al.* 2011).

Table 1. Comparative overview of plant-mediated green synthesis of silver nanoparticles using different plant sources, highlighting plant parts, major phytochemicals, synthesis conditions, physicochemical characteristics, characterization techniques, and potential applications

Plant Source	Plant Part	Major Phytochemicals	Particle Size (nm)	Shape	Characterization	Main Application	Reference
Azadirachta indica	Leaf	Quercetin, terpenoids, flavonoids	15–40	Spherical	UV–Vis, XRD, FTIR, SEM	Antimicrobial	Moinuzzaman *et al.* (2021)
Camellia sinensis	Leaf	Catechins, polyphenols	20–50	Spherical	UV–Vis, XRD, TEM	Antioxidant	Khan *et al.* (2017)
Musa paradisiaca	Peel	Polysaccharides, phenolics	10–30	Quasi-spherical	UV–Vis, XRD, SEM	Catalytic	Niluxsshun *et al.* (2021)
Punica granatum	Peel	Polyphenols, tannins	20–60	Irregular	UV–Vis, XRD, TEM	Antioxidant	Villagrán *et al.* (2024)
Cinnamomum zeylanicum	Bark	Cinnamaldehyde, phenolics	25–45	Spherical	UV–Vis, XRD, DLS	Antibacterial	Noureen *et al.* (2025)

2.2 Reaction Conditions

Synthesis parameters such as pH, temperature, reaction time, precursor concentration, and plant extract dosage significantly influence nanoparticle size, morphology, and stability. Khalil *et al.* (2020) reported that optimizing these parameters improves nanoparticle formation and enhances their potential for abiotic stress tolerance applications. Neem-mediated AgNP synthesis under optimized reaction conditions produced highly effective nanoparticles against antibiotic-resistant bacteria. AgNPs synthesized using *Azadirachta indica* and *Ocimum sanctum* extracts showed enhanced antimicrobial activity, emphasizing the importance of controlled synthesis conditions. *Citrus fruit* peel extracts produced stable nanoparticles with excellent antibacterial activity under optimized reaction parameters, whereas Moza *et al.* (2025) reported that *Citrus sinensis* peel extract generated uniformly distributed AgNPs with improved physicochemical characteristics. Recent studies further concluded that systematic optimization of reaction parameters and the selection of appropriate plant metabolites are essential for producing reproducible, stable, and application-specific silver nanoparticles suitable for biomedical, catalytic, and environmental applications.

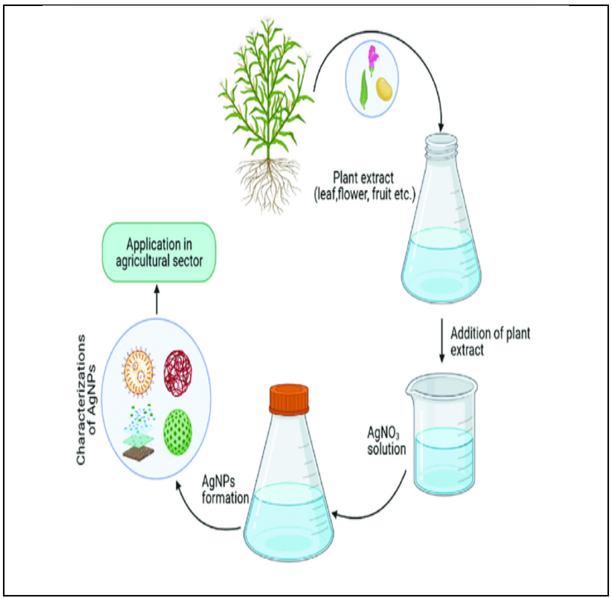

Fig. 1: Schematic diagram of the synthesis of AgNPs using plant extracts (Nadiyah *et al.* 2021)

3. PLANT EXTRACTS USED IN SILVER NANOPARTICLE SYNTHESIS

Researchers have investigated AgNP synthesis using a variety of plant species. Representative examples are compiled in the following subsections according to the plant parts used:

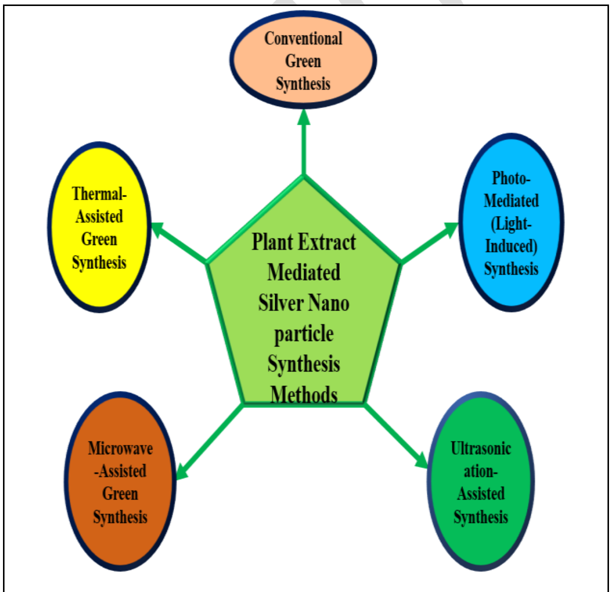

Fig. 2: Different green synthesis methods for AgNPs using plant extracts

3.1 Leaf Extracts

Azadirachta indica (Neem): Strong reducing substances such as terpenoids and flavonoids confer strong antibacterial activity on AgNPs.

Leaf extracts from *Azadirachta indica* were employed in the green synthesis of silver nanoparticles (Pragyan *et al.* 2017). Terpenoids and flavonoids in the extract serve as reducing and capping agents. Using a selective medium, microorganisms (Gram-positive bacteria and *Escherichia coli*) were isolated from borewell water. The silver nanoparticles showed antibacterial activity against *E. coli* and Gram-positive bacteria.

The green synthesis, a plant-mediated biogenic technique, was used to produce silver nanoparticles (S. Prakash *et al.* 2013). Quercetin dihydrate (QDH) (10 mL of 0.06% w/v in alcohol), 2, 3-dehydrosalanol (2, 3-DHS) (10 mL of 0.03% w/v in alcohol), and neem leaf extract (10 mL of 10% w/v in distilled water) were used to synthesize the AgNPs (Bodaballa *et al.* 2016). A magnetic stirrer was used to maintain 90 mL of a 2 mM silver nitrate ($AgNO_3$) solution at 80 °C, while each of the aforementioned chemicals was introduced dropwise. The mixture was then maintained at room temperature for 24 h following the addition. A noticeable change in the hydrosol indicated NP synthesis. The hydrosol's UV-Vis spectrum confirmed the reduction of silver ions (Ag^+). The hydrosol was centrifuged for 4 min at 10,000 rpm to separate the AgNPs for further analysis. The concentration of AgNPs was determined using an inductively coupled plasma optical emission spectrophotometer. A 20 mL aliquot was introduced into the automatic sampler racks after diluting the samples tenfold with distilled water. The concentration of AgNPs in the sample was determined by averaging three measurements.

3.2 Fruit Extracts

Citrus sinensis (Orange peel): AgNPs have antibacterial and photocatalytic properties, and their high ascorbic acid and limonene content speeds up reduction.

Oranges (*Citrus sinensis* L.), a ubiquitous fruit crop grown worldwide, have peels that make up almost half of the fruit's bulk (Sanjeev *et al.* 2023). Orange peel was utilized as an environmentally benign material for the synthesis of silver nanoparticles (AgNPs). Using various extraction techniques, aqueous extracts of appropriately treated peel were prepared, and their phytochemical profiles were determined (Kaviya *et al.* 2011). The boiled peel extract appeared to be the most promising in terms of phytochemical screening, the quantity of primary phytochemicals, the reducing power, the ability to scavenge free radicals, and the antioxidant activity. Thus, the primary constituents of this extract were determined using gas chromatography-mass spectrometry.

Fruit peels of *Citrus sinensis* and *Citrus limetta* were washed with double-distilled water, and 10 g of the peels were heated for 45 min at 80 °C in 100 mL of water. After filtering, the extract was cooled and maintained at 5 °C. The extracts were used within 48 h for uniformity, but they had a slightly acidic pH and remained stable for up to 7 days (Bardees *et al.* 2024). To synthesize AgNPs, 50 mL of 0.1 M $AgNO_3$ solution was swirled for 30 min, and then 10 mL of the peel extract was added dropwise and stirred for 15 min. In the biogenic synthesis, phytochemicals in the extract served as organic reducing and stabilizing agents, producing small, stable nanoparticles (Balaji *et al.* 2025). NaOH (0.02 M) was added in modest amounts to accelerate the reduction process. AgNPs were produced by centrifuging the mixture for 15 min at 8000 rpm, washing it three times with water, and drying it at 80 °C. A yield of around 0.78 ± 0.20 g was attained.

3.3 Flower Extracts

Hibiscus rosa-sinensis: Anthocyanins act as reducing agents and produce nanoparticles with enhanced surface plasmon resonance. *Hibiscus rosa-sinensis* (Tanmoy *et al.* 2020) leaf extract has been utilized in the green synthesis of gold and silver nanoparticles with different shapes. This is a simple, economical, aqueous, room-temperature synthesis method that is durable and reproducible for producing self-assembled Au and Ag nanoparticles. By altering the proportion of metal salt to extract in the reaction solution (Nayak *et al.* 2015), the shape and size of Au nanoparticles can be controlled. Silver nanoparticles with varying shapes are produced by altering the pH of the reaction medium.

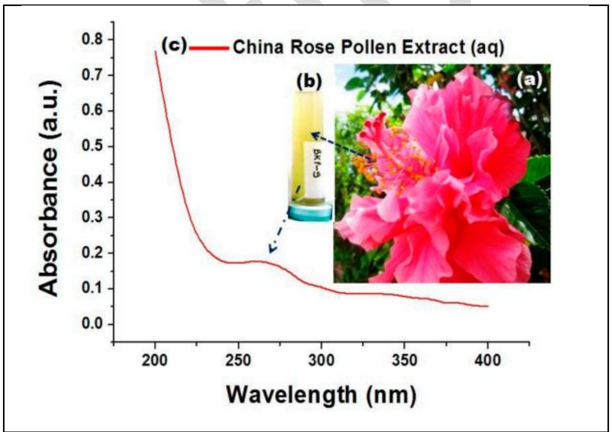

Fig. 3: (a) Photographic image of the double-petal China rose (*H. rosa-sinensis*) flower, (b) its pollen extract, and (c) UV–Vis spectrum of its pollen extract (Brajesh *et al.* 2022)

To synthesize AgNPs using the pollen of the double-petal H. rosa-sinensis (China rose) (Fig. 3a), 10 mg of yellow pollen grains were immediately added to a round-bottom flask containing 20 mL of a 1 mM $AgNO_3$ solution (Brajesh *et al.* 2022). The mixture was then agitated at 65–67 °C for 2 h. The reaction mixture's color then changed progressively over 30 min, and the mixture was incubated at room temperature (25 ± 2 °C) for the next 24 h. After centrifuging the reaction mixture for 4 min at 5000 rpm to remove the pollen, a brownish-yellow supernatant containing AgNPs was produced. The AgNPs were then stored at 4 °C for further spectroscopic and microscopic examination.

3.4 Stem, Bark and Root Extracts

Cinnamomum zeylanicum (Cinnamon bark): The effective reduction of Ag^+ ions yields crystalline AgNPs. Cinnamaldehyde from cinnamon (Priyanga *et al.* 2022) is used in traditional medicine as a treatment for gynecological, intestinal, and respiratory conditions. Numerous medicinal properties of *Cinnamomum zeylanicum* (CZ) have been demonstrated by *in vitro* and *in vivo* investigations worldwide.

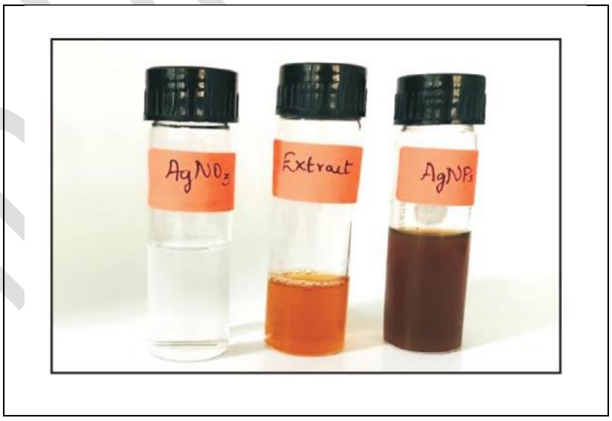

Fig. 4: Color change of the reaction mixture of $AgNO_3$ and *C. zeylanicum* bark aqueous extract after 40 min of exposure to intense sunlight (Supritha, 2021)

1 mL of the *C. zeylanicum* bark aqueous extract was combined with 100 mL of silver nitrate solution (300 ppm). After 40 min of exposure to intense sunlight, the mixture's color transformed from light brown to dark brown, as shown in Fig. 4, signifying the formation of silver nanoparticles (Supritha, 2021). UV–Vis spectrophotometry was first used to analyze the decrease in Ag+. For additional experiments involving nanopriming of onion seeds, the synthesized AgNPs were stored at -80 °C. The solution was kept for 10 min and then centrifuged at 15,000 rpm to characterize the AgNPs. The pellet was then collected and dried for 48 h at 35 °C in a vacuum oven for further characterization of the synthesized AgNPs.

Characterization provides information on the stability, shape, and crystallinity of nanoparticles, in addition to confirming their production (Vijayakumar *et al.* 2013). *Pedalium murex* fresh leaves were aqueously extracted to produce Ag nanoparticles. Because of their numerous uses, various biological processes are becoming more popular for synthesizing AgNPs.

4. LEAF EXTRACTS

4.1 X-Ray Diffraction of *Azadirachta indica*-mediated AgNPs

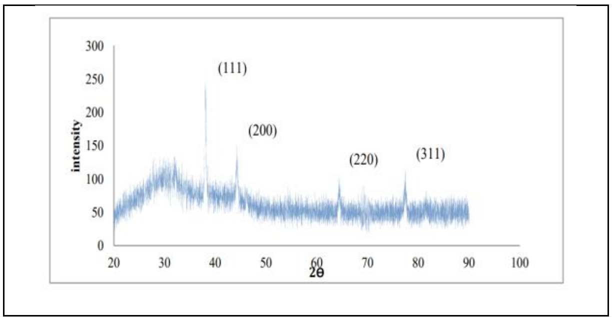

Fig. 5: XRD pattern of AgNPs prepared using aqueous *A. indica* (Neem) leaf extract (Moinuzzaman *et al.* 2021)

The crystalline structure and phase purity of green-synthesized AgNPs are commonly characterized by X-ray diffraction (XRD), which confirms the successful formation of metallic silver nanoparticles. Dhir *et al.* (2024) reported characteristic diffraction peaks at 2θ values of 38.06°, 44.22°, 64.46°, and 77.38°, corresponding to the (111), (200), (220), and (311) planes of face-centered cubic (FCC) silver, confirming the crystalline nature of AgNPs. Similarly, well-defined FCC diffraction peaks were observed for AgNPs synthesized using *C. limetta* peel extract, indicating high crystallinity and phase purity. Comparable XRD patterns for *A. indica*-mediated AgNPs, with the (111) plane exhibiting the highest diffraction intensity, suggested preferential crystal growth. Orange peel-mediated AgNPs possessed sharp diffraction peaks with improved crystallinity owing to the effective capping action of phytochemicals (Thomas *et al.* 2024). Furthermore, optimization of green tea extract concentration significantly influenced crystallite size and peak intensity, whereas controlled synthesis conditions produced highly crystalline AgNPs suitable for electrochemical applications. Across these studies, variations in peak positions and crystallite size were attributed to differences in plant metabolites, synthesis conditions, and capping efficiency. The crystallite size of AgNPs is estimated using the Scherrer equation (Patterson, 1939), where broader diffraction peaks correspond to smaller crystallite dimensions. Therefore, comparative XRD studies consistently show that plant-mediated synthesis produces highly crystalline FCC AgNPs with structural characteristics strongly dependent on the selected plant extract and reaction conditions.

4.2 UV–Vis Spectroscopy

The silver nanoparticles were confirmed by measuring the reaction mixture's wavelength in the Thermo Fisher spectrophotometer's UV–Vis spectrum at a resolution of 1 nm (between 300 and 600 nm) in a 2 mL quartz cuvette with a 1 cm path length. 1 mL of the material was pipetted into a test tube, and it was then inspected at room temperature.

The structure of the silver nanoparticles was investigated using UV–Vis spectroscopy (Raghupathi *et al.* 2022). The absorption spectra of the brown silver nano-solution prepared with *A. indica* leaf extract showed a surface plasmon absorption band with a maximum of 430 nm, indicating the presence of AgNPs (Fig. 6a). The absorption spectra of the deep mustard yellow silver nano-solution prepared with *Ocimum sanctum* leaf extract showed a surface plasmon absorption band with a maximum of 420 nm, indicating the presence of AgNPs (Fig. 6b).

4.3 Fourier Transform Infrared (FTIR) Spectroscopy

FTIR analysis was carried out to identify potential functional groups in the *C. aromaticus* leaf broth responsible for reducing silver ions Silver nanoparticles are linked to these useful compounds. In the FTIR spectra shown in Fig. 7, the bands at 3843 and 2640 cm^{-1} represent the NH group of amines. The faint band at 3337 cm^{-1} clearly indicates O–H stretching of secondary alcohols. The band at 1636 cm^{-1} is linked to nitrogen groups and the C=O stretching of the alcohol amide band (Vanaja and Annadurai, 2013). The band at 1383 cm^{-1} represents the C–N stretching vibrations of aromatic amines. The absorbance peak at 1058 cm^{-1} in the capped AgNPs disappeared because of the C–N stretching vibrations of aliphatic amines, alcohols, or phenols, indicating the presence of polyphenols, which may be flavonoids. Secondary alcohols, phenolic groups, amide (I) groups, and aromatic amines may act as reducing agents to produce AgNPs, according to this analysis.

5. FRUIT EXTRACTS

5.1 XRD of *Citrus sinensis*-mediated AgNPs

The XRD pattern of the biosynthesized AgNPs shows diffraction peaks at 2θ values of 37.2°, 44.08°, 64.44°, and 77.28°, which correspond to the FCC (face-centered cubic) lattice structure of metallic silver shown in Fig. 8. The (111), (200), (220), and (311) planes are represented by these peaks, respectively. Additional peaks at 2θ values of 27.98°, 31.24°, 46.52°, 54.96°, 57.36°, and 76.92° may be associated with crystalline and amorphous organic phases coexisting with the crystalline AgNPs (Moza *et al.* 2025).

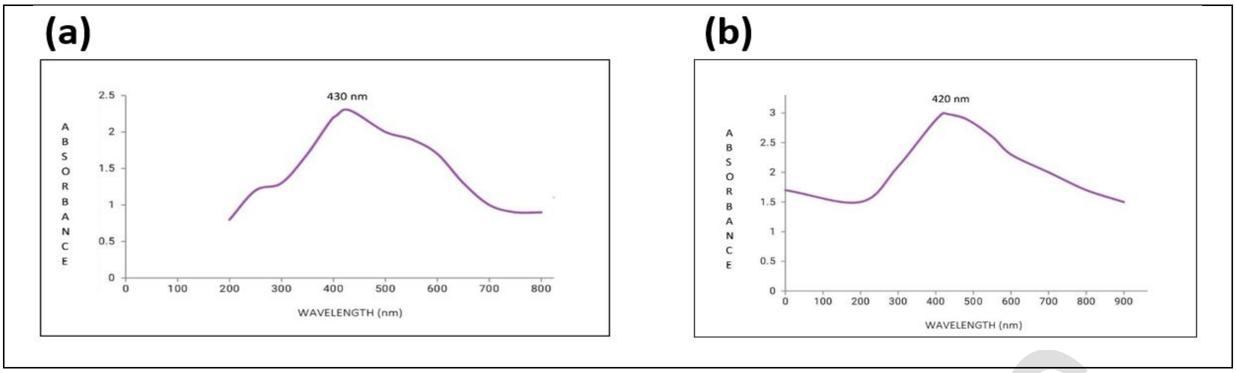

Fig. 6: (a) UV–Vis absorption peak of AgNPs prepared using *A. indica,* showing a peak at 430 nm, sample (10:3); (b) UV–Vis absorption peak of AgNPs prepared using *Ocimum sanctum,* showing a peak at 420 nm, sample (5:5) (Raghupathi *et al.* 2022)

5.2 UV–Vis Spectroscopy of *C. sinensis*-mediated AgNPs

Figs. 9(a–b) display UV–Vis spectra of aqueous orange and green orange peel extracts in a silver nitrate solution, recorded at various time intervals. The spectra show an absorption band at approximately 430–450 nm, consistent with literature values and characteristic of the surface plasmon resonance (SPR) absorption of metallic AgNPs. The slight variation in absorbance values suggests differences in the size or shape of the synthesized nanoparticles (Moira *et al.* 2021). After 48 h of reaction, the surface plasmon resonance band became nearly constant, indicating reaction completion. However, after two weeks, the intensity of the orange peel peak began to decline (Fig. 9(a)), while the absorption peak of the green orange peel extract shifted to a higher wavelength (Fig. 9(b)). The color of the solutions did not significantly change during this process.

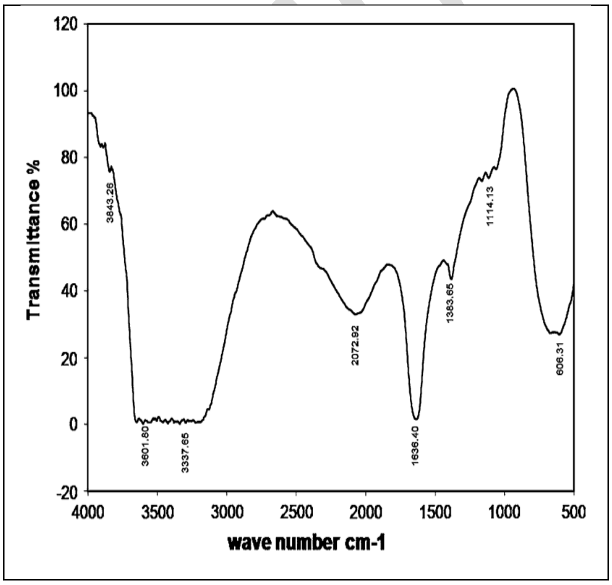

Fig. 7: FTIR spectrum of leaf extract associated with AgNPs (Vanaja and Annadurai, 2013)

Variations in the absorption peaks show that the silver nanoparticles produced using these fruit peel extracts remained stable for roughly two to three weeks before the particles began to aggregate

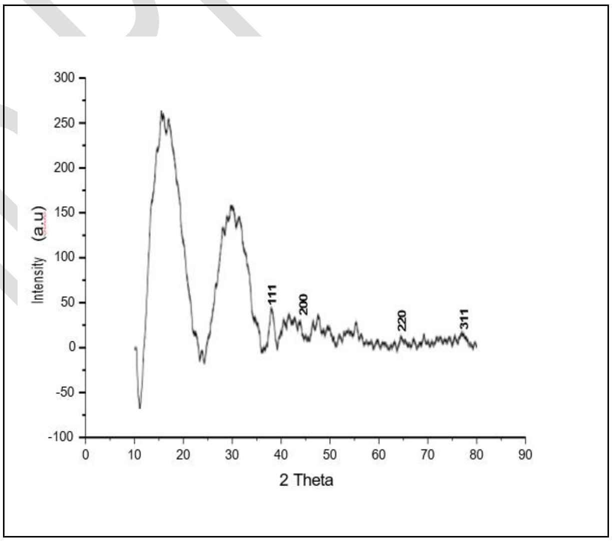

Fig. 8: XRD pattern of AgNPs synthesized using orange peel extract (Moza *et al.* 2025)

6. FLOWER EXTRACT

6.1 XRD of *Hibiscus rosa-sinensis*-mediated AgNPs

The characteristic powder XRD pattern of AgNPs synthesized using the petal extract of H.rosa-sinensis is shown in figure.10. Distinct Bragg diffraction peaks corresponding to the (111), (200), (311), (222), and (400) lattice planes were observed and indexed to the face-centered cubic (FCC) structure of silver. The experimental diffraction pattern confirm the formation through JCPDS data (file no. 04-0783), a crystalline FCC silver. The average grain size of the synthesized AgNPs was estimated using Scherer's equation [d = Kl/βcosθ], where d represents the mean particle diameter, K is the shape factor (0.9), l denotes the X-ray radiation wavelength (0.154 nm), β corresponds to (π/180) × full-width at half-maximum, and θ is the Bragg angle. Based on this calculation, the average grain size of the synthesized AgNPs was approximately 18.79 nm confirming formation of nanocrystalline structures for supporting enhanced properties.

6.2 UV–Vis Spectroscopy of *H. rosa-sinensis*-mediated AgNPs

UV–Vis spectroscopy is a useful technique for monitoring AgNP production. Surface plasmon resonance (SPR) arises from the collective oscillation of free electrons on the surface of metallic nanoparticles when excited by an external energy source. Investigating this characteristic optical property of AgNPs provides information about their physical state (Debasis *et al.* 2015). The spectral responses also provide information regarding the aggregation of the synthesized nanoparticles and are influenced by particle size. Plasmon resonance peaks generally broaden and shift toward longer wavelengths with increasing particle size and aggregation. AgNPs exhibit different plasmon resonance characteristics when they aggregate, owing to electronic coupling between adjacent nanoparticles. This aggregation can cause changes in the absorption band, including a shift toward the red or infrared region, with an overall increase in absorption intensity. The reaction mixtures were incubated at various temperatures (20, 40, 60, and 80 °C), and the solutions were periodically scanned using a UV–Vis spectrophotometer in the 400–600 nm range at 5, 10, 15, 25, 35, 45, and 60 min until a discernible change in the color of the reaction mixture was observed (Fig. 11). A large absorption peak was observed at approximately 430 nm, indicating the formation of AgNPs. The synthesis of AgNPs was completed within one hour, as shown in Fig. 11a. Similarly, when the synthesized nanoparticles were incubated at 80 °C, Fig. 11b showed a distinct absorption peak (Chhangte *et al.* 2021). According to Andreescu et al., Fig. 11c confirmed that an alkaline medium (pH 10) was optimal for AgNP synthesis. By varying the pH from 2 to 10 under the optimized temperature and reaction-time conditions, the optimal pH for nanoparticle synthesis was determined.

7. STEM, BARK, AND ROOT EXTRACTS

7.1 Dynamic Light Scattering and Zeta Potential

Dynamic Light Scattering (DLS) and zeta potential analyses were performed to determine the particle size and colloidal stability of the cinnamon-mediated AgNPs. DLS analysis provides information on the hydrodynamic particle size and size distribution of nanoparticles dispersed in a colloidal solution. The average particle size of the cinnamon-mediated AgNPs was approximately 118 nm. This analysis confirms the nanoscale nature of the synthesized particles and provides information on their size distribution in the suspension.

Zeta potential is an important parameter for evaluating the surface charge and colloidal stability of nanoparticles. As shown in Fig. 12, the cinnamon-mediated AgNPs exhibited an average zeta potential of −31.7 mV. The magnitude of the zeta potential reflects the electrostatic repulsion between particles in a colloidal suspension. Nanoparticles with relatively high positive or negative zeta-potential values tend to exhibit greater electrostatic repulsion, thereby reducing particle aggregation and improving colloidal stability. In contrast, particles with zeta-potential values close to zero generally exhibit weaker electrostatic repulsion and are more susceptible to aggregation and flocculation. A zeta-potential magnitude of approximately 30 mV or higher is commonly considered indicative of relatively good colloidal stability. Therefore, the zeta potential of −31.7 mV suggests that the cinnamon-mediated AgNPs possess relatively good colloidal stability. The DLS and zeta-potential results together provide information on the particle size and stability of the synthesized AgNPs (Munnaluri *et al.* 2015).

7.2 UV-Vis Spectroscopy of Cinnamon-mediated AgNPs

Fig. 13 displays the UV–Vis absorption spectrum of AgNPs, showing a single, sharp peak at approximately 435 nm. Similarly, Reyam and Ayad (2021) recorded a surface plasmon resonance band at around 450 nm for AgNPs synthesized using cinnamon bark. The absorption peaks of the cinnamon bark-mediated AgNPs were reported at 435 and 429 nm, respectively. A spectrophotometer was used to monitor the reduction of silver ions to nanoparticles. The synthesized AgNPs exhibited an absorption band at 435 nm, corresponding to their characteristic surface plasmon resonance. As shown in Fig. 13, the absorption spectrum was almost bell-shaped, indicating the formation of AgNPs through the reduction of silver ions.

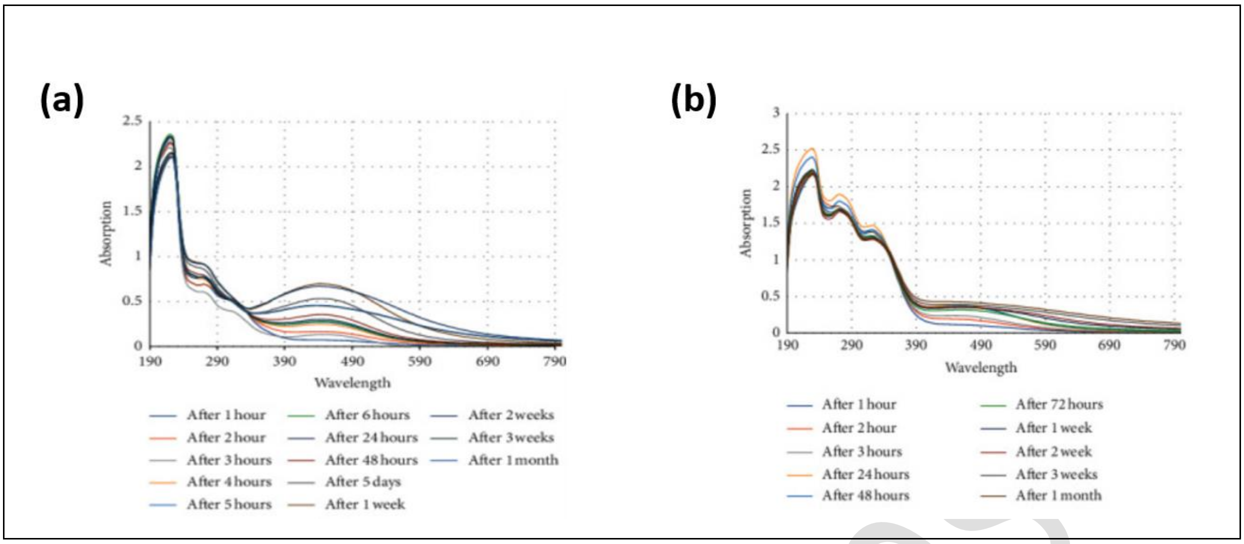

Fig. 9: UV–Vis spectra recorded at different time intervals for a 1 mM $AgNO_3$ solution with (a) orange peel extract and (b) green orange peel extract (Moira *et al.* 2021)

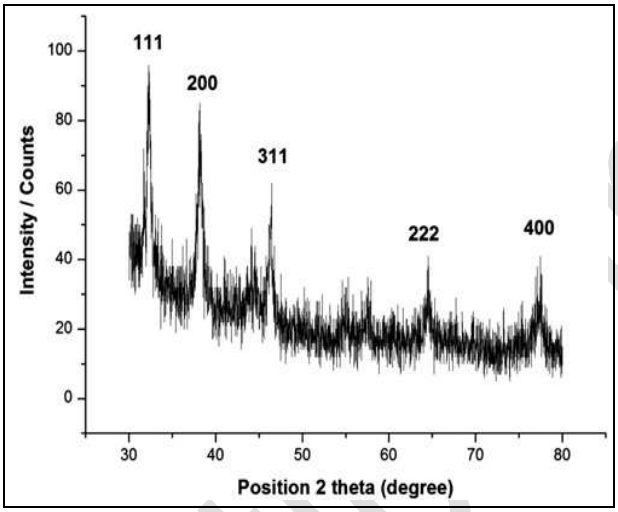

Fig. 10: XRD patterns of synthesized AgNPs (Debasis *et al.* 2015)

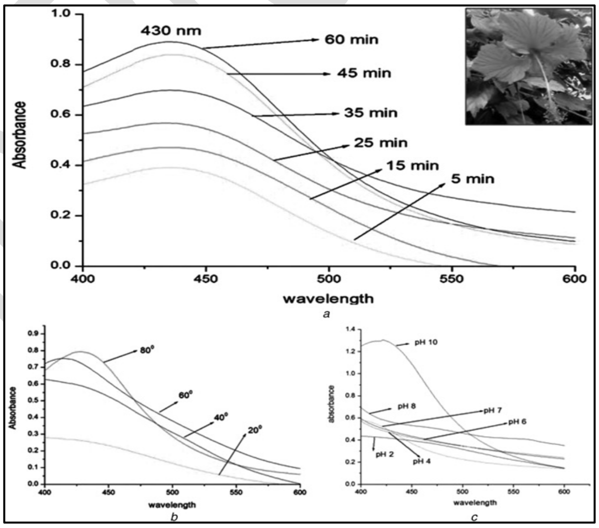

Fig. 11: UV–Vis spectra of AgNP synthesis using *H. rosa-sinensis* extract under varying (a) reaction time, (b) temperature, and (c) pH conditions (Debasis *et al.* 2015)

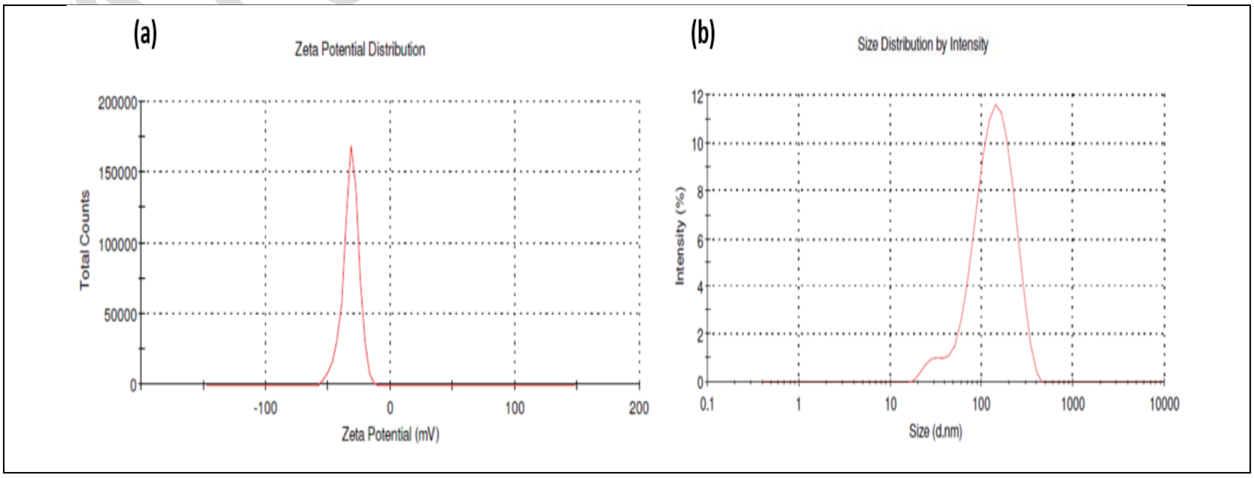

Fig. 12: (a) Zeta potential and (b) size distribution of AgNPs synthesized using cinnamon extract (Chhangte *et al.* 2021)

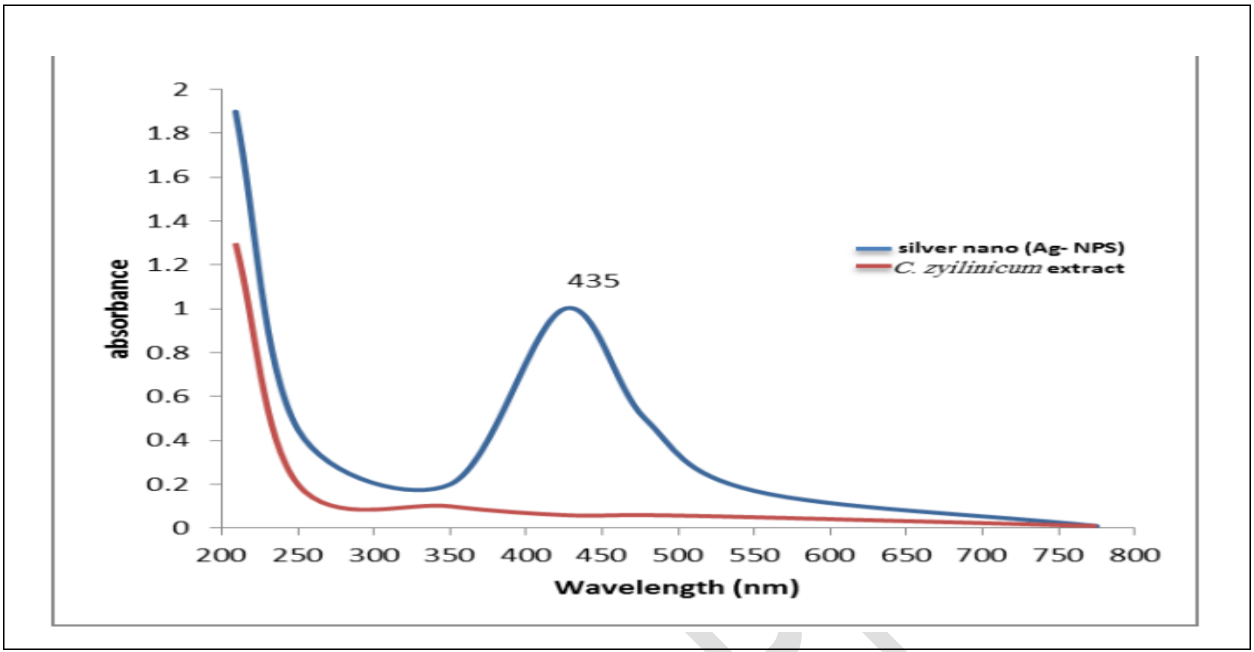

Fig. 13: Surface plasmon resonance peak of AgNPs at 435 nm (Reyam and Ayad, 2021)

8. COMPARATIVE STUDY OF DIFFERENT PLANT EXTRACTS

Table 2. Comparative overview of plant-mediated AgNP synthesis

Plant Source	Major Phytochemicals	Particle Size (nm)	Shape	Key Application	Reference
Neem (*A. indica*)	Flavonoids, terpenoids	15–40	Spherical	Antimicrobial	(Kashan *et al.* 2021)
Green Tea (*C. sinensis*)	Catechins	20–50	Spherical	Antioxidant	(Anna and Zygmunt, 2023)
Banana Peel (*M. paradisiaca*)	Polysaccharides	10–30	Quasi-spherical	Catalytic	(Kokila *et al.* 2015)
Pomegranate (*P. granatum*)	Polyphenols	20–60	Irregular	Antioxidant	(Randa *et al.* 2024)
Cinnamon Bark (C. *zeylanicum*)	Cinnamaldehyde	25–45	Spherical	Antibacterial	(Asia *et al.* 2025)

9. APPLICATIONS OF GREEN-SYNTHESIZED AgNPs

9.1 Antimicrobial and Antifungal Activity

AgNPs degrade cell membranes, generate reactive oxygen species (ROS), and exhibit broad-spectrum antibacterial activity against both Gram-positive and Gram-negative bacteria (Pal *et al.* 2007).

9.2 Antioxidant Activity

AgNPs have potent free radical-scavenging capabilities due to the bio-capped phytochemicals they contain. Biosynthesis is a current nanotechnology approach that reduces the toxicity of metal nanoparticles. The green chemistry approach claims that using plant material has made it possible to integrate nanotechnology with biotechnology in a reliable, simple, nontoxic, and ecologically beneficial way (Sathiya *et al.* 2016).

9.3 Catalytic and Environmental Applications

Green-synthesized AgNPs can treat wastewater because they efficiently degrade dyes such as rhodamine B and methylene blue. *Peltophorum pterocarpum* leaf (PPLE) aqueous extract (Ogundare *et al.* 2023) is a readily available and affordable source of stabilizing and reducing substances for producing silver nanoparticles

(AgNPs). Biosynthesis was completed in 45 min at 80 °C and pH 9.

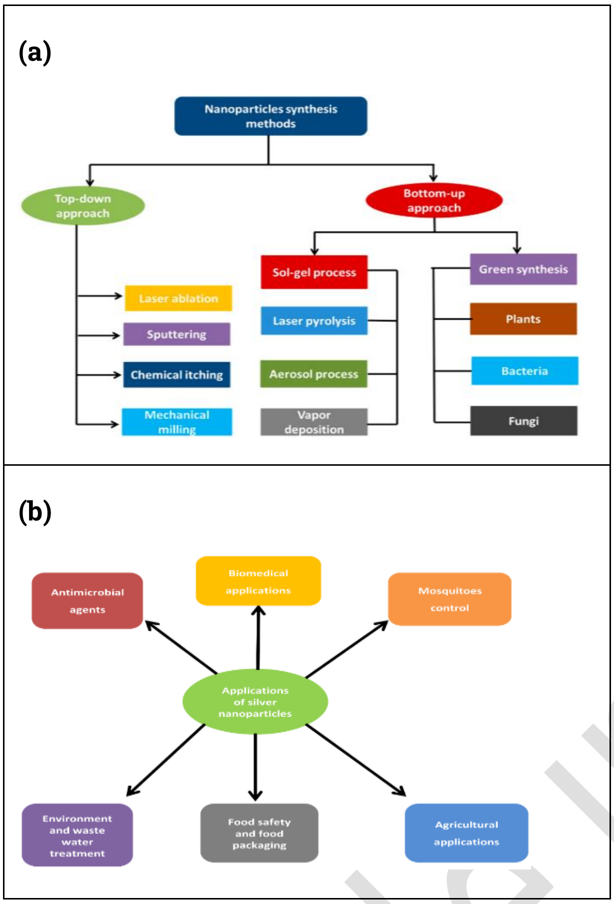

Fig. 14: (a) Various methods for synthesizing AgNPs using top-down and bottom-up approaches and (b) applications of AgNPs (Tijjani *et al.* 2022)

9.4 Biomedical Applications

AgNPs' biocompatibility enables their use in biosensing, targeted drug delivery, and wound healing. AgNPs' unique physicochemical properties have attracted significant interest in biomedical applications (Tijjani *et al.* 2022). AgNPs' roles in cancer management, wound healing, and antibacterial activity highlight their potential to address important health issues.

Several chemical, physical, and biological techniques produce silver nanoparticles in various sizes and forms for a range of applications. These synthesis techniques are divided into two main categories: "top-down" and "bottom-up" approaches (Savita *et al.* 2017). Bottom-up methods (self-assembly) entail dissolving salts in a solvent, reducing silver ions to elemental silver with a reducing agent, and stabilizing the resulting neutral silver nanoparticles with stabilizing agents. Top-down approaches use mechanical methods such as lithography, laser ablation, mechanical milling, and other processes that reduce the size of silver metal from its bulk form to the nanoscale, as shown in Figs. 14a–b. Fig. 14 (a) provides a schematic illustration of top-down and bottom-up methods for creating silver nanoparticles.

Microorganisms are robust and tend to develop resistance to certain antibiotics. There is a pressing need to combat bacterial resistance to several medicines, including alternative treatment substances that are hazardous to microorganisms but safe for humans (Hatice *et al.* 2024; Ahmed *et al.* 2024). Thus, developing nanoparticle-mediated antibacterial drugs is well justified. As shown in Fig.14 (a), many researchers have focused on nanoparticle-based therapeutic medicines synthesized using different methods to target various bacterial species (Yasmeen *et al.* 2024; Khwaja *et al.* 2018). The applications of silver nanoparticles across different fields are growing day by day, as shown in Fig.14 (b).

10. CHALLENGES AND FUTURE PROSPECTS

Consistent size control, scalability, and mechanistic understanding of phytochemical interactions remain challenging despite tremendous advancements (Vidyasagar *et al.* 2023). Sophisticated analytical and computational techniques can optimize reaction conditions and clarify reduction pathways.

Future studies ought to concentrate on:

- Determining the precise active substances responsible for the reduction (Chaudhari *et al.* 2024).
- Developing scalable, automated bioreactors for continuous synthesis (Fatemeh and Ahmad, 2025).
- Assessing biocompatibility and cytotoxicity for biomedical applications (Shimaa *et al.* 2025).

11. CONCLUSION

Green production of silver nanoparticles has emerged as a viable, safe alternative to traditional physical and chemical processes. This review emphasizes the role of plant-derived biomolecules in facilitating the reduction, stabilization, and controlled growth of AgNPs, yielding well-defined crystalline structures and nanoscale morphologies. Characterization methods include UV-Vis spectroscopy, transmission electron microscopy, and X-ray diffraction; these methods, as reported in the literature, consistently confirm the formation of mostly spherical, face-centered cubic AgNPs typically 10 to 50 nm in size. The reviewed literature demonstrates that plant-mediated green synthesis offers an efficient, sustainable, and environmentally friendly approach for producing silver nanoparticles with controlled physicochemical properties. Comparative studies consistently show that the choice of plant extract, phytochemical composition, and synthesis parameters significantly influence nanoparticle size, morphology, crystallinity, stability, and functional performance. Green-synthesized AgNPs show strong potential in antimicrobial, antioxidant, catalytic, biomedical, and environmental applications, highlighting their versatility across diverse fields. However, challenges related to reproducibility, standardized synthesis protocols, large-scale production, long-term stability, and comprehensive toxicity assessment continue to limit their commercial implementation. Future research could focus on mechanistic understanding, process optimization, scalable green synthesis strategies, and regulatory evaluation to facilitate the safe and sustainable development of AgNP-based technologies. Overall, plant-mediated silver nanoparticles represent a promising platform for advancing sustainable nanotechnology and expanding their practical applications in healthcare, environmental remediation, and industrial sectors.

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AUTHOR CONTRIBUTIONS

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DECLARATION

The corresponding author states, on behalf of all authors, that the manuscript is their own work.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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