

# A Review on Green Synthesis of Silver Nanoparticles Using Plant Extracts and Their Antibacterial Properties

Wayan Gracias<sup>1\*</sup>, Indah Miftakhul Janah<sup>2</sup>

<sup>1</sup>Department of Chemistry, Faculty of Mathematics and Natural Sciences, University of Lampung, Bandar Lampung 35145, Indonesia

<sup>2</sup>Research Center for Food Technology and Processing, National Research and Innovation Agency (BRIN), Yogyakarta 55861, Indonesia

<sup>1</sup>[gracias.wayan@fmipa.unila.ac.id](mailto:gracias.wayan@fmipa.unila.ac.id), <sup>2</sup>[indah.miftakhul.janah@brin.go.id](mailto:indah.miftakhul.janah@brin.go.id)

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## ABSTRACT

The escalating challenge of antimicrobial resistance (AMR) has prompted growing scientific attention toward plant-assisted green synthesis of silver nanoparticles (AgNPs) as a sustainable source of antimicrobial materials. This literature review synthesizes findings from 32 peer-reviewed studies published between 2020 and 2026, encompassing more than 32 plant species across 14 countries, to examine how synthesis conditions influence physicochemical characteristics and in vitro antibacterial activity. The reviewed studies indicate that AgNPs formation and performance are shaped more by synthesis parameters than by plant identity itself. The most favorable conditions were generally AgNO<sub>3</sub> concentrations of 1–3 mM, temperatures of 45–75 °C, pH 7–9, extract-to-precursor ratios of 1:9 to 2:1, and reaction times of 30–60 minutes in aqueous systems, typically yielding spherical nanoparticles of 10–30 nm. Smaller particles often showed stronger antibacterial effects, although colloidal stability remained an important determinant of performance. Among the reported systems, *Azadirachta indica*-derived AgNPs showed the strongest antibacterial activity. Overall, the evidence suggests that plant-based AgNP synthesis is a promising and environmentally benign approach, while methodological standardization and broader testing against resistant pathogens remain necessary for more reliable comparison and future application.



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## A. INTRODUCTION

The persistent rise of antimicrobial resistance (AMR) is now widely acknowledged as a critical issue in modern biomedicine, with far-reaching implications for global health systems of the twenty-first century. The diminishing effectiveness of conventional antibiotics now threatens not only the treatment of infectious diseases, but also the safety of routine surgery, immunosuppressive therapy, organ transplantation, and intensive care medicine (Tacconelli et al., 2018; WHO, 2023). Particularly concerning is the escalating emergence of multidrug-resistant pathogens, including the ESKAPE group namely, *Enterococcus faecium*, *Staphylococcus aureus*, *Klebsiella pneumoniae*, *Acinetobacter baumannii*, *Pseudomonas aeruginosa*, and *Enterobacter* species. These organisms are recognized for their capacity to evade multiple therapeutic classes through enzymatic degradation, target modification, biofilm formation, and active efflux systems (Centers for Disease Control and Prevention, 2019; Ventola, 2015). As bacterial adaptation continues to outpace antibiotic discovery, the search for antimicrobial

platforms with fundamentally different mechanisms has become an urgent scientific priority (Laxminarayan et al., 2016).

Silver nanoparticles (AgNPs) are widely regarded as attractive candidates owing to their ability to inhibit a broad range of bacterial species and multi-target mode of action (Dakal et al., 2016). Unlike conventional antibiotics that often act on a single biochemical pathway, AgNPs can simultaneously disrupt cell membranes, induce reactive oxygen species, impair respiratory enzymes, denature proteins, and damage genetic material (Yu et al., 2020). This multifaceted mechanism lowers the probability of rapid resistance development (Baptista et al., 2018). AgNPs have demonstrated effectiveness against both Gram-positive and Gram-negative bacteria, including resistant clinical isolates (Khalifa et al., 2025).

The synthesis route strongly influences the functionality, safety, and reproducibility of AgNPs. Traditional chemical and physical approaches often rely on hazardous reagents and substantial energy input, or expensive instrumentation (Rauf et al., 2025). On the other hand, synthesis routes utilizing plant extracts offer a greener and more practical alternative. Plant extracts contain flavonoids, tannins, terpenoids, sugars, proteins, and related metabolites which facilitate the reduction of  $\text{Ag}^+$  ions to their metallic  $\text{Ag}^0$  state while simultaneously stabilizing the nanoparticle surface (Dhaka et al., 2023a). This dual role simplifies processing, reduces chemical waste, and may improve biocompatibility (Gheisizadeh et al., 2025).

Despite rapid progress, current evidence remains fragmented. Many studies report successful synthesis or inhibition-zone assays without adequately correlating reaction parameters with final nanoparticle properties. Variables such as  $\text{AgNO}_3$  concentration, pH, temperature, extract-to-precursor ratio, solvent type, and reaction time strongly affect nucleation, growth, aggregation, and surface chemistry (Eker et al., 2025). Inconsistent reporting of minimum inhibitory concentration (MIC), minimum bactericidal concentration (MBC), zeta potential, and control standards further limits cross-study comparison (Yin et al., 2020).

This literature review therefore examines how synthesis parameters, phytochemical composition, and colloidal stability jointly determine the physicochemical features along with antibacterial performance of plant-derived AgNPs. It aims to identify the most reproducible conditions for producing stable, spherical, nano-sized silver particles, clarify the role of zeta potential and other key characterization outputs, and highlight methodological limitations that need to be addressed to advance the development of more reliable and potentially translatable antimicrobial nanomaterials for combating AMR.

## B. METHODS

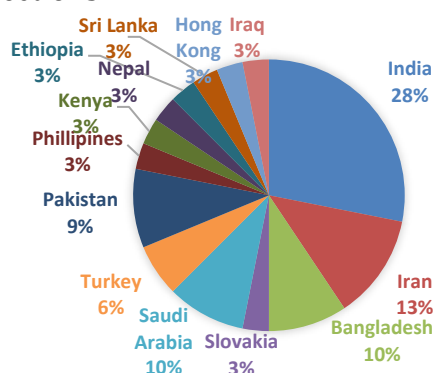
A structured literature review was conducted to examine recent progress in green synthesis of AgNPs using plant extracts and their antibacterial properties. Relevant studies published between 2020 and 2026 were identified through targeted searches of Scopus, ScienceDirect, PubMed, and Google Scholar using combinations of the terms *silver nanoparticles* or *AgNPs* with *green synthesis*, *plant extract*, *antimicrobial*, and *antibacterial*. Additional pertinent articles were traced from the reference lists of selected publications. Only peer-reviewed original research articles were considered when they reported AgNPs synthesis exclusively from plant tissues (leaves, fruits, seeds, roots, bark, or flowers), included quantitative synthesis parameters such as  $\text{AgNO}_3$  concentration and temperature, characterized particle size using at least one analytical technique, and provided measurable in vitro antibacterial results. Studies employing microbial or algal extracts, lacking sufficient characterization data, or published as reviews, conference

papers, or preprints were excluded. The final dataset was then comparatively analyzed to identify relationships between synthesis conditions, nanoparticle properties, and antibacterial performance from an inorganic materials chemistry perspective. The complete dataset of the 32 selected articles, including full bibliographic details, synthesis parameters, characterization data, and antibacterial results, is provided in Supplementary Information.

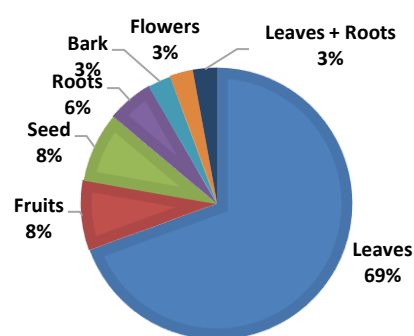
## C. RESULT AND DISCUSSION

### 1. Plant Sources and Geographical Distribution

A review of 32 selected studies (see Supplementary Table S1) identified more than 32 plant species from different genera as phytochemical sources for silver nanoparticles synthesis, highlighting the flexibility of green synthesis in utilizing locally available biological resources. As illustrated in Figure 1, the geographical distribution of research contributions reveals a marked dominance by certain regions. India was the leading contributor with 9 studies (28%), followed by Iran with 4 studies (13%). Bangladesh, Saudi Arabia, and Pakistan each accounted for 3 studies, Turkey contributed 2 studies (6%), while Slovakia, the Philippines, Kenya, Nepal, Ethiopia, Sri Lanka, Hong Kong, and Iraq each represented 1 study (3%). This distribution indicates that plant-mediated AgNPs research is particularly active in developing regions, where rich biodiversity and the urgent need for affordable strategies to address AMR have driven growing scientific interest. As seen in Figure 2, leaves were the most frequently utilized plant organ (69%), consistent with their high abundance of flavonoids, polyphenols, terpenoids, and proteins that can efficiently mediate  $\text{Ag}^+$  reduction and nanoparticle stabilization (Dhaka et al., 2023b; Huq et al., 2022). Moreover, leaf harvesting is generally non-destructive, making it more compatible with sustainable biomass utilization. These findings suggest that future AgNPs development should prioritize not only plant diversity, but also phytochemical richness and resource sustainability as key criteria for scalable green synthesis. This intricate relationship between plant source and phytochemical composition forms the fundamental basis for understanding the subsequent influence of synthesis parameters on AgNPs characteristics, which will be elaborated in the following sections.



**Figure 1.** Country Contributions to AgNPs Research



**Figure 2.** Plant Parts Used in AgNPs Synthesis

### 2. Phytochemical Mechanisms of Reduction and Stabilization

Phytochemicals naturally found within plant extracts, particularly polyphenols, flavonoids, terpenoids, and proteins, are the principal agents responsible for the eco-friendly synthesis of AgNPs. This process is fundamentally a redox reaction that proceeds through three sequential stages: reduction, nucleation, and stabilization (Konkal et al., 2026). During reduction, reactive functional groups including hydroxyl ( $-\text{OH}$ ), carbonyl

(C=O), and carboxyl (-COOH) donate electrons to promote the reduction of Ag<sup>+</sup> into metallic Ag<sup>0</sup>. The generated silver atoms subsequently aggregate into nanoscale nuclei and grow into nanoparticles under controlled conditions. In the final stage, phytochemicals adsorb onto the nanoparticle surface, forming an organic capping layer that suppresses aggregation through steric and electrostatic effects, thereby enhancing colloidal stability and particle uniformity. Accordingly, plant metabolites function as active regulators of nanoparticle size, morphology, and overall performance (Rajeshkumar & Bharath, 2017), as summarized in Table 1.

**Table 1.** Mechanistic Overview of Green-Synthesized AgNPs Formation and Stabilization Mediated by Phytochemicals

Mechanistic Aspect	Representative Indicator	Interpretation in Green AgNPs Formation	References
<b>Reduction Stage</b>	O-H stretching shifts (3200–3500 cm <sup>-1</sup> )	Hydroxyl groups from polyphenols/flavonoids donated electrons to reduce Ag <sup>+</sup> into Ag <sup>0</sup> .	(Abdulwahhab et al., 2026; Ali et al., 2026; Divyalakshmi & Thoppil, 2025; Lemeitaron et al., 2026; Sharif et al., 2026; Sivalingam, 2026b)
	C=O band emergence or shift (1600–1750 cm <sup>-1</sup> )	Oxidation of phytochemicals during electron transfer and coordination with the silver surface.	(Ali et al., 2026; Chakravarty et al., 2022; Divyalakshmi & Thoppil, 2025; Lemeitaron et al., 2026; Shoily et al., 2025; Sivalingam, 2026b)
	Rapid color change / SPR confirmation	Indicative of Ag <sup>0</sup> formation and nanoparticle nucleation through collective electron excitation.	(Alamdari et al., 2025; Ali et al., 2026; Chakravarty et al., 2022; Sharif et al., 2026; Singh et al., 2020; Sivalingam, 2026b)
<b>Nucleation and Growth Stage</b>	Particle size < 20 nm	Rapid nucleation and efficient growth control mediated by biomolecules.	(Asif et al., 2022; Dayana et al., 2026; Oves et al., 2022; Singh et al., 2020)
	Particle size 20–40 nm	Most frequently reported nanoscale range under optimized synthesis conditions.	(Ali et al., 2026; Güneş et al., 2025; Lemeitaron et al., 2026; Sivalingam, 2026b)
	Predominantly spherical morphology	Controlled crystal growth favored isotropic particle formation.	(Ali et al., 2026; Baran et al., 2026; Chakravarty et al., 2022; Oves et al., 2022; Shoily et al., 2025; Sivalingam, 2026b)
<b>Stabilization Stage</b>	N-H / amide bands (1500–1650 cm <sup>-1</sup> )	Proteins and enzymes adsorbed onto AgNPs surfaces as stabilizing (capping) agents.	(Baran et al., 2026; Dayana et al., 2026; Lemeitaron et al., 2026; Oves et al., 2022; Sivalingam, 2026b)
	Negative zeta potential reported	Electrostatic repulsion enhanced colloidal stability and reduced agglomeration.	(Ali et al., 2026; Dayana et al., 2026; Lemeitaron et al., 2026; Pungle et al., 2022; Sivalingam, 2026b)
	Strong negative zeta potential (< -20 mV)	High resistance to long-term aggregation and sedimentation.	(Ali et al., 2026; Dayana et al., 2026; Sivalingam, 2026b)

Mechanistic Aspect	Representative Indicator	Interpretation in Green AgNPs Formation	References
	PDI $\leq$ 0.50	Narrow particle size distribution and good dispersion uniformity.	(Ali et al., 2026; Dayana et al., 2026; Haghi et al., 2025; Lemeitron et al., 2026; Sivalingam, 2026b)
	Ag-O / metal-ligand peaks ( $<900\text{ cm}^{-1}$ )	Strong chemical bonding between oxygen-donor phytochemicals and AgNPs surfaces.	(Akhtar et al., 2025; Bedoura et al., 2026; Lemeitron et al., 2026; Madheslu et al., 2026; Sivalingam, 2026b)

The reviewed studies consistently confirmed this dual reductive-stabilizing role through Fourier Transform Infra-Red (FTIR) analysis. As shown in Table 1, shifts at  $3200\text{--}3500\text{ cm}^{-1}$  indicated the participation of hydroxyl groups in  $\text{Ag}^+$  reduction, whereas bands at  $1600\text{--}1750\text{ cm}^{-1}$  reflected oxidation processes and carbonyl coordination at the silver surface interface (Ali et al., 2026; Baran et al., 2026; Chakravarty et al., 2022). Signals within  $1500\text{--}1650\text{ cm}^{-1}$  further demonstrated the involvement of proteins and amide-containing biomolecules as capping agents (Ali et al., 2026; Dayana et al., 2026; Sivalingam, 2026b). Additional peaks at  $500\text{--}850\text{ cm}^{-1}$ , attributed to Ag-O or metal-ligand interactions, provided evidence of strong interfacial bonding (Acebo et al., 2025; Khambhati et al., 2026; Sivalingam, 2026b). These results suggest that the balance between phytochemical reducing capacity and capping efficiency governs nanoparticle formation rate, particle size distribution, predominantly spherical morphology, and long-term colloidal stability (Dayana et al., 2026; Güneş et al., 2025; Madheslu et al., 2026). Therefore, plant extracts should be considered not merely reaction media, but complex bioreactors that determine the final characteristics of green-synthesized AgNPs (Dayana et al., 2026; Sharif et al., 2026).

### 3. Effect of Synthesis Parameters on AgNPs Properties

The physicochemical characteristics of green-synthesized silver nanoparticles, including particle size, morphology, crystallinity, and colloidal stability, are strongly influenced by synthesis conditions (Güneş et al., 2025; Ojha et al., 2026; Salayová et al., 2021). Based on the 32 reviewed studies, six controllable variables were consistently identified as the principal determinants of final nanoparticle quality, namely  $\text{AgNO}_3$  concentration, temperature, pH, extract-to-metal precursor ratio, reaction time, and extraction solvent (Ali et al., 2026; Divyalakshmi & Thoppil, 2025; Kandiah et al., 2026; Madheslu et al., 2026). Table 2 summarizes the reported ranges in the literature, the evidence-based optimal conditions, and their corresponding effects on nanoparticle properties along with the underlying mechanisms.

**Table 2.** Summary of Synthesis Parameters and Their Effects on Green-Synthesized AgNPs Properties

Parameter	Reported Range in Literature	Evidence-Based Recommended Range	Expected Effect on AgNP Properties	Key Mechanism	References
$\text{AgNO}_3$ concentration	0.1 mM – 100 mM	1–3 mM	Smaller size, improved dispersion, reduced	Balanced nucleation rate allows sufficient phytochemical capping of	(Madheslu et al., 2026; Salayová et al., 2021)

Parameter	Reported Range in Literature	Evidence-Based Recommended Range	Expected Effect on AgNP Properties	Key Mechanism	References
Temperature	RT – 100°C / sunlight	45–75°C	aggregation risk Faster synthesis, narrower size distribution, controlled growth	newly formed nuclei Moderate heating accelerates reduction kinetics without severe degradation of bioactive capping agents	(Güneş et al., 2025; Naveed et al., 2022)
pH	3.2 – 11	7–10	Smaller particles, higher crystallinity, stronger colloidal stability	Deprotonation of phenolic groups enhances electron donation and metal ion reduction	(Ali et al., 2026; Sivalingam, 2026b)
Extract-to-AgNO <sub>3</sub> ratio	1:100 – 10:1	1:9 – 2:1	Better size control and surface stabilization	Greater phytochemical availability improves reduction efficiency and capping coverage	(Madheslu et al., 2026; Pungle et al., 2022)
Reaction time	15 min – 24 h	30–60 min (heated); 4–6 h (Room Temperature)	Complete reduction with limited secondary aggregation	Adequate contact time promotes nucleation and growth completion; excessive duration may induce ripening	(Baran et al., 2026; Khambhati et al., 2026)
Solvent system	Water, ethanol, methanol, mixed	Water (primary choice); ethanol for targeted extraction	Influences reducing power, capping profile, and stability	Solvent polarity determines extracted phytochemical composition	(Sivalingam, 2026b, 2026a)

### 1. Effect of AgNO<sub>3</sub> concentration

AgNO<sub>3</sub> concentration is a key parameter that regulates the availability of Ag<sup>+</sup> ions and, consequently, the nucleation and growth kinetics of silver nanoparticles. Across the 32 reviewed studies, precursor concentrations varied widely from 0.1 mM to 100 mM, although 1 mM was the most frequently employed condition (16/32 studies; 50%). At moderate concentrations, particularly around 1 mM, nucleation proceeds in

a controlled manner, allowing phytochemical capping agents to adequately stabilize newly formed particles before aggregation occurs. In contrast, higher concentrations (>5 mM) often accelerate  $\text{Ag}^0$  formation beyond the stabilizing capacity of the extract, thereby increasing the risk of particle agglomeration (Naveed et al., 2022). Notably, Madheslu et al (2026) reported that even at 100 mM  $\text{AgNO}_3$ , particles of approximately 20 nm were successfully produced under optimized conditions (45°C, pH 9, extract ratio 1:9). This finding highlights that precursor concentration should not be interpreted in isolation, as nanoparticle formation is inherently governed by the interaction of multiple synthesis parameters.

## 2. Effect of Synthesis Temperature

Temperature strongly influences in governing the reduction behaviour of  $\text{Ag}^+$  ions and the final properties of green-synthesized AgNPs primarily by altering the reactivity of phytochemical functional groups (Güneş et al., 2025; Lemeitaron et al., 2026). Across the reviewed studies, synthesis was conducted under room temperature, moderate heating, high-temperature conditions, and sunlight-assisted systems, demonstrating the broad thermal flexibility of plant-mediated methods compared with conventional high-energy routes. Room-temperature synthesis generally preserved thermolabile phytochemicals and produced narrow size distributions, although longer reaction times were required; for example, *Acer oblongifolium* yielded 3–8 nm particles after 24 hours at 25°C (Naveed et al., 2022). Moderate temperatures (45–75°C) provided an effective balance between rapid formation and particle-size control, whereas higher temperatures (80–100°C) accelerated nucleation and often reduced particle size, as reported for *Viburnum opulus* (~20–25 nm at 90–100°C) (Ali et al., 2026; Güneş et al., 2025; Pungle et al., 2022). However, excessive heating may denature proteins and other capping agents, increasing aggregation risk, as observed in *Berberis vulgaris* (Salayová et al., 2021). Sunlight-assisted synthesis offers an energy-efficient alternative with promising nanoparticle quality, although process reproducibility may depend on irradiation intensity (Bedoura et al., 2026).

## 3. Effect of pH and Extract-to-Precursor Ratio on AgNPs Formation

Both pH and the extract-to- $\text{AgNO}_3$  ratio serve as key factors in determining the quality of green-synthesized AgNPs because they influence both the reducing activity of plant compounds and the availability of stabilizing agents (Ali et al., 2026; Ojha et al., 2026; Sharif et al., 2026). In many studies, alkaline conditions (pH 8–11) gave better results than neutral or acidic media, and pH 10 was repeatedly identified as favorable for AgNP formation in plant-mediated systems (Ali et al., 2026; Singh et al., 2020; Sivalingam, 2026a). At higher pH, phenolic hydroxyl groups release electrons more easily, which speeds up the reduction of  $\text{Ag}^+$  ions and promotes the production of smaller, more uniform, and highly crystalline nanoparticles with improved stability. This pattern was reported for *Barleria gibsonii* and *Bacopa monnieri*, where synthesis at pH 10 produced stable and well-dispersed AgNPs (Ali et al., 2026; Sivalingam, 2026a). The extract-to- $\text{AgNO}_3$  ratio is equally important because it determines how many reducing and capping molecules are available relative to silver ions. A higher proportion of extract, such as the commonly used 1:9 ratio or even 10:1 in *Tridax procumbens*, generally supports controlled nucleation and stronger surface protection, resulting in smaller and more stable particles (Pungle et al., 2022; Salayová et al., 2021). This factor also interacts with precursor concentration, since a

sufficient amount of phytochemicals can stabilize nanoparticle formation even at high AgNO<sub>3</sub> levels, as observed at 100 mM in *Clitoria ternatea* (Madheslu et al., 2026). However, too much extract may create excessive surface coating that restricts normal particle growth (Asif et al., 2022). Therefore, careful adjustment of both pH and extract ratio is crucial in yielding consistent and high-quality AgNPs (Ali et al., 2026; Madheslu et al., 2026; Sharif et al., 2026).

#### 4. Effect of Reaction Time

Reaction time strongly influences the efficiency and final properties of green-synthesized AgNPs (Güneş et al., 2025; Ojha et al., 2026). In thermal systems, AgNP formation can occur rapidly within 15 to 60 minutes, with a color transition from light yellow to brown used as a practical indicator of nanoparticle formation (Baran et al., 2026; Khambhati et al., 2026). By contrast, room-temperature synthesis often requires much longer incubation, such as 24 to 48 h in *Acer oblongifolium* and overnight to 24 hours in other plant-mediated systems (Acebo et al., 2025; Naveed et al., 2022; Sivalingam, 2026b). Rapid synthesis ( $\leq 30$  min) was commonly observed under higher temperatures or extract-rich conditions; for example, *Elaeagnus angustifolia* AgNPs formed within 15 min at 30°C with 5 mM AgNO<sub>3</sub> (Baran et al., 2026), while *Phyllanthus maderaspatensis* reached completion within 15 min at 80°C (Khambhati et al., 2026). Therefore, optimizing reaction time is essential to obtain small, uniform, and stable nanoparticles.

#### 5. Effect of Extraction Solvent

Extraction solvent serves as a key factor in governing the phytochemical profile available for AgNPs synthesis and, consequently, the final nanoparticle properties (Akhtar et al., 2025; Aljazzar et al., 2026). Water was the dominant solvent in this dataset (78% of studies), mainly extracting polar biomolecules such as phenolics, flavonoid glycosides, proteins, and polysaccharides that contribute as reducing and stabilizing agents (Güneş et al., 2025; Ojha et al., 2026; Sharif et al., 2026). Ethanol-based extracts, including *Swietenia macrophylla* and *Bacopa monnieri*, produced highly stable AgNPs with strongly negative zeta potentials (−29 and −31.5 mV, respectively), indicating effective surface capping (Sivalingam, 2026b, 2026a). Sequential extraction of *Maytenus gracilipes* used dichloromethane, followed by methanol and water, and the resulting AgNPs were predominantly spherical with an average diameter of  $34.05 \pm 10.5$  nm (Anza et al., 2026). Likewise, methanolic extract of *Garcinia xanthochymus* yielded relatively small particles (13.6–26.6 nm) with strong bioactivity (Divyalakshmi & Thoppil, 2025). Overall, solvent selection influences the type and abundance of extracted phytochemicals, making it a key parameter for controlling AgNP size, stability, and functional performance.

#### 4. Characterization of Green-Synthesized AgNPs

Characterization of green-synthesized AgNPs requires integrated analytical techniques to confirm formation and define their physicochemical properties. UV-Vis spectroscopy consistently verifies nanoparticle formation through the Surface Plasmon Resonance (SPR) band within the ~400–450 nm region, while XRD confirms the well-defined face-centered cubic (fcc) lattice of elemental silver (Ali et al., 2026; Sivalingam, 2026b). FTIR identifies functional groups involved in reduction and capping, and TEM/SEM reveal morphology, typically showing predominantly spherical particles in these studies (Ali et al., 2026; Anza et al., 2026; Baran et al., 2026; Divyalakshmi & Thoppil,

2025; Ojha et al., 2026). Together, these methods provide consistent evidence linking optical, structural, and chemical characteristics of AgNPs.

Particle size and surface charge are key factors governing functionality and stability. Particle sizes across the reviewed studies ranged broadly from approximately 10 to 50 nm, with examples such as 11.1–45.4 nm, 15.95–43.04 nm, 20–25 nm, and 20–50 nm (Ali et al., 2026; Bedoura et al., 2026; Lemeitaron et al., 2026; Pungle et al., 2022; Shoily et al., 2025). Smaller particles often show higher antibacterial activity because their larger surface area facilitates more direct cell contact and faster Ag<sup>+</sup> release (Acebo et al., 2025; Ali et al., 2026; Sharif et al., 2026). However, stability is more reliably indicated by zeta potential, typically observed in the range of –20 to –35 mV, reflecting effective electrostatic repulsion from phytochemical capping layers (Haghi et al., 2025; Pungle et al., 2022; Sivalingam, 2026b). Inconsistent reporting of zeta potential highlights a methodological gap, as it is essential for predicting long-term colloidal stability and practical performance.

## 5. Antibacterial Activity

Plant-mediated synthesized AgNPs exhibit broad-spectrum antimicrobial activity against both Gram-negative and Gram-positive bacteria, with *Escherichia coli* and *Staphylococcus aureus* among the most frequently investigated organisms in this review. (Acebo et al., 2025; Aljazzar et al., 2026; Bedoura et al., 2026; Güneş et al., 2025; Lemeitaron et al., 2026). Common evaluation methods include agar well diffusion, disc diffusion, and microdilution assays; however, variations in methodology and nanoparticle concentrations limit direct comparison across studies. Overall, AgNPs consistently exhibit significant antibacterial effects, with some systems showing superior performance to conventional antibiotics. To facilitate a structured comparison of these findings, Table 3 summarizes representative antibacterial data across selected studies, including plant sources, test organisms, methods, and efficacy indicators.

**Table 3.** Representative antibacterial activity of plant-mediated synthesized AgNPs across selected studies

Reference	Plant Source	Bacterium (Gram)	Method	AgNPs (µg/mL)	Inhibition Zone (mm)	MIC (µg/mL)
(Aljazzar et al., 2026)	<i>Azadirachta indica</i>	<i>E. coli</i> (–)	AWD	50–100	45 ± 0.21	7
(Aljazzar et al., 2026)	<i>Azadirachta indica</i>	<i>S. aureus</i> (+)	AWD	50–100	33 ± 0.13	5
(Ali et al., 2026)	<i>Barleria gibsonii</i>	<i>S. aureus</i> (+)	AWD	500	21.5	15.6
(Ali et al., 2026)	<i>Barleria gibsonii</i>	<i>E. coli</i> (–)	AWD	500	20.5	31.2
(Baran et al., 2026)	<i>Elaeagnus angustifolia</i>	<i>E. coli</i> (–)	DD + MIC	113–524	24.32	113
(Oves et al., 2022)	<i>Conocarpus lancifolius</i>	<i>E. coli</i> (–)	DD	60	24	NR
(Sharif et al., 2026)	<i>Eichhornia crassipes</i>	MDR isolates (–)	DD + Microdilution	60	10–13	15

Reference	Plant Source	Bacterium (Gram)	Method	AgNPs ( $\mu\text{g/mL}$ )	Inhibition Zone (mm)	MIC ( $\mu\text{g/mL}$ )
(Salayová et al., 2021)	<i>Brassica nigra</i>	<i>E. coli</i> , <i>P. aeruginosa</i> (-)	DD	50–100	16–18	~25
(Abdulwahab et al., 2026)	<i>Ocimum sanctum</i>	<i>B. cereus</i> (+)	AWD	—	27 (33 synergy)	NR
(Shoily et al., 2025)	<i>Calathea ornata</i>	<i>E. coli</i> (-), <i>S. aureus</i> (+)	ASTM E2149	—	—	—

**Note:** AWD = agar well diffusion; DD = disc diffusion; MIC = minimum inhibitory concentration; NR = not reported; MDR = multidrug-resistant. Inhibition zone values are expressed as mean diameter (mm), and AgNPs concentrations are presented as reported in the respective studies.

Notably, *Azadirachta indica*-derived AgNPs exhibited the strongest activity, resulting in inhibition zones of up to 45 mm for *E. coli* and 33 mm for *S. aureus*, along with low MIC values (5–7  $\mu\text{g/mL}$ ), indicating high potency (Aljazzar et al., 2026). Despite these promising results, the limited inclusion of multidrug-resistant strains highlights a gap in clinical relevance. The combined findings highlight that AgNPs synthesized through plant-mediated pathways display marked inhibitory effects against bacterial systems, while emphasizing the need for standardized testing approaches and broader evaluation against resistant pathogens.

#### D. CONCLUSION

This literature review of 32 studies across more than 32 plant species and 14 countries shows that green synthesis with plant extracts is a robust and widely applicable route to producing antimicrobially active silver nanoparticles, but the strongest determinant of performance is not plant identity alone, rather the careful optimization of synthesis conditions. Across the studies, the most reproducible results came from aqueous systems using  $\text{AgNO}_3$  around 1 to 3 mM, temperatures of 45 to 75°C, pH 7 to 10, extract-to- $\text{AgNO}_3$  ratios near 1:9 to 2:1, and reaction times of 30 to 60 minutes, which typically yielded spherical AgNPs in the 10 to 30 nm range with good colloidal stability and strong antibacterial activity.

A key mechanistic conclusion is that zeta potential and aggregation behavior are as important as nominal particle size, because well-stabilized nanoparticles with moderately negative surface charge consistently show better functional performance than smaller but unstable particles. Overall, the evidence indicates that green-synthesized AgNPs using plant extracts are promising broad-spectrum antimicrobial agents, including against multi drug resistance-related targets, but future progress depends on standardized testing, mandatory zeta potential reporting, long-term stability studies, and in vivo validation to support translation beyond the laboratory.

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