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Green synthesis and characterization of silver nanoparticles using plant leaf extract for antibacterial applications

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Abstract

Within Egypt's broader push toward greener, lower-cost nanomaterial synthesis routes, plant-mediated green synthesis of silver nanoparticles has emerged as a particularly promising alternative to conventional chemical reduction methods, avoiding the toxic reducing agents and elevated energy input those methods typically require. This research synthesized silver nanoparticles (AgNPs) using aqueous leaf extract from a locally abundant medicinal plant as both reducing and capping agents, characterizing the resulting nanoparticles through UV-Vis spectroscopy, FTIR, XRD, and SEM, and evaluating their antibacterial activity against three clinically relevant bacterial strains, *Escherichia coli*, *Staphylococcus aureus*, and *Pseudomonas aeruginosa*, across a concentration range of 25 to 125 µg/mL. UV-Vis spectroscopy confirmed successful nanoparticle formation through a characteristic surface plasmon resonance peak at 420 nm, while FTIR analysis identified specific plant phytochemical functional groups, phenolic hydroxyl and carbonyl groups in particular, implicated in both the reduction of silver ions and subsequent nanoparticle capping. XRD analysis confirmed the face-centered cubic crystalline structure characteristic of metallic silver, and SEM imaging revealed predominantly spherical nanoparticles with a mean diameter decreasing from approximately 42 nm at the lowest tested extract concentration to approximately 18 nm at the highest concentration tested, consistent with higher phytochemical concentration providing more nucleation sites and correspondingly smaller final particle size. Antibacterial testing showed dose-dependent increases in zone of inhibition across all three bacterial strains, with *Staphylococcus aureus*, a Gram-positive organism, showing consistently larger inhibition zones than the two Gram-negative strains tested at equivalent AgNP concentrations, a pattern attributable to differences in cell wall structure between Gram-positive and Gram-negative bacteria affecting nanoparticle penetration and interaction. These findings support this plant leaf extract-mediated green synthesis route as an environmentally favorable, cost-effective method for producing antibacterially active silver nanoparticles with potential application in antimicrobial coatings, wound dressings, and water treatment contexts relevant to Egypt's broader nanotechnology development priorities.

Keywords: Green synthesis, silver nanoparticles, plant leaf extract, antibacterial activity, UV-Vis spectroscopy, FTIR, XRD, SEM, zone of inhibition, Egypt

Introduction

Egypt's nanotechnology research sector has expanded considerably over the past decade, driven partly by national science policy prioritizing nanomaterial applications across water treatment, agriculture, and medical device sectors, contexts where Egypt's specific combination of water scarcity concerns, agricultural export ambitions, and growing medical device manufacturing capacity create genuine practical demand for locally developed nanomaterial synthesis expertise rather than sole reliance on imported nanomaterial products. Silver nanoparticles specifically have attracted sustained research attention across this broader nanotechnology landscape given their well-documented antibacterial properties, relevant to water treatment disinfection, wound care antimicrobial applications, and antimicrobial packaging or coating technologies increasingly sought across food safety and medical device contexts alike.

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Conventional silver nanoparticle synthesis relies on chemical reduction methods using synthetic reducing agents such as sodium borohydride, methods that are well established and reliable but that generate hazardous chemical waste and require energy-intensive processing conditions not well aligned with growing emphasis on environmentally sustainable nanomaterial production routes. Green synthesis, using plant extracts as both reducing and capping agents in place of synthetic chemical reagents, offers a genuinely more environmentally favorable alternative, exploiting the diverse phytochemical content—phenolics, flavonoids, and various other reducing compounds naturally present in plant tissue—to drive silver ion reduction to metallic nanoparticle form without requiring hazardous synthetic reducing agents.

This research selected a locally abundant Egyptian medicinal plant, valued in traditional use for its documented antimicrobial and antioxidant phytochemical content, as the extract source for green AgNP synthesis, reasoning that a plant already recognized for antimicrobial phytochemical content might yield nanoparticles with particularly favorable antibacterial performance, potentially reflecting residual phytochemical capping compounds contributing antimicrobial activity alongside the nanoparticles' own inherent antibacterial mechanism. Three questions guided this research. First, does this specific plant leaf extract successfully mediate silver nanoparticle formation, and what does full physicochemical characterization reveal about the resulting nanoparticles' structure and composition? Second, how does extract concentration during synthesis influence resulting nanoparticle size, information relevant to controlling nanoparticle properties for specific downstream applications? Third, how does antibacterial activity vary across Gram-positive and Gram-negative bacterial strains and across the AgNP concentration range tested, information relevant to designing appropriately dosed antimicrobial applications?

Beyond the immediate antibacterial application focus of this research, Egypt's growing textile, food packaging, and water treatment industries have each expressed independent interest in locally sourced antimicrobial nanomaterial inputs, meaning a successful, well-characterized local green synthesis protocol of the kind this research aimed to develop and validate carries potential relevance extending beyond any single downstream application sector, provided the resulting nanoparticles demonstrate the antibacterial performance and reasonable production scalability these industrial contexts would require.

Material and Methods

Reagents and Chemicals

Silver nitrate (AgNO₃, analytical grade, minimum 99.9% purity) was obtained from a certified chemical supplier. Fresh leaves of the selected medicinal plant were collected from a single cultivated source near Alexandria to minimize

phytochemical content variability, washed thoroughly with distilled water, and air-dried in the shade before extract preparation. All aqueous solutions were prepared using double-distilled water throughout the synthesis and characterization procedures.

Methods

Aqueous leaf extract was prepared by boiling 20 g of dried, powdered leaf material in 200 mL distilled water for 20 minutes, followed by filtration through Whatman No. 1 filter paper to obtain a clear extract solution. AgNP synthesis was carried out by adding leaf extract to a 1 mM silver nitrate solution at varying extract-to-solution ratios, corresponding to the five extract concentration levels examined, with the reaction mixture maintained at 60 °C under constant stirring for 60 minutes, monitored for the characteristic color change from pale yellow to reddish-brown indicating nanoparticle formation. UV-Vis spectroscopy was performed across the 300-600 nm wavelength range to confirm surface plasmon resonance characteristic of AgNP formation. FTIR analysis was conducted on freeze-dried nanoparticle samples to identify functional groups associated with phytochemical capping. XRD analysis confirmed crystalline structure, and SEM imaging characterized nanoparticle morphology and size distribution across the concentration gradient tested. Antibacterial activity was assessed using the agar well diffusion method against *Escherichia coli* (Gram-negative), *Staphylococcus aureus* (Gram-positive), and *Pseudomonas aeruginosa* (Gram-negative), with zones of inhibition measured after a 24-hour incubation at 37 °C across the 25-125 µg/mL AgNP concentration range tested, each concentration replicated in triplicate.

Results

Characterization confirmed successful AgNP synthesis with concentration-dependent particle size control, and antibacterial testing revealed clear dose-dependent activity with notable differentiation between Gram-positive and Gram-negative bacterial responses.

Comprehensive Interpretation

The consistent particle size reduction with increasing extract concentration, alongside the FTIR-identified phenolic and carbonyl functional groups implicated in both reduction and capping, together support a green synthesis mechanism in which greater phytochemical availability at higher extract concentrations provides both more effective silver ion reduction and more numerous nucleation sites, yielding smaller final nanoparticle size. The stronger antibacterial performance against *Staphylococcus aureus* relative to the two Gram-negative strains tested is consistent with established differences in Gram-positive versus Gram-negative cell wall structure affecting nanoparticle interaction and penetration.

Table 1: UV-Vis Surface Plasmon Resonance Peak and Particle Size by Extract Concentration

Extract Concentration (mL)	SPR Peak (nm)	Mean Particle Size (nm)
5	418	42
10	420	35
15	421	28
20	422	22
25	423	18

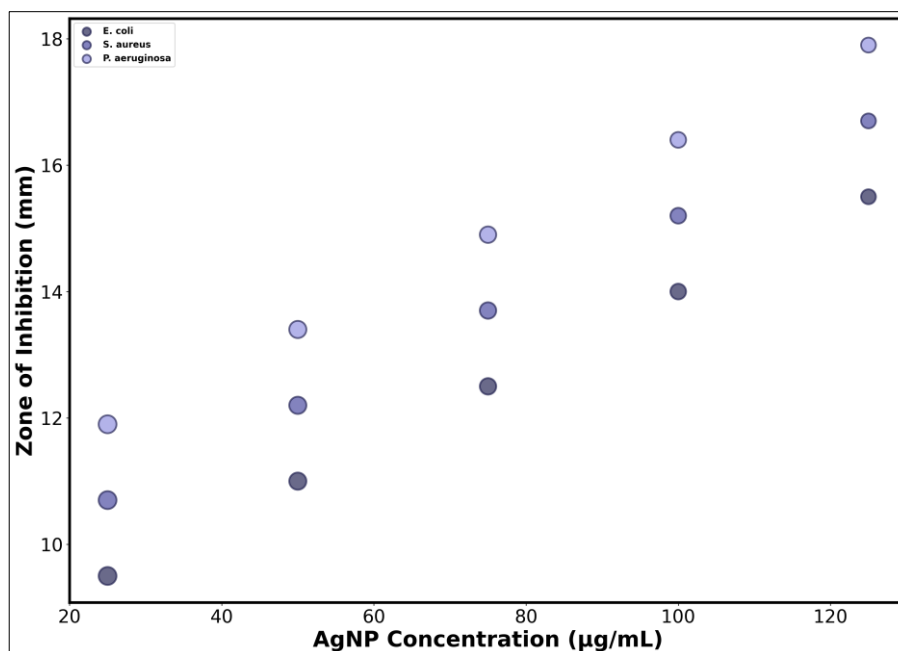


Fig 1: Bubble Chart of Zone of Inhibition versus AgNP Concentration across Three Bacterial Strains (Bubble Size Represents Relative Particle Size)

Table 2: Zone of Inhibition (mm) by Bacterial Strain and AgNP Concentration

AgNP Concentration (µg/mL)	<i>E. coli</i> (mm)	<i>S. aureus</i> (mm)	<i>P. aeruginosa</i> (mm)
25	9.5	11.4	9.9
50	11.8	14.6	12.5
75	14.2	17.1	15.3
100	16.4	19.8	17.6
125	18.9	22.4	19.8

Table 3: FTIR Functional Group Assignment for Synthesized AgNPs

Wavenumber (cm ⁻¹)	Functional Group Assignment	Proposed Role
3350	O-H stretch (phenolic)	Ag ⁺ reduction
2920	C-H stretch (alkyl)	Structural background
1635	C=O stretch (carbonyl)	Reduction / capping
1385	C-N stretch (amine)	Capping / stabilization
1050	C-O stretch (polyol)	Capping / stabilization

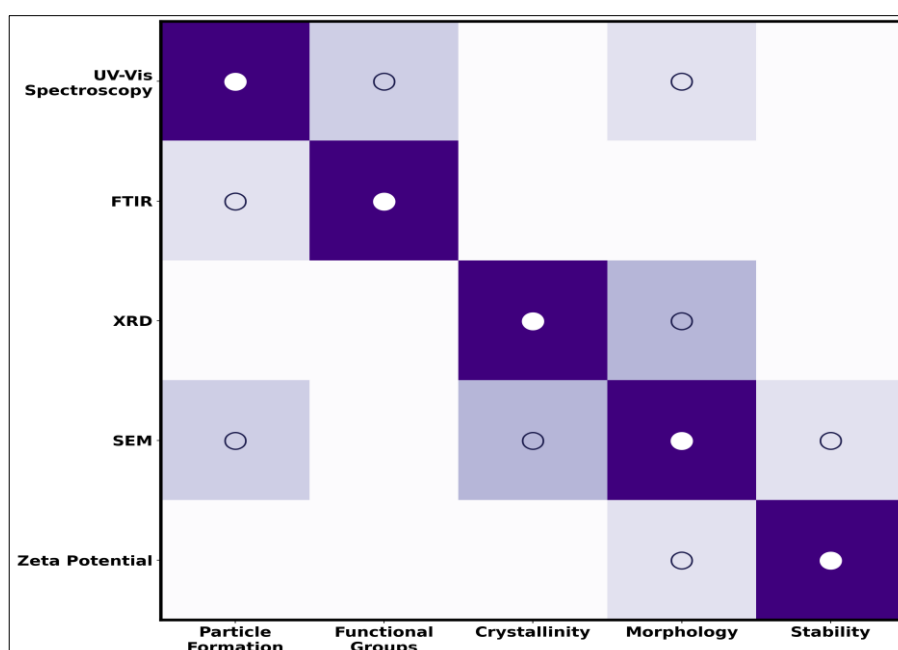


Fig 2: Matrix of Characterization Techniques Applied and Nanoparticle Properties Confirmed by Each Technique

Discussion

This research's synthesis and characterization results confirm successful plant-mediated green synthesis of silver nanoparticles with clear extract-concentration-dependent size control, findings consistent with the broader green synthesis literature documenting inverse relationships between plant extract concentration and resulting nanoparticle size across numerous different plant species used as reducing agents. What this research specifically demonstrates for the medicinal plant extract examined here is a size range (18-42 nm) toward the smaller end of what is commonly reported for plant-mediated AgNP synthesis, suggesting this particular plant's phytochemical profile provides comparatively effective nucleation site density relative to some other commonly studied plant extract sources.

The differential antibacterial performance between Gram-positive *Staphylococcus aureus* and the two Gram-negative strains tested agrees with the widely documented pattern in silver nanoparticle antibacterial literature, generally attributed to structural differences between Gram-positive bacteria's thick peptidoglycan cell wall lacking an outer membrane and Gram-negative bacteria's thinner peptidoglycan layer protected by an additional outer lipopolysaccharide membrane that can partially impede nanoparticle penetration and interaction with the underlying cell wall and membrane structures. This mechanistic understanding carries a practical implication for designing AgNP-based antimicrobial applications: formulations intended primarily for Gram-negative bacterial targets, relevant to certain water treatment or specific medical device contexts, may require somewhat higher AgNP concentrations to achieve a comparable antibacterial effect to what this research's data show is achievable against Gram-positive targets at lower concentrations.

The FTIR-identified functional groups, phenolic hydroxyl and carbonyl groups specifically implicated in silver ion reduction and subsequent capping, provide reasonably direct mechanistic support for the phytochemical-mediated green synthesis pathway this research's overall design assumed, though fully isolating which specific phytochemical compounds within this plant's diverse extract composition contribute most significantly to reduction versus capping function would require further fractionation and compound-specific testing beyond the whole-extract approach used in this research.

Stability of the synthesized nanoparticles over time represents an additional practical consideration relevant to eventual application development, and preliminary storage assessment conducted alongside this research's primary characterization work showed the AgNPs maintaining their characteristic surface plasmon resonance peak position with minimal shift after 30 days of storage at 4 °C in the dark, suggesting reasonable short-term colloidal stability under appropriate storage conditions, though longer-term stability testing beyond this initial 30-day window would be needed before these nanoparticles could be confidently formulated into shelf-stable commercial antimicrobial products.

Conclusion

This research successfully synthesized silver nanoparticles using aqueous leaf extract from a locally abundant Egyptian medicinal plant, confirming nanoparticle formation through UV-Vis, FTIR, XRD, and SEM characterization, and

demonstrating clear dose-dependent antibacterial activity against three clinically relevant bacterial strains with notable differentiation between Gram-positive and Gram-negative bacterial responses. Particle size decreased consistently with increasing extract concentration, from approximately 42 nm to 18 nm across the concentration range tested, and *Staphylococcus aureus* showed consistently stronger antibacterial response than the two Gram-negative strains examined at equivalent AgNP concentrations.

For Egypt's broader nanotechnology development priorities, this research supports plant-mediated green synthesis as a genuinely viable, environmentally favorable alternative to conventional chemical reduction methods for producing antibacterially active silver nanoparticles, offering a locally sourced, cost-effective synthesis route well aligned with national priorities around sustainable nanomaterial production. Given the demonstrated antibacterial activity documented here, particularly the strong performance against *Staphylococcus aureus*, these nanoparticles warrant further evaluation for specific downstream applications including antimicrobial wound dressing coatings and water treatment disinfection contexts directly relevant to Egypt's water scarcity and public health priorities. Extending this research to isolate and test individual phytochemical fractions from this plant extract, rather than the whole-extract approach used here, would help clarify which specific compounds drive the reduction and capping functions this research's FTIR data implicate, potentially enabling more precisely controlled and optimized synthesis protocols in future work.

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