

Programming Silver Nanoparticle Functionality through Organ-Specific Seed and Pod Extracts of *Amomum aromaticum*

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Abstract

Silver nanoparticles (AgNPs) synthesized via green routes are increasingly explored for biomedical applications; however, most studies rely on a single plant organ or whole-plant extracts, overlooking the inherent phytochemical heterogeneity within individual plant species. In this work, we demonstrate that different organs of the same medicinal plant can program distinct nanoparticle properties and biological functions. Aqueous seed and pod extracts of *Amomum aromaticum* (Bengal cardamom) were employed as reducing and stabilizing agents to synthesize AgNPs under controlled near-neutral conditions (pH 6.0 ± 0.2). Comprehensive characterization using UV–Vis spectroscopy, FTIR, XRD, TEM, DLS, EDX, and zeta potential analysis confirmed the formation of stable, crystalline AgNPs with organ-dependent differences in size and surface chemistry. Seed-derived AgNPs exhibited smaller particle sizes (15–20 nm), higher colloidal stability (-25.4 ± 1.2 mV), and superior antibacterial activity against *Staphylococcus aureus* and *Escherichia coli*. In contrast, pod-derived AgNPs were comparatively larger (25–30 nm) but showed enhanced antioxidant activity ($81 \pm 2.1\%$) and wound-healing efficiency ($78 \pm 3.1\%$ closure within 24 h). These functional differences are attributed to the dominance of flavonoids in seeds, which promote rapid nucleation and smaller particle formation, and phenolic/tannin compounds in pods, which favor antioxidant and regenerative behavior. This study provides experimental evidence that organ-specific phytochemical composition can be used as a practical handle to tailor AgNP functionality for targeted biomedical applications.

1. Introduction

1.1 Background

Nanotechnology has significantly influenced the development of advanced materials for biomedical and environmental applications by enabling control over matter at the nanoscale. Among metallic nanomaterials, silver nanoparticles (AgNPs) have been extensively studied due to their unique optical properties, high surface reactivity, and broad-spectrum antimicrobial activity [1–3]. These characteristics have led to their application in wound dressings, antibacterial coatings, antioxidant systems, and drug delivery platforms [4–6]. Traditional chemical and physical methods used for AgNP synthesis often require toxic reducing agents, elevated temperatures, or high energy input, which can limit their biomedical applicability and environmental sustainability [7]. In this context, green synthesis approaches—particularly plant-mediated methods—have emerged as viable alternatives. Plant extracts contain diverse phytochemicals capable of reducing Ag^+ ions to Ag^0 while simultaneously stabilizing the formed nanoparticles, thereby eliminating the need for hazardous reagents and improving biocompatibility [8–10].

1.2 Research gap: limitations of current green synthesis studies

Although numerous studies have reported the successful synthesis of AgNPs using plant extracts, most investigations rely on either whole-plant materials or a single plant organ, such as leaves or fruits [11–13]. This approach implicitly assumes that different parts of the same plant contribute similarly to nanoparticle formation. However, plants exhibit strong organ-specific metabolic specialization, and the qualitative and quantitative composition of secondary metabolites can vary considerably between seeds, pods, leaves, and roots [14, 15]. Only a limited number of reports have examined intra-species organ-level variation in nanoparticle synthesis, and even fewer have attempted to link such variation to distinct biological functions of the resulting nanoparticles [16, 17]. As a result, the potential of plant organ selection as a controllable and rational parameter for tailoring nanoparticle properties remains insufficiently explored.

1.3 Rationale for selecting *Amomum aromaticum*

Amomum aromaticum Roxb. (Bengal cardamom), belonging to the family Zingiberaceae, is a medicinal spice traditionally used for its antimicrobial, anti-inflammatory, and digestive properties [18, 19]. Phytochemical studies have shown that different organs of *A. aromaticum* possess distinct chemical profiles. The seeds are reported to be rich in flavonoids and related polyphenols, which are effective electron donors and can promote rapid metal ion reduction [20]. In contrast, the pods contain higher levels of phenolic acids and tannins, compounds well known for their antioxidant capacity and involvement in wound-healing processes [21, 22]. This inherent phytochemical heterogeneity within a single plant species provides a suitable model to investigate how organ-specific chemistry influences nanoparticle nucleation, growth, surface stabilization, and biological performance under identical synthesis conditions.

1.4 Aim and significance of the present study

The present work was designed to systematically evaluate whether different organs of *A. aromaticum* can generate AgNPs with distinct physicochemical characteristics and biomedical functions. Silver nanoparticles were synthesized separately using seed and pod extracts under controlled near-neutral conditions, followed by comprehensive characterization using UV–Vis spectroscopy, FTIR, XRD, TEM, DLS, EDX, and zeta potential analysis. The biological performance of the synthesized AgNPs was assessed through antioxidant, antibacterial, cytotoxicity, biofilm inhibition, and wound-healing assays with appropriate controls and statistical validation [23–26]. By directly correlating organ-specific phytochemical composition with nanoparticle properties and biological outcomes, this study demonstrates that plant organ selection can serve as a rational design parameter in green nanoparticle synthesis rather than a purely experimental convenience.

Novelty of the Present Study

The novelty of this work lies in its organ-specific, intra-species approach to green nanoparticle synthesis, rather than the commonly reported use of a single plant organ or cross-species comparisons. Although plant-mediated synthesis of silver nanoparticles is well established, systematic evaluation of how

different organs of the same medicinal plant regulate nanoparticle properties and biological functions remains limited.

In the present study, seed and pod extracts of *Amomum aromaticum* were employed under identical synthesis conditions, allowing the influence of organ-specific phytochemical composition to be isolated without confounding effects from reaction parameters such as pH, temperature, or precursor concentration. This controlled design demonstrates that plant organs inherently differ in their ability to direct nanoparticle nucleation, growth, surface stabilization, and colloidal behavior. More importantly, the study reveals functional divergence rather than marginal variation. Seed-derived AgNPs preferentially exhibit enhanced antibacterial activity due to smaller particle size and higher surface stability, whereas pod-derived AgNPs show superior antioxidant and wound-healing performance associated with phenolic- and tannin-rich surface capping. This clear separation of biomedical functionality originating from different organs of the same plant represents a conceptual advance beyond descriptive green synthesis studies. By establishing plant organ selection as an intrinsic design parameter, this work provides a rational and reproducible strategy for tailoring nanoparticle functionality using naturally occurring phytochemical heterogeneity.

2. Materials and Methods

2.1 Chemicals and reagents

Silver nitrate (AgNO_3 , $\geq 99.9\%$ purity) was procured from an analytical-grade supplier and used without further purification. All aqueous solutions were prepared using double-distilled water. Chemicals and reagents required for antioxidant, antibacterial, cytotoxicity, biofilm inhibition, and wound-healing assays were of analytical grade and prepared according to standard protocols [23].

2.2 Plant material collection and authentication

Fresh fruits of *Amomum aromaticum* Roxb. (Bengal cardamom) were collected from Tirupati, Andhra Pradesh, India. Botanical authentication was performed by Dr. A. Indira Priyadarshini, Department of Botany, Government Degree College (Autonomous), Nagari. A voucher specimen (Voucher No. AAR-2025-01) was deposited in the institutional herbarium for future reference. The fruits were thoroughly washed with distilled water, manually separated into seeds and pods, and dried in a hot-air oven at 50°C until constant weight was achieved to prevent phytochemical degradation.

2.3 Preparation of seed and pod extracts

Dried seed and pod materials were ground separately into fine powders using a sterile mechanical grinder. For aqueous extraction, 5 g of each powdered sample was boiled in 100 mL of distilled water for 20 min. The extracts were cooled to room temperature and filtered through Whatman No. 1 filter paper to remove particulate matter. The resulting extracts corresponded to an approximate concentration of 50 mg mL^{-1} (dry weight basis) and were stored at 4°C until use. These extracts served as both reducing and stabilizing agents during silver nanoparticle synthesis [1, 8].

2.4 Green synthesis of silver nanoparticles

A freshly prepared 1 mM aqueous AgNO_3 solution was mixed with each plant extract in a 1:1 (v/v) ratio under ambient conditions. The pH of the reaction mixture was adjusted and maintained at 6.0 ± 0.2 using 0.1 M NaOH or HCl and monitored using a calibrated digital pH meter. Preliminary optimization experiments conducted over a pH range of 4–8 indicated that near-neutral pH produced intense surface plasmon resonance bands and stable colloidal suspensions, consistent with previous reports on plant-mediated AgNP synthesis [27–30]. The reaction mixtures were incubated at $25 \pm 2^\circ\text{C}$ without stirring. Formation of AgNPs was confirmed visually by a gradual color change from pale yellow to reddish brown.

2.5 Characterization of silver nanoparticles

2.5.1 UV–Visible spectroscopy

UV–Visible absorption spectra were recorded between 300 and 600 nm using a UV–Vis spectrophotometer to confirm surface plasmon resonance characteristics of the synthesized AgNPs [31].

2.5.2 Fourier Transform Infrared (FTIR) spectroscopy

FTIR spectra were recorded in the range of $4000\text{--}400\text{ cm}^{-1}$ using the KBr pellet method to identify functional groups involved in Ag^+ reduction and nanoparticle surface capping [32].

2.5.3 X-ray diffraction (XRD)

Crystalline structure and phase purity were analyzed using an X-ray diffractometer equipped with Cu K α radiation ($\lambda = 1.5406\text{ \AA}$). Diffraction patterns were recorded over a 2θ range of $10^\circ\text{--}80^\circ$ [33].

2.5.4 Transmission electron microscopy (TEM)

Particle morphology, size, and dispersion were examined using transmission electron microscopy. Particle size distributions were estimated by measuring multiple nanoparticles from representative micrographs [34].

2.5.5 Dynamic light scattering (DLS) and zeta potential

Hydrodynamic diameter, polydispersity index (PDI), and zeta potential were measured using a particle size analyzer to evaluate colloidal stability of the synthesized AgNPs [35].

2.5.6 Energy-dispersive X-ray spectroscopy (EDX)

Elemental composition of the nanoparticles was confirmed using energy-dispersive X-ray spectroscopy attached to the electron microscope [36].

2.6 Biological activity evaluation

All biological assays were performed in triplicate (n = 3).

2.6.1 Antioxidant activity

Free radical scavenging activity was evaluated using the DPPH assay following the method described by Brand-Williams et al. [37]. Results were expressed as percentage radical scavenging activity.

2.6.2 Antibacterial activity

Antibacterial activity was assessed using the agar well diffusion method against *Staphylococcus aureus* and *Escherichia coli*. AgNP concentrations ranged from 50 to 200 $\mu\text{g mL}^{-1}$. Ciprofloxacin (10 $\mu\text{g mL}^{-1}$) and distilled water were used as positive and negative controls, respectively [38].

2.6.3 Cytotoxicity assay

Cytotoxicity was evaluated using the MTT assay on human dermal fibroblast (HDF) cell lines obtained from the National Centre for Cell Science (NCCS), Pune, India, following standard procedures. Cells were cultured in Dulbecco's Modified Eagle Medium (DMEM) supplemented with 10% fetal bovine serum and 1% penicillin–streptomycin at 37°C in a humidified atmosphere containing 5% CO₂. Cell viability was expressed as a percentage relative to untreated controls [39].

2.6.4 Biofilm inhibition assay

Biofilm inhibition was quantified using the crystal violet staining method as previously described [40].

2.6.5 In vitro wound-healing (scratch) assay

Cell migration and wound closure were evaluated using an in vitro scratch assay on confluent fibroblast monolayers. Wound closure percentage was calculated after 24 h of incubation [39].

2.7 Statistical analysis

All data were expressed as mean $\pm$ standard deviation. Statistical analysis was performed using one-way analysis of variance (ANOVA), with $p < 0.05$ considered statistically significant. GraphPad Prism software was used for data analysis [41].

3. Results and Discussion

3.1 Formation and optical characteristics of AgNPs

The successful formation of silver nanoparticles using seed and pod extracts of *Amomum aromaticum* was initially indicated by a visible color change of the reaction mixture from pale yellow to reddish brown within 30 min. This color development is characteristic of surface plasmon resonance (SPR), arising from the collective oscillation of conduction band electrons in metallic silver nanoparticles upon interaction with light [31, 35]. The UV–Visible spectra (Fig. 1) further confirmed nanoparticle formation. Seed-derived AgNPs exhibited a well-defined SPR peak centered at **432 $\pm$ 2 nm**, whereas pod-derived

AgNPs showed a red-shifted SPR peak at **445 ± 3 nm**. Such red-shifting is commonly associated with an increase in particle size and differences in dielectric environment surrounding the nanoparticles [35, 38]. The comparatively narrower SPR band observed for Seed-AgNPs suggests a more uniform size distribution, while the broader peak for Pod-AgNPs indicates greater polydispersity. These observations imply that organ-specific phytochemicals influence nucleation and growth kinetics during AgNP synthesis.

3.2 Role of phytochemicals in reduction and stabilization

FTIR analysis (Fig. 2) was employed to identify the functional groups responsible for Ag⁺ reduction and nanoparticle stabilization. Broad absorption bands around **3420 cm^{-1}** correspond to O–H stretching vibrations of hydroxyl groups present in flavonoids and phenolic compounds [32, 37]. Peaks near **1634 cm^{-1}** are attributed to C = O stretching of amide or conjugated carbonyl groups, while bands around **1385 cm^{-1}** indicate C–N stretching or aromatic C = C vibrations. Notably, Seed-AgNPs exhibited stronger flavonoid-associated absorption bands, whereas Pod-AgNPs showed pronounced signals corresponding to phenolic acids and tannins. These differences reflect the intrinsic phytochemical composition of the respective plant organs. Flavonoids are known to act as efficient electron donors, facilitating rapid reduction of Ag⁺ ions and promoting the formation of smaller nanoparticles [20, 37]. In contrast, phenolic acids and tannins, with their multiple hydroxyl groups, provide strong surface capping and stabilization, which can slow particle growth and enhance antioxidant properties [21, 22]. Thus, FTIR results support the hypothesis that organ-specific phytochemicals play a decisive role in directing nanoparticle formation.

3.3 Crystallinity and phase confirmation

XRD patterns of Seed- and Pod-AgNPs (Fig. 3) exhibited characteristic diffraction peaks at **(111), (200), (220), and (311)** planes, corresponding to the face-centered cubic (FCC) structure of metallic silver (JCPDS No. 04-0783) [33, 36]. The absence of extraneous peaks confirms the high purity and crystalline nature of the synthesized nanoparticles. Seed-AgNPs displayed sharper and more intense diffraction peaks than Pod-AgNPs, indicating higher crystallinity and smaller crystallite size. The average crystallite sizes calculated using the Scherrer equation were approximately **18 nm for Seed-AgNPs** and **27 nm for Pod-AgNPs**. Smaller crystallite size is generally associated with faster nucleation rates, which can be attributed to the flavonoid-rich seed extract facilitating rapid reduction of Ag⁺ ions [28, 34].

3.4 Morphology and size distribution

TEM analysis (Fig. 4) provided direct visualization of nanoparticle morphology and size. Seed-AgNPs were predominantly spherical, well dispersed, and ranged between **15–20 nm**, whereas Pod-AgNPs exhibited semi-spherical morphology with a broader size distribution of **25–30 nm** and minor aggregation. The observed morphological differences can be attributed to variations in phytochemical composition and reduction kinetics. Rapid nucleation promoted by flavonoids tends to limit particle growth, resulting in smaller and more uniform nanoparticles. In contrast, phenolic- and tannin-rich

extracts provide stronger surface capping, which can restrict particle aggregation but allow relatively larger particle growth [28, 34]. DLS measurements (Fig. 5) further supported these findings, with Seed-AgNPs showing a smaller hydrodynamic diameter (22.5 ± 1.6 nm) compared to Pod-AgNPs (31.8 ± 2.1 nm). The slightly larger sizes obtained from DLS relative to TEM are expected due to solvation layers and organic capping molecules present on the nanoparticle surface [35].

3.5 Elemental composition and colloidal stability

EDX spectra (Fig. 6) confirmed the presence of elemental silver through a strong signal at approximately **3 keV**, along with minor peaks corresponding to carbon and oxygen. These additional elements originate from phytochemical residues adsorbed on the nanoparticle surface, providing further evidence of plant-mediated capping [36, 38]. Zeta potential analysis (Fig. 7) revealed values of -25.4 ± 1.2 mV for Seed-AgNPs and -18.1 ± 0.9 mV for Pod-AgNPs. Zeta potential values exceeding ± 20 mV generally indicate good colloidal stability due to electrostatic repulsion [35]. Accordingly, Seed-AgNPs exhibited higher dispersion stability, which can enhance their interaction with microbial cells and improve antibacterial performance.

3.6 Antibacterial activity

The antibacterial efficacy of the synthesized AgNPs against *Staphylococcus aureus* and *Escherichia coli* is presented in Figs. 8 and 9. Seed-AgNPs produced significantly larger zones of inhibition against *S. aureus* (18.2 ± 1.3 mm) and *E. coli* (16.7 ± 1.1 mm) compared to Pod-AgNPs (14.1 ± 0.9 mm and 12.9 ± 1.0 mm, respectively; $p < 0.05$). The enhanced antibacterial activity of Seed-AgNPs can be attributed to their smaller size, higher surface-area-to-volume ratio, and greater colloidal stability, which facilitate stronger interaction with bacterial cell membranes, increased membrane permeability, and enhanced generation of reactive oxygen species (ROS) [38–40]. Smaller nanoparticles are also more effective in penetrating bacterial biofilms, leading to improved antibacterial outcomes.

3.7 Antioxidant and wound-healing activity

In contrast to antibacterial performance, Pod-AgNPs exhibited superior antioxidant and wound-healing activity. The DPPH assay demonstrated higher radical scavenging activity for Pod-AgNPs ($81 \pm 2.1\%$) compared to Seed-AgNPs. This enhanced antioxidant capacity is attributed to phenolic and tannin compounds retained on the nanoparticle surface, which are known for their hydrogen-donating and free-radical-scavenging abilities [21, 22]. The in vitro scratch assay (Fig. 10) further revealed that Pod-AgNPs promoted significantly greater wound closure ($78 \pm 3.1\%$ within 24 h) compared to Seed-AgNPs ($55 \pm 2.8\%$). Phenolic-rich surface capping can modulate cellular redox balance, enhance fibroblast migration, and promote extracellular matrix remodeling, all of which are critical for wound healing [39].

3.8 Organ-specific functional divergence

Collectively, the results demonstrate clear **organ-specific functional divergence** in AgNPs synthesized from *A. aromaticum*. Seed-derived nanoparticles are optimized for antibacterial applications due to smaller size, higher crystallinity, and superior stability, whereas pod-derived nanoparticles are more suitable for antioxidant and regenerative applications owing to phenolic-rich surface chemistry. Importantly, these differences arise despite identical synthesis conditions, confirming that intrinsic organ-specific phytochemistry is the primary determinant of nanoparticle behavior.

4. Discussion

The present study demonstrates that organ-specific phytochemical composition within a single medicinal plant can govern both the physicochemical characteristics and biomedical functionality of silver nanoparticles, even when synthesis conditions are held constant. Unlike conventional green synthesis reports that focus on particle formation alone, this work provides experimental evidence that seed and pod extracts of *Amomum aromaticum* impart distinct nucleation kinetics, surface chemistry, and biological performance to the resulting AgNPs. The smaller size, higher crystallinity, and greater colloidal stability observed for Seed-AgNPs correlate strongly with their enhanced antibacterial activity, which can be attributed to increased surface-area-to-volume ratio and improved interaction with bacterial membranes. In contrast, Pod-AgNPs, characterized by larger size and phenolic- and tannin-rich surface capping, exhibit superior antioxidant capacity and wound-healing efficiency. These findings confirm that the observed functional divergence arises from intrinsic phytochemical differences between plant organs rather than from external synthesis parameters.

Conclusion

This study demonstrates that different organs of *Amomum aromaticum* can be strategically exploited to synthesize silver nanoparticles with distinct physicochemical properties and complementary biomedical functions. Seed-derived AgNPs are smaller, more stable, and exhibit enhanced antibacterial activity, whereas pod-derived AgNPs show superior antioxidant and wound-healing performance. By establishing a controlled, intra-species organ-specific synthesis approach, this work advances green nanotechnology beyond descriptive synthesis and provides a rational strategy for tailoring nanoparticle functionality using naturally occurring phytochemical diversity.

Future Aspects

Although the present study clearly demonstrates that organ-specific phytochemical composition of *Amomum aromaticum* can regulate the physicochemical properties and biomedical functionality of silver nanoparticles, several directions remain open for further investigation. Advanced phytochemical profiling of seed and pod extracts using HPLC, LC–MS, or GC–MS would enable quantitative identification of individual flavonoids, phenolic acids, and tannins responsible for nanoparticle reduction and stabilization, thereby strengthening mechanistic correlations. Further optimization of synthesis

parameters within each organ-derived system may allow finer control over particle size and stability. In addition, in vivo evaluation will be essential to assess biosafety, biodistribution, and therapeutic efficacy, particularly for wound-healing and antimicrobial applications. Finally, extending this organ-specific approach to other medicinal plants with well-defined phytochemical diversity may help establish generalizable principles for plant-guided nanoparticle design.

Declarations

Ethics approval and consent to participate

Not applicable. The present study did not involve human participants or animals.

Consent for publication

Not applicable.

Availability of data and materials

The data generated and analyzed during the current study are included in this published article and its supplementary information. Additional data are available from the corresponding author upon reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

P. Naveen conceived and designed the study, carried out the synthesis of silver nanoparticles, performed physicochemical characterization, analyzed and interpreted the data, and drafted the original manuscript.

Dr. Gopi Mamidi contributed to the experimental design, supervised the nanomaterial synthesis and characterization studies, and critically reviewed the manuscript for scientific content.

Dr. A. Indira Priyadarsini was responsible for plant material identification, botanical authentication, and provided expertise on phytochemical relevance and interpretation of organ-specific differences.

Dr. G. Swathi contributed to the biological experiments, including antibacterial, antioxidant, cytotoxicity, and wound-healing assays, and assisted in data interpretation related to biomedical applications.

All authors reviewed, edited, and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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Tables

Table 1. Physicochemical characteristics of Seed- and Pod-derived AgNPs

Parameter	Seed-AgNPs	Pod-AgNPs
UV–Vis λ_{max} (nm)	432 $\pm$ 2	445 $\pm$ 3
TEM size (nm)	15–20	25–30
DLS mean (nm)	22.5 $\pm$ 1.6	31.8 $\pm$ 2.1
PDI	0.28	0.32
Zeta potential (mV)	–25.4 $\pm$ 1.2	–18.1 $\pm$ 0.9
Crystallite size (XRD, nm)	18.3	27.4
Dominant capping group	Flavonoids/amide	Phenolics/tannins
Morphology	Spherical	Semi-spherical

Table 2. Elemental composition of AgNPs by EDX

Element	Seed-AgNPs (wt %)	Pod-AgNPs (wt %)
Ag	85.6	82.4
O	7.9	9.8
C	6.5	7.8

Table 3. Biological activities of Seed- and Pod-AgNPs

Assay	Unit	Seed-AgNPs	Pod-AgNPs
DPPH scavenging	%	67 ± 2.4	81 ± 2.1
<i>S. aureus</i> ZOI	mm	18.2 ± 1.3	14.1 ± 0.9
<i>E. coli</i> ZOI	mm	16.7 ± 1.1	12.9 ± 1.0
Cell viability (100 µg/mL)	%	82 ± 3	85 ± 4
Wound closure (24 h)	%	55 ± 2.8	78 ± 3.1
Biofilm inhibition	%	49 ± 2.2	51 ± 2.5

Figures

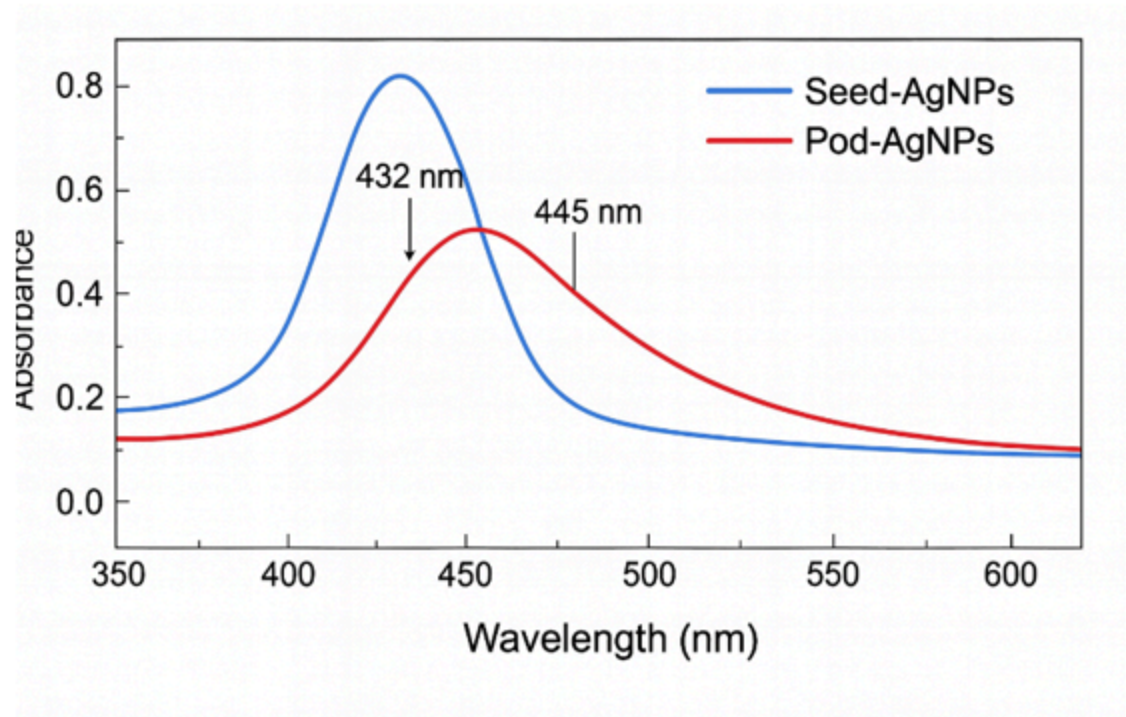


Figure 1

UV–Visible absorption spectra of silver nanoparticles synthesized using seed and pod extracts of *A. aromaticum*.

Distinct surface plasmon resonance (SPR) peaks appear at 432 nm (Seed-AgNPs) and 445 nm (Pod-AgNPs), confirming nanoparticle formation and indicating smaller particle size for seed-derived samples.

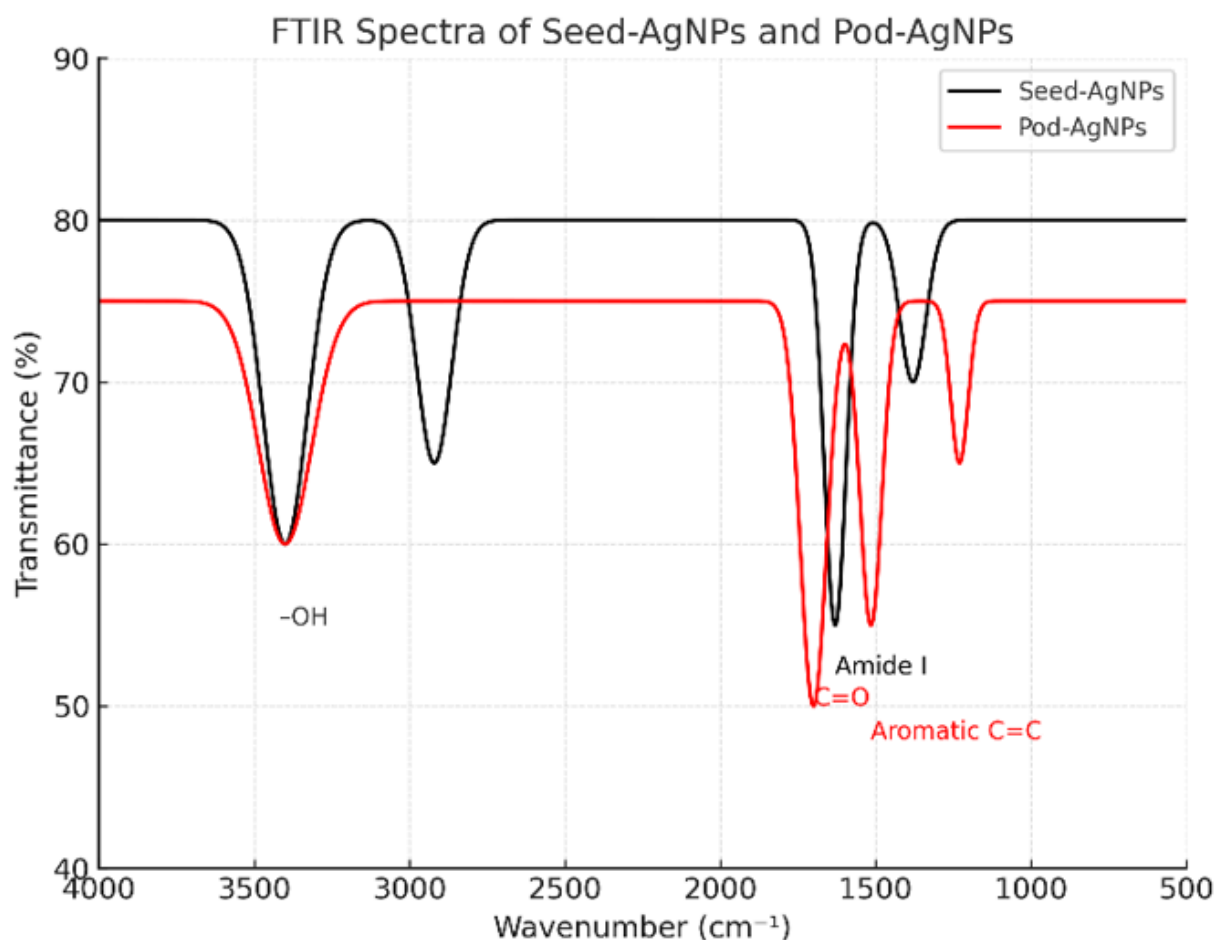


Figure 2

FTIR spectra of seed and pod extracts and their corresponding AgNPs.

Major absorption bands at 3420 cm⁻¹ (O–H stretch), 1634 cm⁻¹ (C=O stretch), and 1385 cm⁻¹ (C–N vibration) denote flavonoid and phenolic participation in reduction and capping

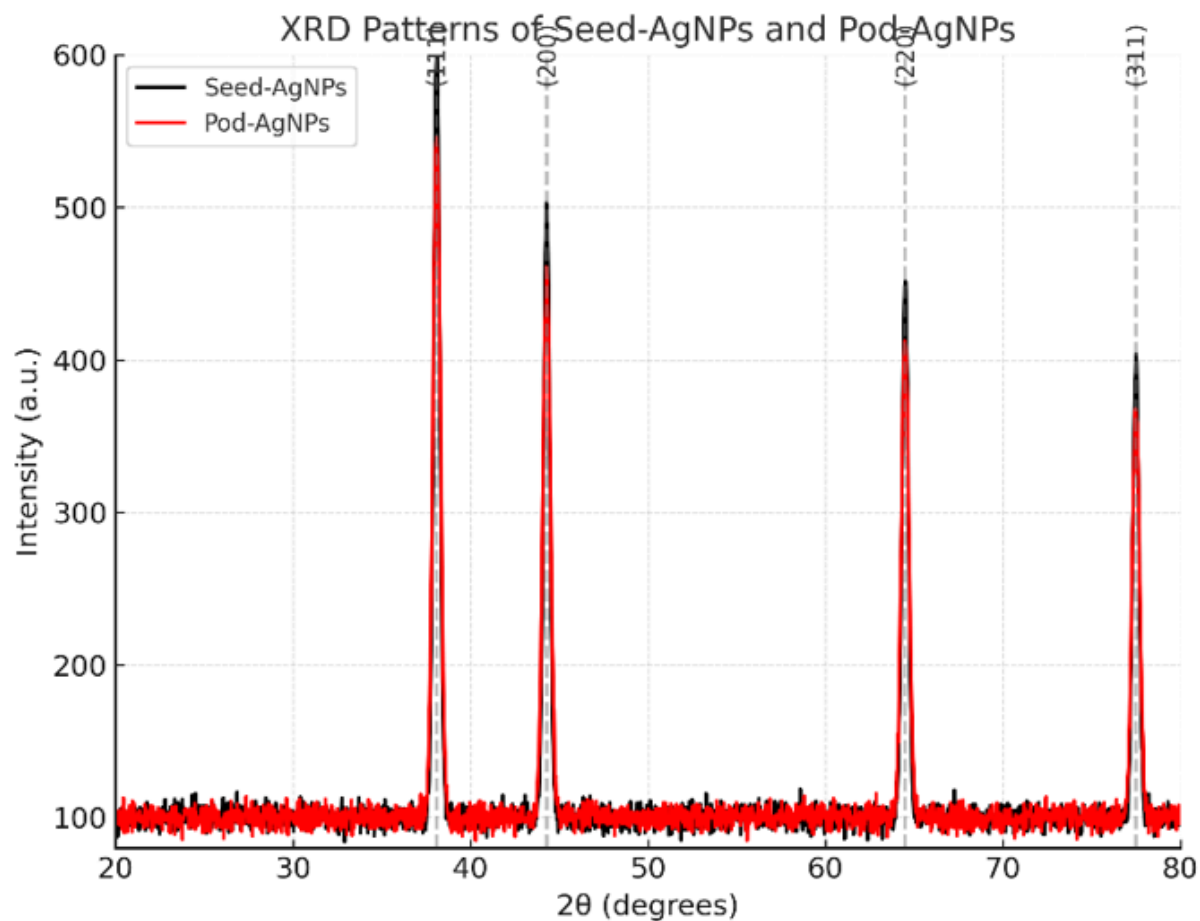


Figure 3

X-ray diffraction (XRD) patterns of Seed-AgNPs and Pod-AgNPs.

Characteristic Bragg reflections at (111), (200), (220), and (311) correspond to face-centered cubic (FCC) silver (JCPDS No. 04-0783). Sharper peaks for Seed-AgNPs indicate smaller crystallite size (~18 nm).

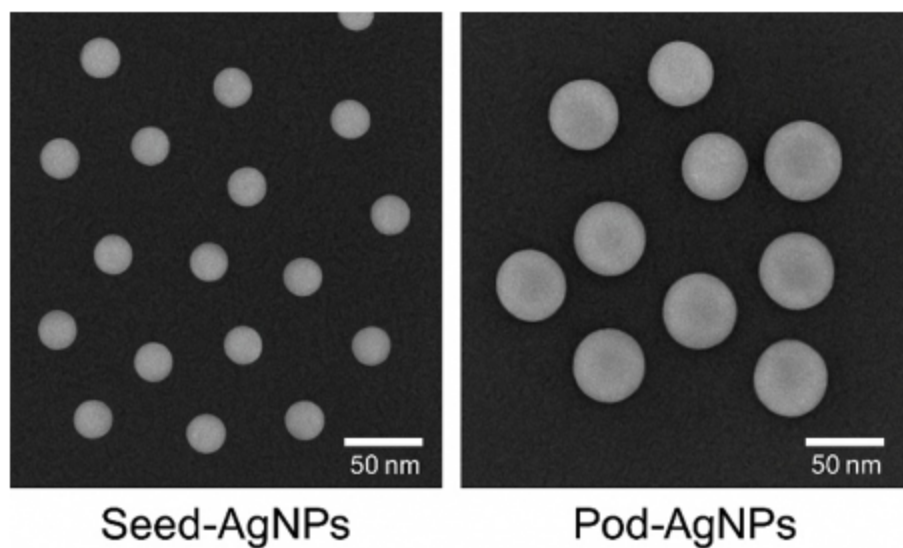


Figure 4

Transmission electron microscopy (TEM) images and particle size histograms.

Seed-AgNPs: well-dispersed, spherical particles (15–20 nm).

Pod-AgNPs: semi-spherical, slightly aggregated particles (25–30 nm).

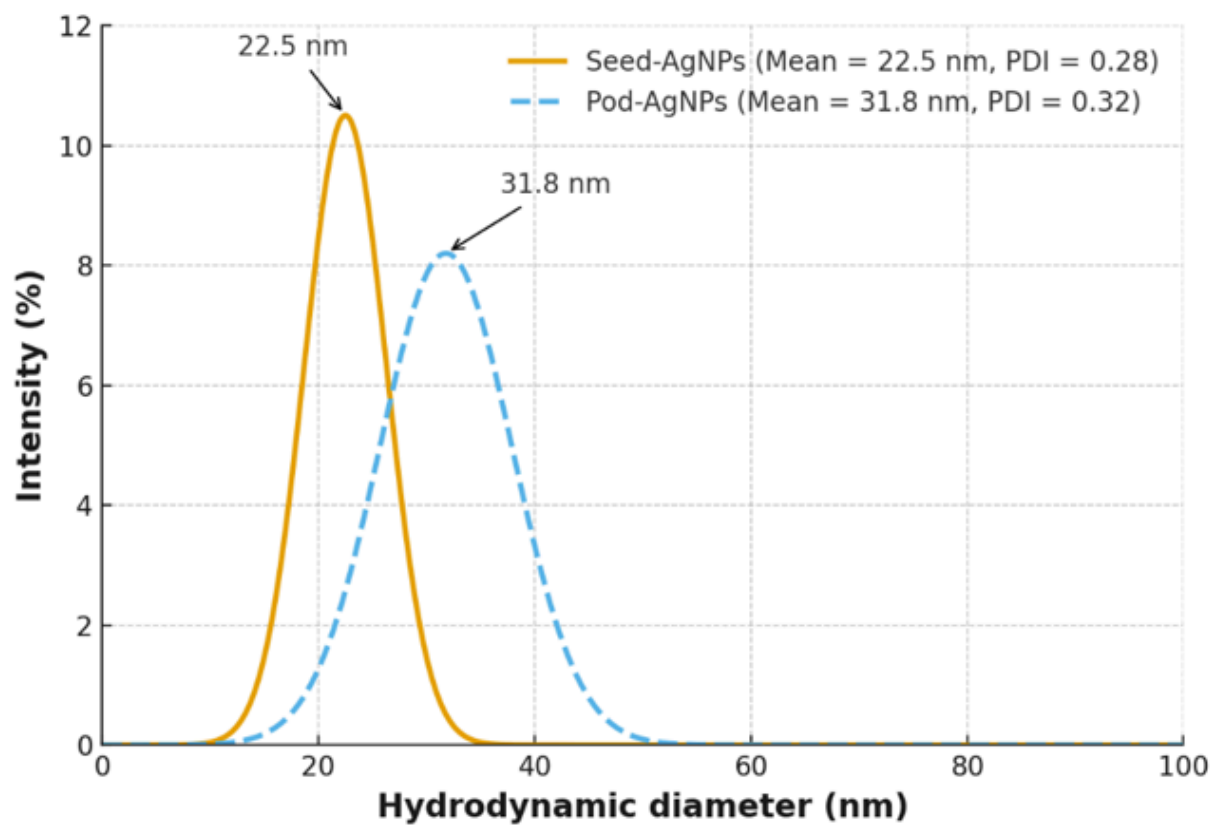


Figure 5

Dynamic light scattering (DLS) analysis of Seed- and Pod-AgNPs.

Hydrodynamic diameter distribution shows mean sizes of **22.5 nm (Seed)** and **31.8 nm (Pod)** with polydispersity indices of 0.28 and 0.32, respectively, confirming narrow distribution and stability.

Energy-dispersive X-ray (EDX) analysis of AgNPs

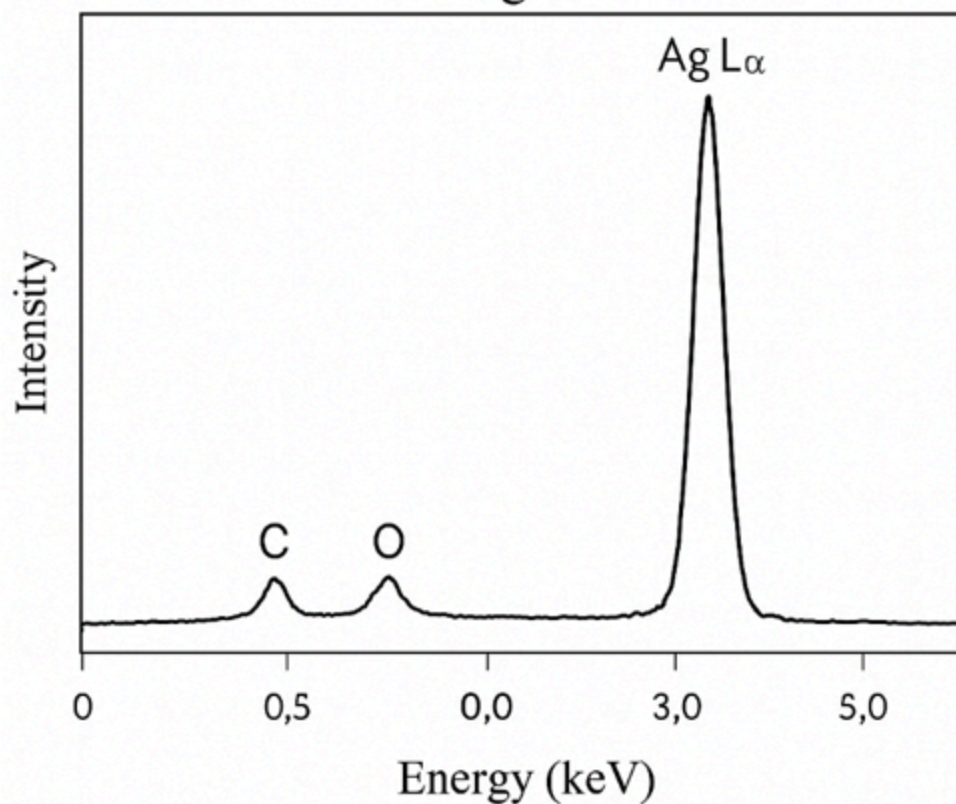


Figure 6

Energy-dispersive X-ray (EDX) spectrum of AgNPs.

Strong Ag peak at ~3 keV verifies elemental silver; minor carbon (0.28 keV) and oxygen (0.52 keV) peaks arise from organic capping residues.

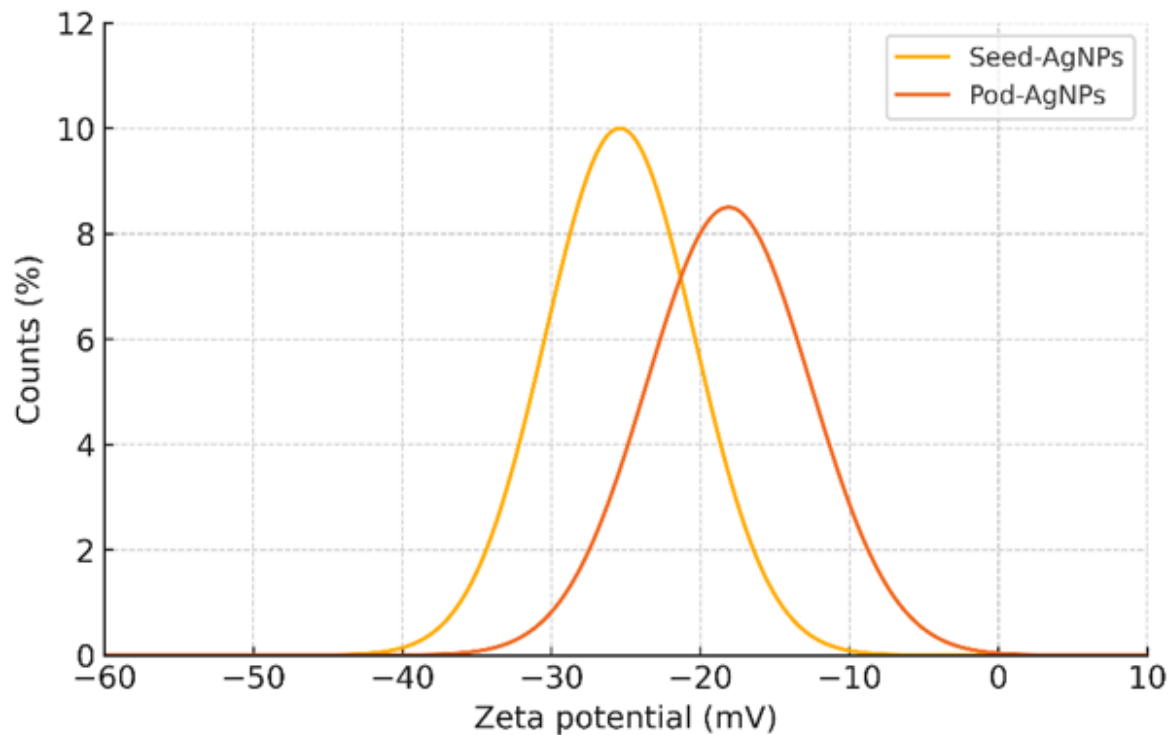


Figure 7

Zeta potential distribution curves of biosynthesized AgNPs.

Seed-AgNPs show -25.4 mV and Pod-AgNPs -18.1 mV, indicating stable colloidal suspensions with higher electrostatic repulsion for seed-derived particles.

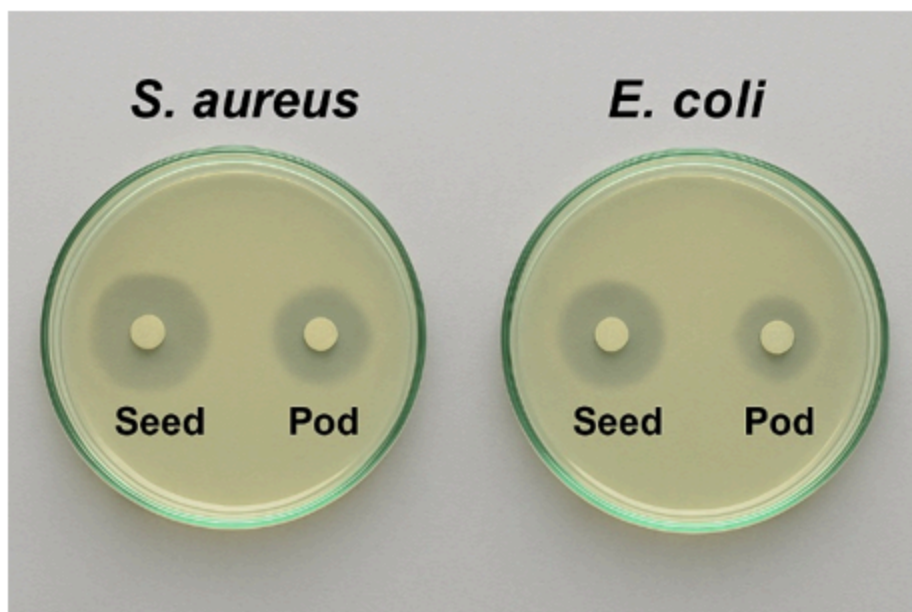


Figure 8

Antibacterial assay plates showing inhibition zones of Seed- and Pod-AgNPs against *S. aureus* and *E. coli*.

Clear inhibition zones demonstrate effective antibacterial action, with larger zones observed for Seed-AgNPs compared to Pod-AgNPs.

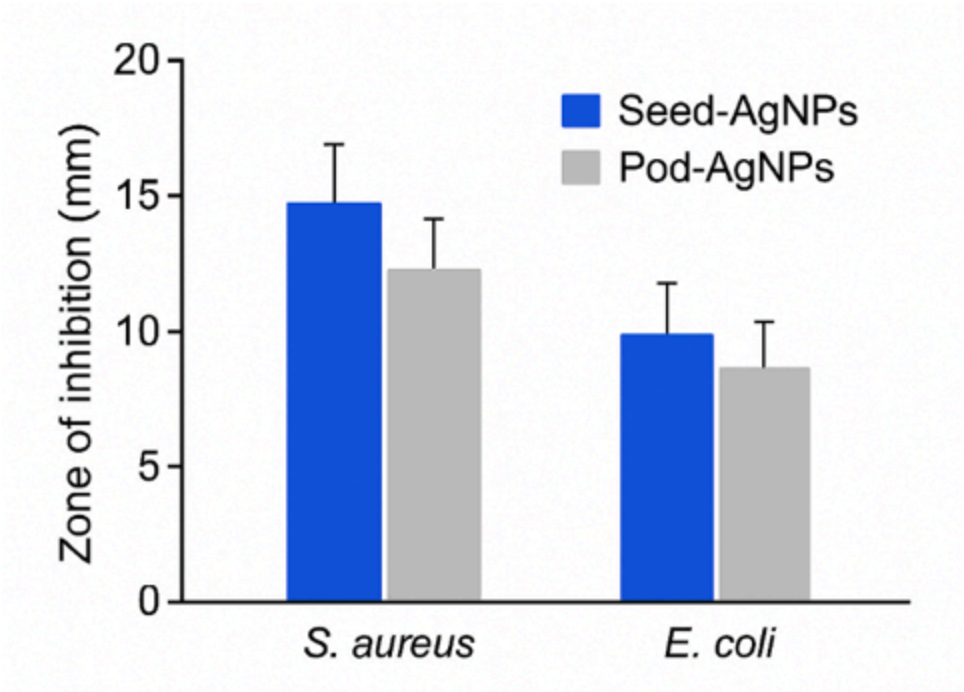


Figure 9

Antibacterial activity of Seed- and Pod-AgNPs against *S. aureus* and *E. coli*.

Zone of inhibition (mm) values confirm stronger antibacterial efficacy of smaller Seed-AgNPs; bars represent mean $\pm$ SD (n = 3).

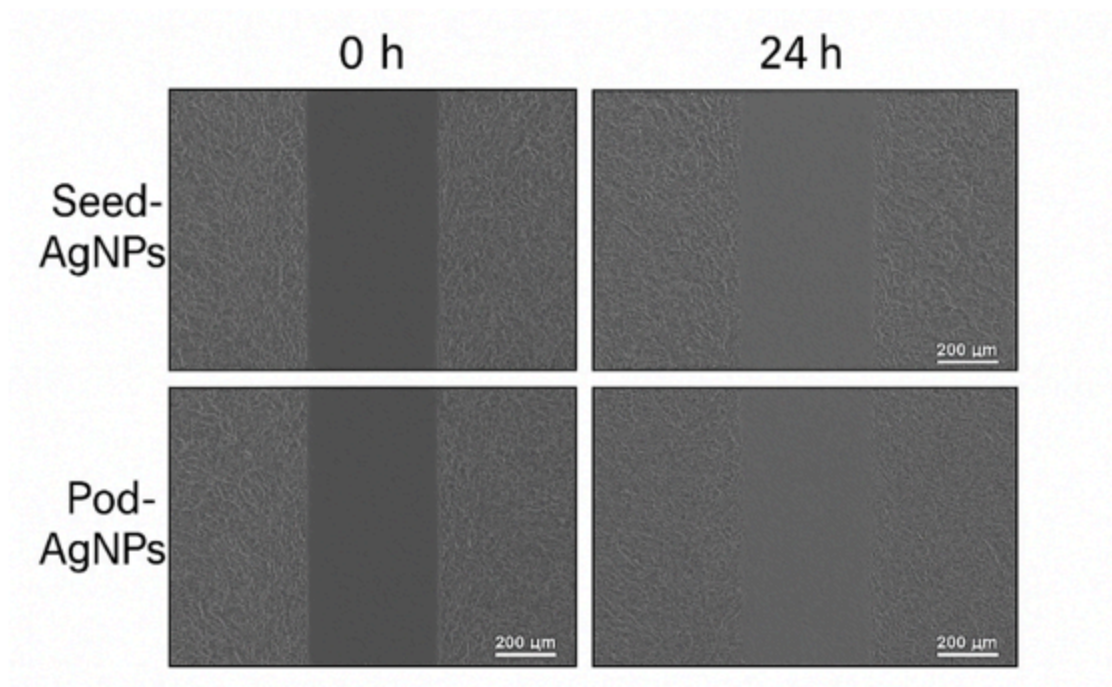


Figure 10

Wound-healing assay (scratch test) on human fibroblast monolayers.

Images at 0 h and 24 h show ~78 % closure for Pod-AgNPs versus ~55 % for Seed-AgNPs, indicating higher regenerative efficiency of phenolic-capped nanoparticles.

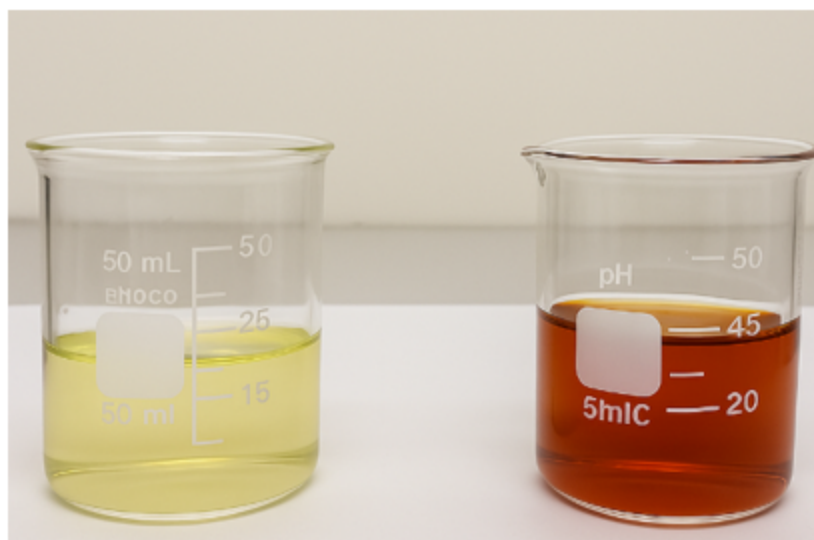


Figure 11

Unnumbered image in the results and discussion section.

Supplementary Files

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- [spsupply.docx](#)
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