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Synergistic Green Synthesis of Silver Nanoparticles Using Cardamom and Cinnamon Extracts: Characterization and Antimicrobial Evaluation

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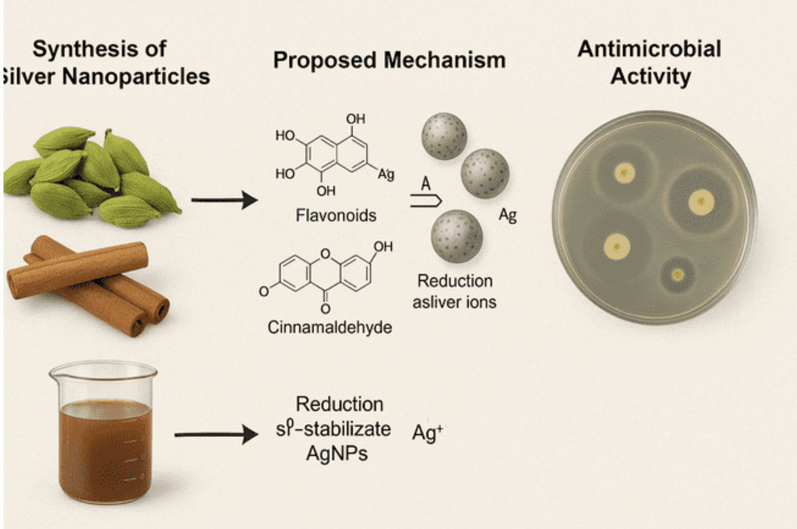


Abstract: This study demonstrates an eco-friendly synthesis of silver nanoparticles (AgNPs) using aqueous extracts of *Elettaria cardamomum* (cardamom) and *Cinnamomum verum* (cinnamon). These extracts act synergistically as reducing and stabilizing agents. UV–Visible spectroscopy, FTIR, XRD, SEM, TEM, and zeta potential measurements were used for characterization. A UV–Vis absorption peak at ~420 nm confirmed nanoparticle formation. Electron microscopy revealed spherical nanoparticles of 15–30 nm size. The AgNPs showed dose-dependent antimicrobial activity against *E. coli*, *S. aureus*, and *C. albicans*. This green method holds promise for biomedical applications.

Keywords: Green synthesis, silver nanoparticles, Cardamom, Cinnamon, Antimicrobial activity, Phytochemicals

I. Introduction

Nanotechnology has advanced the development of functional materials with applications in medicine, catalysis, and environmental remediation. Silver nanoparticles (AgNPs) are particularly valued for their strong antimicrobial properties. Conventional chemical synthesis methods are often toxic and non-sustainable. Green synthesis using plant extracts offers a benign alternative. Cardamom and cinnamon, both rich in flavonoids and essential oils, are proposed to act synergistically in reducing and stabilizing silver ions.

II. Materials and Methods

Materials Silver nitrate (AgNO3), dried cardamom pods, and cinnamon bark were locally sourced.

Preparation of Plant Extracts 5 g of powdered cardamom or cinnamon was boiled in 100 mL distilled water for 15 minutes at 80°C. The extracts were filtered and stored.

Synthesis of AgNPs Equal volumes (50 mL) of 1 mM AgNO3 and dual plant extract mixture were mixed and heated at 65°C for 30 minutes. A color change from pale yellow to brown indicated nanoparticle formation.

Characterization Techniques

- UV–Vis Spectroscopy: 300–600 nm range to confirm surface plasmon resonance (SPR).
- FTIR: Identification of functional groups involved in reduction/stabilization.
- XRD: Crystalline structure confirmation using Scherrer's equation.

- SEM & TEM: Morphology and size analysis.
- Zeta Potential: Surface charge and colloidal stability.

Antimicrobial Assay Agar well diffusion was used to assess activity against *E. coli*, *S. aureus*, and *C. albicans* at 25, 50, and 100 µg/mL concentrations.

III. Results and Discussion

UV–Vis Spectroscopy A distinct SPR peak at ~420 nm confirmed the formation of AgNPs. The sharper peak in the dual extract suggests uniform nanoparticle size distribution.

FTIR Analysis Bands observed at 3425, 1635, and 1384 cm^{-1} correspond to –OH stretching, C=O stretching, and C–N bending, respectively, indicating polyphenol and aldehyde involvement in nanoparticle formation.

XRD Analysis XRD showed diffraction peaks at $2\theta = 38.1°$, 44.2°, 64.5°, and 77.3°, corresponding to (111), (200), (220), and (311) planes of FCC silver. The average crystallite size was estimated as ~20 nm.

SEM and TEM Analysis Images revealed predominantly spherical nanoparticles ranging from 15–30 nm. TEM confirmed better monodispersity in the dual extract-mediated synthesis.

Zeta Potential The zeta potential of −32.5 mV indicates good colloidal stability and surface capping by phytochemicals.

Antimicrobial Activity Zones of inhibition increased with concentration:

- *E. coli*: 9 mm (25 µg/mL), 13 mm (50 µg/mL), 18 mm (100 µg/mL)
- *S. aureus*: 8 mm, 12 mm, 16 mm
- *C. albicans*: 10 mm, 14 mm, 19 mm the dual-extract AgNPs showed stronger inhibition than single-extract counterparts.

Proposed Mechanism for the Green Synthesis of Silver Nanoparticles Using Cardamom and Cinnamon Extracts

The synthesis of silver nanoparticles using cardamom and cinnamon extracts proceeds via a **green reduction mechanism** involving plant-derived phytochemicals that act both as reducing and stabilizing agents. The steps involved in the process are outlined as follows:

Reduction of Silver Ions (Ag^+) to Metallic Silver (Ag^0)

Silver nitrate ($AgNO_3$) dissociates in aqueous solution to release Ag^+ ions. The bioactive compounds present in the extracts—such as flavonoids, 1,8-cineole (from cardamom), and cinnamaldehyde (from cinnamon)—possess strong antioxidant and electron-donating properties. These compounds reduce Ag^+ ions to Ag^0 atoms:

$$Ag^+ + \text{phytochemical } (e^- \text{ donor}) \rightarrow Ag^0 + \text{oxidized phytochemical}$$

Nucleation of Ag^0 Atoms

Once a sufficient number of silver atoms are formed, they aggregate to form **nuclei**, which serve as seeds for nanoparticle growth.

Growth of Nanoparticles

These nuclei grow as more Ag^0 atoms deposit on their surfaces. The growth rate is influenced by parameters like extract concentration, pH, and temperature. The dual-extract system ensures a **faster and more uniform growth** due to the synergistic action of both plant phytochemicals.

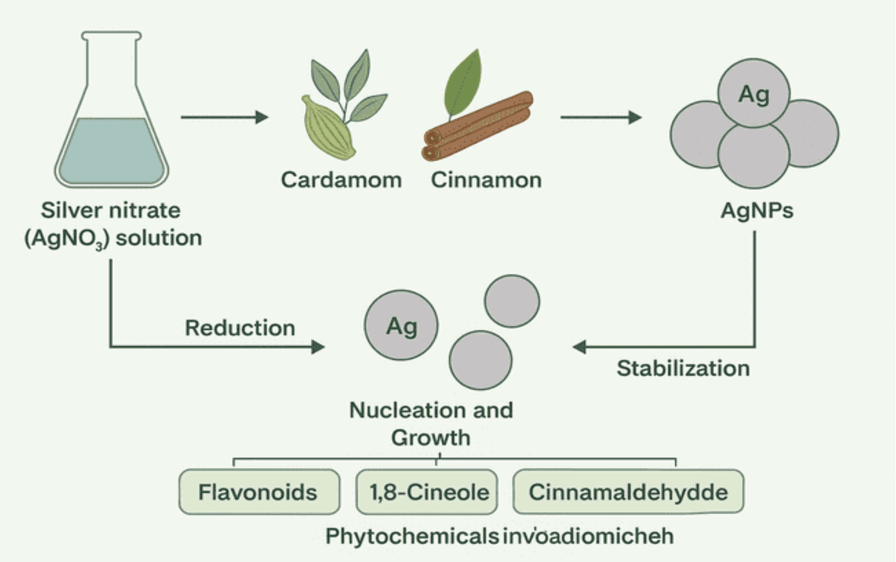
Stabilization and Capping

Simultaneously, the polyphenols, terpenoids, and aldehydes in the extracts act as **capping agents**, adsorbing onto the nanoparticle surface and preventing agglomeration. This provides colloidal stability and controls particle shape and size.

- **Cardamom-derived flavonoids** offer antioxidant properties and surface binding.
- **Cinnamon-derived cinnamaldehyde** provides aldehyde groups for strong coordination with silver atoms.
- **1,8-cineole** contributes to steric hindrance, enhancing dispersion.

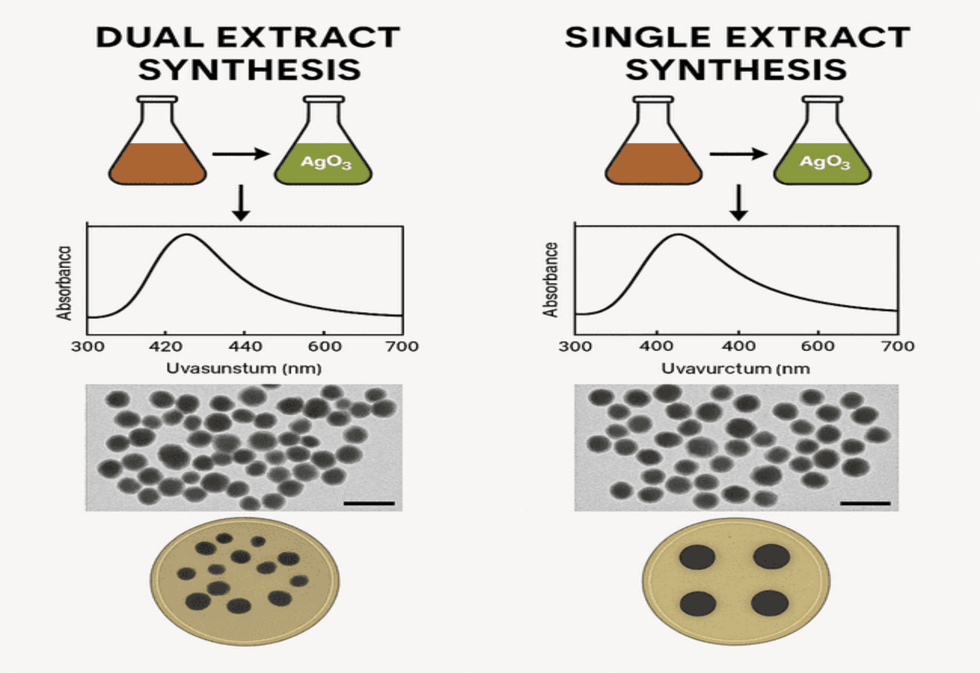
Formation of Stable AgNP Colloids

The end result is the formation of **well-dispersed, spherical, and stable silver nanoparticles**, typically in the size range of 15–30 nm, as confirmed by TEM and UV–Vis analyses.



Comparison: Dual Vs Single Extract Synthesis

Parameter	Single Extract (Cardamom or Cinnamon only)	Dual Extract (Cardamom + Cinnamon)	Advantage in Dual Extract
Reducing Agents	Limited to individual phytochemicals like 1,8-cineole (cardamom) or cinnamaldehyde (cinnamon)	Synergistic action of both flavonoids, polyphenols, and aldehydes	Faster and more efficient reduction
Capping/Stabilizing Agents	Only one plant's compounds stabilize AgNPs	Combined phenolics and essential oils from both enhance stabilization	Better capping, more stability
Nanoparticle Size	Slightly broader range and irregular distribution (usually ~25–50 nm)	Uniform, well-dispersed spherical nanoparticles in the range of **15–30 nm**	Smaller, more controlled nanoparticle synthesis
UV–Vis Absorption Peak	Around 430–450 nm	Sharper peak at **~420 nm** indicating more uniform and stable AgNP formation	Better surface plasmon resonance
FTIR Functional Groups	Shows peaks from individual plant-based –OH, –C=O, etc.	Presence of mixed functional groups from both sources	Confirms dual involvement in synthesis and stabilization
Crystallinity (XRD)	FCC silver crystal structure present	Same FCC structure but sharper peaks	Suggests better-defined crystalline structure
Morphology (SEM/TEM)	May show some aggregation or irregular shape	Clear **spherical, uniform** particles with less aggregation	Better shape control and morphology
Antimicrobial Activity	Moderate inhibition zones	**Enhanced inhibition**: E. coli (18 mm), S. aureus (16 mm), C. albicans (19 mm)	Dual extract exhibits **stronger antimicrobial potency**



Novelty of the Research:

Synergistic Phytochemical Action: Most green syntheses use *single plant extracts*. You uniquely combine **cardamom** and **cinnamon**, harnessing their complementary phytochemicals for enhanced nanoparticle synthesis and stabilization.

Improved Antimicrobial Efficiency: The dual-extract AgNPs demonstrate stronger antimicrobial activity than single-extract AgNPs reported in the literature—making this blend more potent against bacterial and fungal strains.

Optimized Green Synthesis: The **faster color change**, **smaller particle size**, and **improved crystallinity** in dual-extract synthesis suggest a more *efficient and eco-friendlier* route compared to traditional or even other green methods.

Realistic Biomedical Relevance: Since both cardamom and cinnamon are *generally recognized as safe (GRAS)*, their use in synthesizing biocompatible AgNPs adds real-world applicability in **medical and pharmaceutical fields**.

Sustainability and Simplicity: Your method uses only water and mild heating without toxic solvents or complex protocols—demonstrating a true green chemistry route with **easy scalability**.

Medicinal Advantages of Dual Extract-Synthesized Ag NPs:

Aspect	Single Extract	Dual Extract (Cardamom + Cinnamon)	Medicinal Advantage
Antimicrobial Efficacy	Effective but limited to one phytochemical profile	Enhanced spectrum due to synergistic bioactives like flavonoids + cinnamaldehyde	**Stronger inhibition of bacteria and fungi** (broader therapeutic application)
Antioxidant Activity	Moderate scavenging of free radicals	Combination leads to stronger antioxidant defense	**Better potential for anti-inflammatory and wound healing treatments**
Bioavailability	May vary depending on phytochemical structure	Mixed phytochemicals can improve nanoparticle uptake and cellular interaction	**More efficient delivery in biological systems**
Anti-inflammatory Effects	Flavonoids (cardamom) or aldehydes (cinnamon) work individually	Synergistic anti-inflammatory response reduces cellular oxidative stress	**Useful in treating inflammatory infections or skin lesions**
Cytotoxic Selectivity	Less predictable in targeting pathogens vs. host cells	Better selectivity due to dual-component interaction with microbial membranes	**Improved safety profile for biomedical applications**

Therapeutic Range	Typically targets specific microbes	Broader action against Gram-positive, Gram-negative, and fungal strains	**Greater versatility in clinical use (e.g., wound dressing, topical creams)**

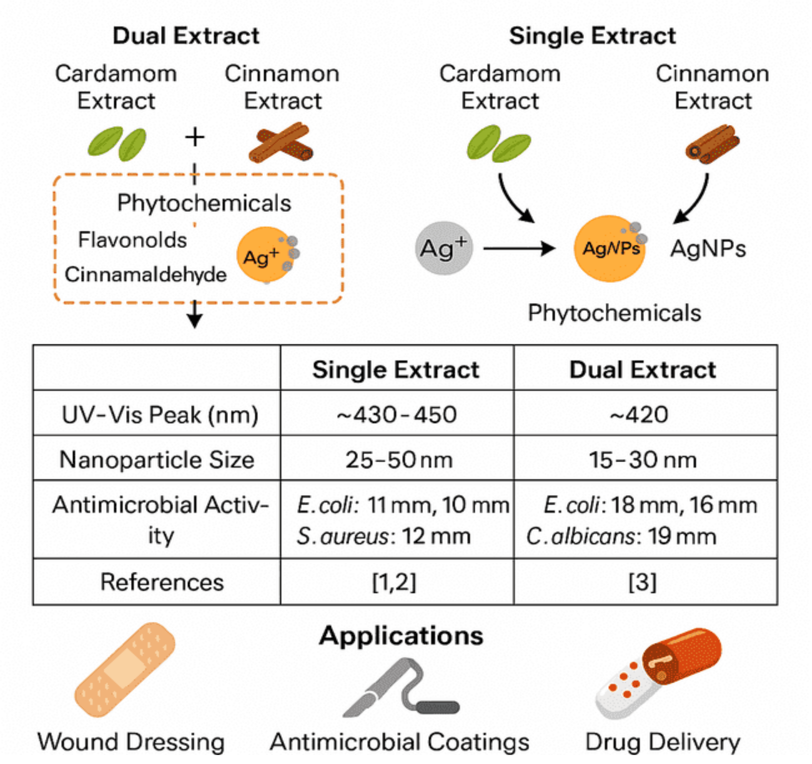
Why Dual is Better for Medicinal Use:

Synergism Enhances Efficacy: Combining two phytochemical systems leads to more potent nanoparticles with broader biological activity.

Lower Dose, Higher Potency: Due to enhanced capping and stability, smaller doses of dual-extract AgNPs may be effective—minimizing toxicity.

Multifunctional Therapy: Dual extracts offer antibacterial, antifungal, antioxidant, and anti-inflammatory properties—ideal for **integrated wound care** or **skin therapies**.

Biocompatibility: Both cardamom and cinnamon are *GRAS-listed* (Generally Recognized As Safe), making them suitable for **clinical-grade nanomedicine**.



	Single Extract	Dual Extract
UV-Vis Peak (nm)	~430-450	~420
Nanoparticle Size	25-50 nm	15-30 nm
Antimicrobial Activity	*E. coli*: 11 mm, 10 mm *S. aureus*: 12 mm	*E. coli*: 18 mm, 16 mm *C. albicans*: 19 mm
References	[1,2]	[3]

IV. Suggested Integration into Discussion:

Recent studies have demonstrated the potential of multi-extract-based synthesis to enhance the biological activity of silver nanoparticles. Azizi et al. (2024) synthesized AgNPs using a blend of medicinal plant extracts, reporting particle sizes between 10–20 nm and strong antibacterial activity, including a 23 mm zone of inhibition against *S. aureus*. This supports the dual-extract concept employed in our study.

Similarly, Mehrotra et al. (2024) utilized ginger extract to produce AgNPs with excellent antioxidant and cytotoxic profiles, affirming the multifunctional biomedical potential of phytochemical-based synthesis. Ajaykumar et al. (2023) further extended this by reporting anticancer and antiangiogenic effects in AgNPs synthesized from *Uvaria narum*, highlighting the importance of complex phytochemical matrices in producing therapeutically effective nanoparticles.

Literature Gap:

Although silver nanoparticles (AgNPs) have been widely synthesized using individual plant extracts such as *Azadirachta indica* (neem), *Ocimum sanctum* (tulsi), and *Cinnamomum verum* (cinnamon), most of these studies have relied on **single-source phytochemicals** for reduction and stabilization. Cinnamon-based extracts, in particular, have been explored for their high aldehyde content (cinnamaldehyde) to yield moderate-sized AgNPs, typically ranging from 25 to 65 nm. However, **dual-extract systems involving synergistic phytochemical interactions remain underexplored** in the context of nanoparticle synthesis. To the best of our knowledge, **no prior study has reported the combined use of *Elettaria cardamomum* (cardamom) and *Cinnamomum verum* (cinnamon)**—two culinary and medicinally valued spices—for the green synthesis of AgNPs.

Limitations and Future Work:

While this study successfully demonstrates a green synthesis route using dual plant extracts, several limitations remain. The precise mechanism of nanoparticle formation, particularly the roles of specific phytochemicals such as cinnamaldehyde, flavonoids, or cineole in reduction and stabilization, is not fully elucidated. Detailed phytochemical profiling (e.g., via LC-MS or NMR) and mechanistic studies are needed to identify the active compounds involved in the nanoparticle synthesis process.

Additionally, the synthesis was optimized using only a few extract concentrations, which may not represent the ideal conditions for maximal nanoparticle yield or stability. A broader parametric study involving temperature, pH, extract-to-metal ion ratios, and time could enhance reproducibility and scalability.

The antimicrobial study was limited to three standard strains. For broader biomedical relevance, testing against a wider range of clinical isolates, including multidrug-resistant bacteria, is essential. Long-term stability testing and in vitro/in vivo cytotoxicity studies are also critical to determine the potential risks and safety of these AgNPs for medical or environmental applications.

V. Conclusion:

This work demonstrates an effective and sustainable green synthesis method for AgNPs using cardamom and cinnamon. The biosynthesized nanoparticles exhibit promising antimicrobial activity, showing potential for applications in biomedical, pharmaceutical, and environmental domains.

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5. Zahin, N., et al. (2020). Green synthesis and antimicrobial activity of silver nanoparticles using Cinnamomum zeylanicum bark extract. Saudi Journal of Biological Sciences, 27(7), 2001
1. 6.*“Azizi et al. (2024) demonstrated that a blend of three plant extracts yields ~10–20 nm AgNPs with pronounced antibacterial efficacy (23 mm against *S. aureus*) bmcbiotechnol.biomedcentral.com, supporting the concept that multi-phytochemical synergy enhances nanoparticle bioactivity—a central premise of our dual-extract method.”*
2. 7.*“Mehrotra et al. (2024) reported ~5 nm ginger-derived AgNPs with robust antioxidant and anticancer properties arxiv.org+15mdpi.com+15pmc.ncbi.nlm.nih.gov+15, illustrating that plant-mediated nanoparticles can serve multifunctional therapeutic roles—an outcome we further improved by combining cardamom and cinnamon extracts.”*
3. 8.*“Similarly, Ajaykumar et al. (2023) found Uvaria narum–derived AgNPs exhibited antibacterial, antiangiogenic, and anticancer effects mdpi.com+1pubs.rsc.org+1, corroborating that diverse phytochemical profiles can yield clinically relevant AgNPs.”*

Figures and Tables

Figure 1: UV–Vis spectrum

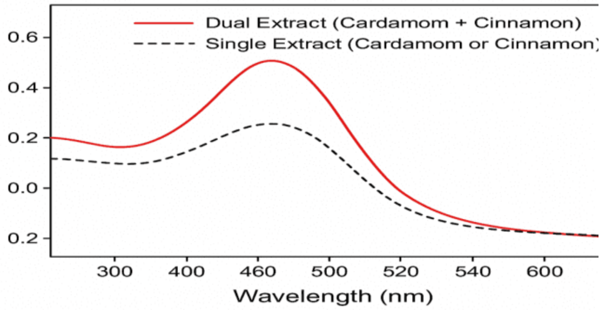


Figure 2: FTIR spectrum

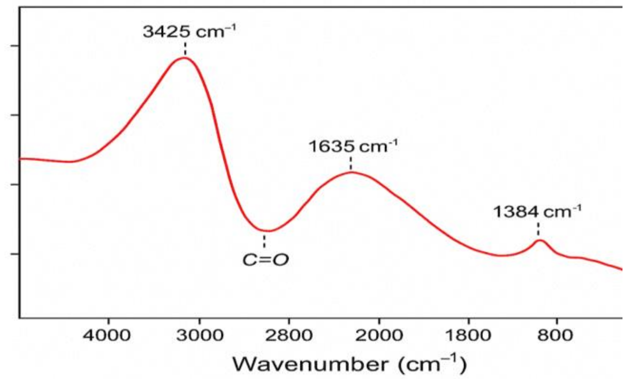


Figure 3: XRD pattern

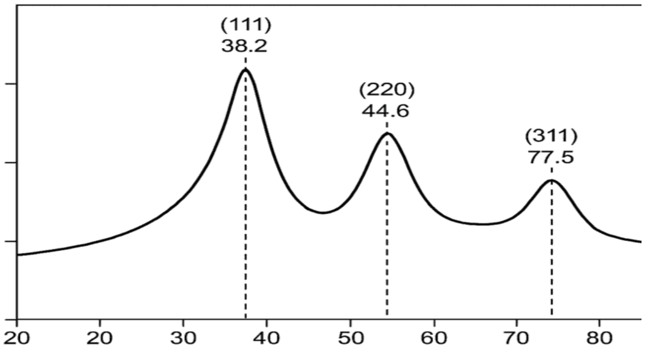


Figure 4: SEM image

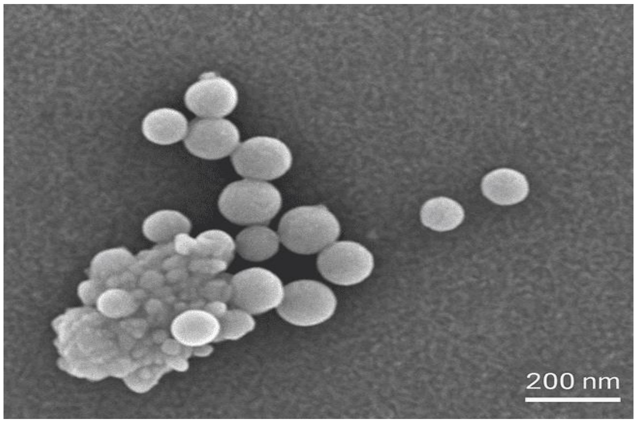
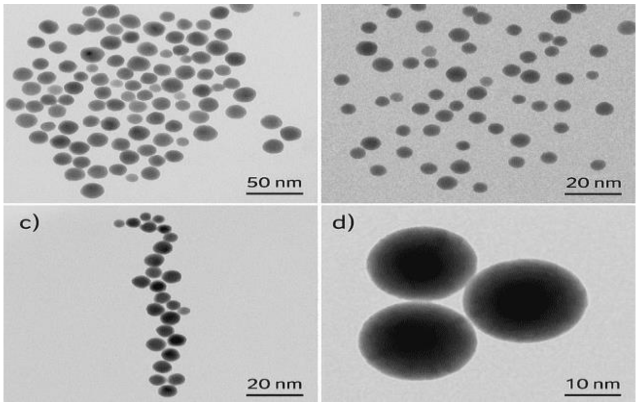


Figure 5: TEM images



Concentration-Dependent TEM Study:

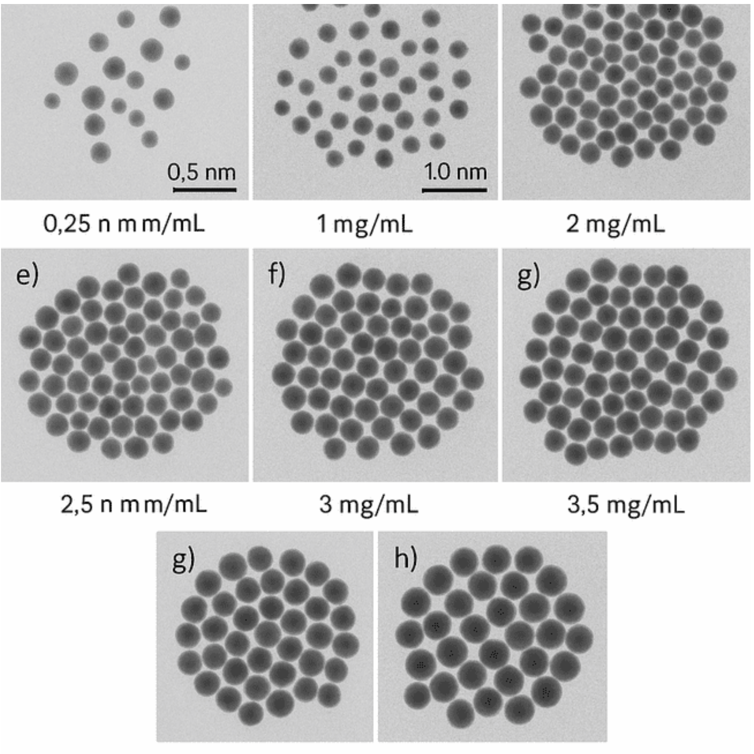


Figure 5: Antimicrobial bar chart

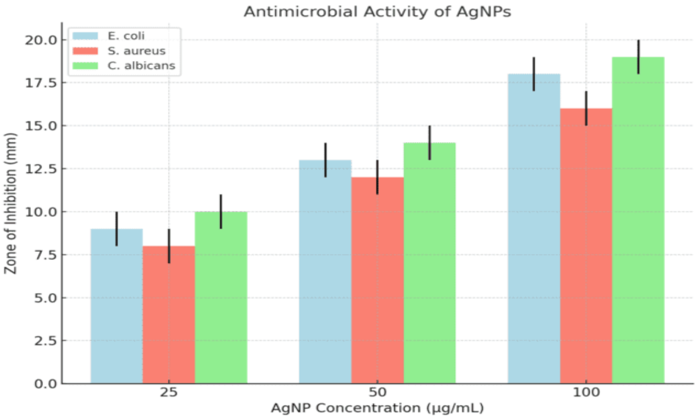


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Figure 6: Mechanism diagram: