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RESEARCH ARTICLE

Green fabrication of silver nanoparticles from *Cinnamomum zeylanicum* bark extract and evaluation of their antimicrobial efficacy

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ABSTRACT

In response to environmental concerns surrounding traditional silver nanoparticle synthesis, this study demonstrates an eco-conscious approach using *Cinnamomum zeylanicum* (*C. zeylanicum*) bark extract as a dual-function biological agent. UV–visible spectroscopy confirmed the successful formation of the AgNPs. The characteristic surface plasmon resonance signal was observed. FTIR spectroscopy identified key functional groups involved in the process. These groups include amines, alkanes, alkenes, and alkyl halides. They play crucial roles in the reduction and stabilization of nanoparticles. TEM revealed quasispherical nanoparticles with a uniform distribution, ranging from 5 to 20 nm in diameter. XRD analysis confirmed their crystalline structure. Zeta potential measurements demonstrated good colloidal stability, and the nanoparticles exhibited significant antimicrobial efficacy, with substantial zones of inhibition in antimicrobial assays. This sustainable synthesis method eliminates the need for harsh chemicals and hazardous reaction conditions, providing a green pathway for producing antimicrobial silver nanoparticles. The approach offers promising applications in pharmaceutical products, medical devices, and water treatment systems while addressing environmental and toxicity concerns associated with traditional synthesis methods.

Keywords: Cinnamomum zeylanicum; AgNPs; green synthesis; antibacterial activity

1. Introduction

Nanotechnology is rapidly becoming a revolutionary discipline that has vast applications in medicine, electronics, and the environmental sciences. Here, the sustainable approach to nanoparticle synthesis is focused mainly on biologically derived material methodologies. The present approach involves greener methodologies than conventional methods do, which often rely on toxic reagents, high costs, and energy-intensive procedures[1]. Biological approaches address the growing demand for safer, less expensive, and scalable nanomaterial production methods, particularly in biomedicine and environmental remediation[2]. Noble metal nanoparticles have attracted considerable research interest because of their unique optical, electrical, and catalytic properties. These characteristics differ significantly from those of their macroscopic counterparts, making noble metal nanoparticles particularly advantageous for a range of applications, including catalysis and targeted drug delivery systems[3]. Silver nanoparticles (AgNPs) stand out for their potent antibacterial properties, which have led to their incorporation into a range of consumer products, such as wound dressings, medical devices, water filters, and textiles[4].

Traditional methods for synthesizing AgNPs, such as vacuum metal deposition, chemical reduction, and lithography, have limitations in terms of environmental impact, cost, and scalability[5]. To address these concerns, green synthesis methods have gained momentum. Plant-based synthesis is favored for its simplicity, low toxicity, and environmental sustainability. Various plant components, including leaves, flowers, seeds, and bark, contain bioactive compounds capable of reducing metal ions and stabilizing nanoparticles[6,7]. This method aligns with the global shift toward sustainable and green technologies. In the context of AgNP production, plant extracts also provide additional capping molecules that increase the stability of the resulting nanoparticles. These bioactive molecules, such as flavonoids, terpenoids, and polyphenols, contribute to the overall efficacy of nanoparticles in biological applications[8]. Recent studies have highlighted the use of *Cinnamomum zeylanicum (C. zeylanicum)* bark extract in nanoparticle synthesis because of its high content of antioxidants and essential oils, which exhibit strong antibacterial and pharmacological activities. The bark is particularly notable for its potential in managing type II diabetes and insulin resistance[9,10]. The green synthesis of AgNPs via plant extracts produces particles of varying sizes with diverse biomedical applications. AgNPs synthesized from *Acacia nilotica* bark extract range from 20–50 nm in size and have anticancer, antidiabetic, and antioxidant properties[11]. Mangosteen pericarp extracts yield 7–38 nm AgNPs, which exhibit strong antimicrobial activity against foodborne pathogens[12]. *Annona squamosa* leaf and fruit extracts produce AgNPs of 35–90 nm and 15–50 nm, respectively, with potential antibacterial, anticancer, and antidiabetic applications[13]. The smallest AgNPs (5–15 nm) were obtained from Pacific Yew tree leaves, whereas *Wedelia urticifolia* flower extracts produced AgNPs <30 nm with the greatest antibacterial effectiveness[14]. These studies demonstrate that green synthesis methods produce AgNPs with sizes ranging from 5–90 nm, offering a sustainable approach to nanoparticle production with promising biomedical applications. The selection of plant materials not only influences nanoparticle size and morphology but also affects the bioactivity of the resulting AgNPs. Bioactive compounds such as flavonoids, terpenoids, and polyphenols act as reducing and stabilizing agents, contributing significantly to nanoparticle stability and biological functionality. Notable examples include the use of *C. zeylanicum* bark extract, which has robust antimicrobial activity, facilitating the formation of AgNPs with strong antioxidant properties.

The present study synthesized and characterized AgNPs from *C. zeylanicum* bark extract via an eco-friendly, plant-mediated approach. This research provides a comprehensive characterization of AgNPs synthesized from *C. zeylanicum* bark extract, distinguishing it from the methods of previous studies that have demonstrated synthesis primarily via various plant extracts. This methodology includes a detailed analysis of nanoparticle properties, encompassing precise size distribution measurements, extensive antimicrobial efficacy assessments, and a thorough evaluation of the green synthesis process.

2. Materials and methods

2.1. Aqueous extraction of *C. zeylanicum* bark extract

Bark samples of *C. zeylanicum* obtained from a local market were subjected to a systematic processing protocol. The plant species was authenticated by a qualified botanist - Dr. P. Palani, University of Madras. The plant material was cleaned with distilled water to remove impurities. The samples were subjected to drying in a hot air oven at 60 ℃ for 48 hours. The dried samples were subsequently finely ground using a mortar and pestle. For the preparation of the extract, 5 g of powdered bark was combined with 125 mL of distilled water and heated at 70 ℃ for 30 minutes. The resulting mixture was then filtered through Whatman No. 1 filter paper[5].

2.2. Green synthesis of AgNPs via *C. zeylanicum* bark extract

The AgNPs synthesis conditions were determined by optimizing the synthesis process with various concentrations of *C. zeylanicum* bark extract. The synthesis of AgNPs was conducted by combining optimized volumes of a silver nitrate solution (1 mM, 2 mL) with the prepared plant extract (8 mL) in a conical flask while maintaining efficient nanoparticle formation. Negative controls using distilled water and silver nitrate solution without bark extract were implemented to confirm the specificity of nanoparticle formation. The formation of AgNPs was monitored visually, as indicated by a colorimetric change to brown at approximately 10 minutes. The synthesized AgNPs were subsequently isolated through centrifugation at 10,000 rpm for 15 minutes. Multiple washing cycles utilizing distilled water were conducted to eliminate any residual biomass. The resulting purified AgNPs were subsequently stored for further characterization analyses[9].

3. Characterization

The characterization of AgNPs was accomplished through various analytical methods.

3.1. Spectrophotometric analysis of the AgNPs

UV–Vis spectroscopy was carried out with spectra recorded at a 1 nm resolution in the range of 300–600 nm via quartz cuvettes (Thermo Scientific Genesys 180 spectrophotometer)[15].

3.2. Infrared Spectroscopy of AgNPs

FTIR spectroscopy of the synthesized AgNPs from C. zeylanicum bark extract was performed in diffuse reflectance mode over 4000–400 cm^{-1} using KBr pellets (Thermo Scientific NICOLET ATR instrument)[16].

3.3. Electron microscopy examination of AgNPs

A dilute suspension of AgNPs was prepared in deionized water and subsequently placed on a carbon-coated copper grid for TEM imaging. Morphological analysis was conducted via a JEOL JEM-2100 Plus microscope operating at an accelerating voltage of 200 kV[15].

3.4. Crystallographic assessment of the AgNPs

The crystallinity of the AgNPs was determined via X-ray diffraction (Bruker AXS D8), and the diffraction pattern was recorded with an additional instrument (ARL EQUINOX 3000).

3.5. DLS Analysis of AgNPs

DLS measurements were carried out with samples filtered through a 0.45 nm nylon syringe filter directly into a polyacrylic cell (HORIBA SZ-100 Zeta Sizer, Windows Z Type Ver. 2.40)[16].

3.6. Antibacterial activity

The antimicrobial efficacy of the biosynthesized AgNPs was evaluated via the disc diffusion method against gram-positive (*S. aureus*) and gram-negative (*E. coli*) bacterial strains. The test organisms were

cultured on nutrient agar media and incubated under standard conditions (37 ℃, 18–24 h). Sterilized Petri dishes (90 mm in size) were created with solidified Muller–Hinton agar. The microorganisms were inoculated into each solidified plate under sterile conditions. Sterile Whatmann filter paper discs were cut into 6 mm diameter discs and loaded with different concentration of AgNP solution and air-dried at room temperature for 30 min before being placed on the culture inoculated MHA plates. The experiment was conducted with various concentrations of AgNPs (10 µg, 20 µg, and 30 µg) to assess their concentration-dependent antibacterial effects. The zone of inhibition surrounding each disc was measured via a zone-measuring device; the absence of a zone of inhibition was interpreted as a lack of antimicrobial activity[17].

4. Results

4.1. Synthesis of AgNPs

The successful formation of AgNPs was visually confirmed by a color change from pale yellow to dark brown, indicating the reduction of silver ions (Ag^+) to metallic silver Ag^0[13–16]. A color shift was observed in the results of Deepa et al.[21], who used a variety of plant extracts and reported comparable outcomes. Liu et al.[22] demonstrated that polyphenolic compounds play crucial roles in stabilizing and reducing agents during the synthesis of AgNPs. The formation of AgNPs through plant-mediated reduction involves intricate interactions between silver ions and phytochemical compounds. Previous studies, such as AgNP synthesis using green tea extract and flaxseed extract, demonstrated comparable color changes. However, our approach utilizing *C. zeylanicum* bark extract provides a greener and potentially more efficient alternative for the reduction process[23,24].

4.2. UV–Vis analysis

UV–visible spectroscopic analysis confirmed the formation of AgNPs through the appearance of a characteristic surface plasmon resonance (SPR) peak at 426 nm (**Figure 1**). In previous research on green synthesis, the absorption maximum was well suited for spherical AgNPs. This peak position aligns with previously reported ranges (420–430 nm) in the literature, suggesting the successful synthesis of nanoparticles with dimensions less than 50 nm[13–16]. A color change in *Achillea maritima* extract from pale yellow to dark brown, as reported by Essghaier et al.[25], confirmed the reduction of Ag^+ ions to Ag^0, indicating AgNP formation. The UV–Vis spectra showed a surface plasmon resonance peak at 420 nm. In contrast, phenol-assisted cubic AgNPs from *Agaricus bisporus* were generated via an ultrasonic-assisted method, yielding cubic nanoparticles with SPR peaks at position 401[26]. Similarly, Ajaykumar et al.[27] observed a plasmon resonance band at 427 nm in the UV–Vis absorption spectra of AgNPs synthesized from *Uvaria narum* leaf extract, indicating the successful formation of silver nanoparticles. The wider peaks observed in traditional chemical synthesis methods are sharp, well defined in shape and indicate a uniform particle size distribution.

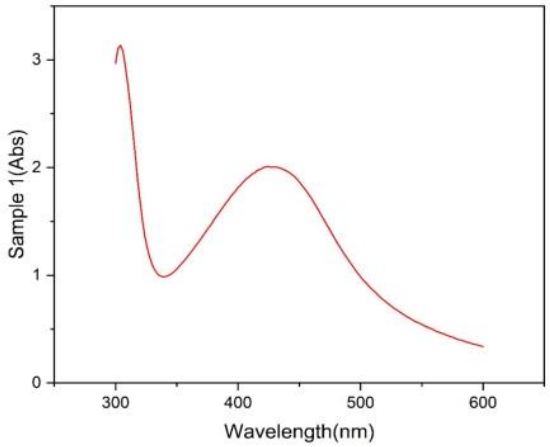

Figure 1. UV–vis spectral analysis of the AgNPs

4.3. FTIR analysis

The FTIR spectra revealed several functional groups involved in the reduction of Ag^+ and capping of the AgNPs. The notable peaks included 3284 cm^{-1} (N–H bonds in amines), which is similar to the findings of Shao et al., who reported similar amine-related peaks in plant extract-mediated AgNP synthesis: 2924 cm^{-1} (H–C–H stretching of alkanes), 1610 cm^{-1} (C=C stretching of alkenes), 1282 cm^{-1} (CH_2X stretching of alkyl halides), and 1076 cm^{-1} (aliphatic amines) (**Figure 2**). These findings align with the FTIR results reported for *Rhazya stricta Decne* extracts, which revealed that similar functional groups, such as OH (3307 cm^{-1}) and carboxyl (2984 cm^{-1}) groups, contribute to AgNP synthesis. While both studies highlight the importance of functional groups such as carbonyls and amines in stabilizing nanoparticles, the current study emphasizes the synergistic role of alkyl halides (1282 cm^{-1}) and aliphatic amines (1076 cm^{-1}) in enhancing stability and antibacterial activity, distinguishing these findings from earlier findings. The functional groups identified in the FTIR spectra, such as amines, alkanes, and alkenes, play crucial roles in capping and stabilizing the AgNPs. Amine groups serve as electron donors, facilitating the reduction and stabilization of silver ions and enhancing antibacterial efficacy through membrane disruption. Alkanes provide hydrophobic interactions that enhance colloidal stability, whereas alkenes, with their double bonds, stabilize AgNPs and improve reactivity. Alkyl halides form a protective barrier, preventing oxidation and agglomeration, thus maintaining antibacterial activity. These functional groups work synergistically to ensure the structural integrity of AgNPs and amplify their antibacterial properties, enabling membrane disruption, protein denaturation, enzyme inhibition, and sustained release of silver ions for effective antibacterial action[15,16,28].

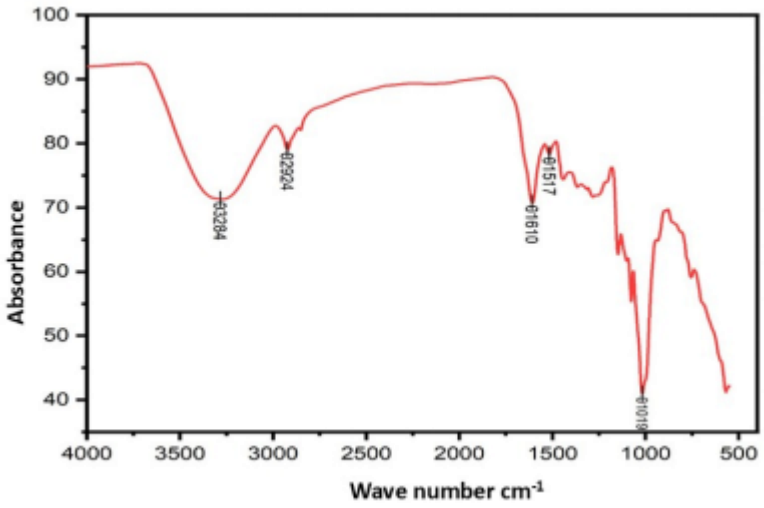

Figure 2. FTIR analysis of the AgNPs

4.4. TEM analysis

TEM analysis revealed good uniformity in size, with an average diameter of 5 nm (**Figure 3a, b**). The crystalline nature of the particles was validated by the SAED pattern (**Figure 3c**). This specific range of sizes is particularly remarkable because Menichetti et al.[29] reported that AgNPs less than 10 nm in size show superior antimicrobial activity than larger AgNPs do[30]. Comparatively, Picoa-AgNPs were synthesized via a desert truffle (*Picoa* sp.), which formed nanoirregular shapes (19.5 nm) with moderate stability (-20.9 mV) and a longer synthesis time of 60 minutes. Shumi et al.[31] reported AgNPs with diameters ranging from 5 to 14 nm, as observed in their TEM micrographs, highlighting the uniformity and small size of the nanoparticles. The green synthesis method used in this study produced AgNPs with a consistent morphology and a narrow size range. This contrasts with many plant-mediated methods, which often result in broader size distributions and irregular shapes[32].

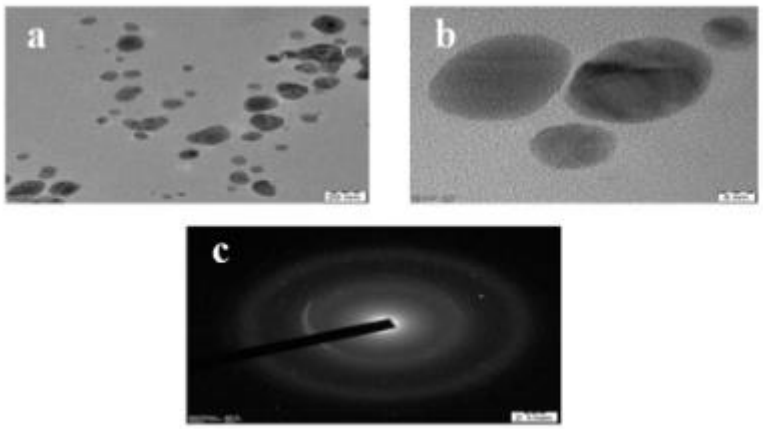

Figure 3. (a) and (b) TEM images of the AgNPs and (c) SAED image of the AgNPs

4.5. XRD analysis

The crystalline nature of the synthesized AgNPs was evident from the XRD analysis, which revealed distinct peaks at 2θ values of 38.12°, 44.06°, 64.31°, and 77.58°, corresponding to the (111), (200), (220), and (311) planes of a face-centered cubic (fcc) structure, respectively (**Figure 4**). These results are consistent with previously reported patterns for FCC configurations[9]. In one study, sharp XRD peaks corresponding to the (111), (200), (220), and (311) Bragg reflection planes of the AgNPs confirmed their face-centered cubic (FCC) crystal structures. Similarly, in this study, XRD analysis revealed distinct peaks at 2θ values of 38.12°, 44.06°, 64.31 °, and 77.58 °, which is consistent with FCC structures, confirming the nanocrystalline nature and high purity of the synthesized AgNPs[33].

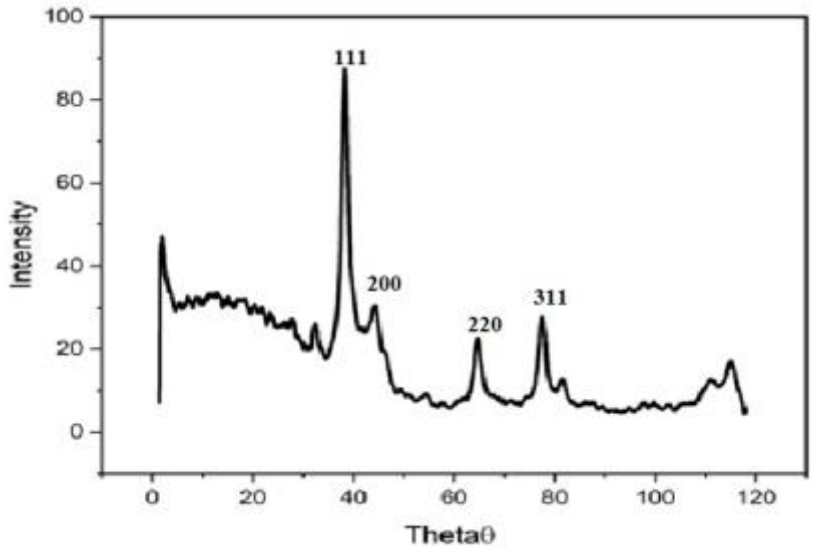

Figure 4. XRD analysis

4.6. Zeta potential/DLS

Zeta potential analysis revealed a value of -25.0 mV (**Figure 5)** for the synthesized AgNPs, indicating moderate colloidal stability. While values greater than ±30 mV are ideal for long-term stability, the observed value is sufficient for many biomedical applications, such as antimicrobial treatments, where the nanoparticles can remain dispersed long enough to exert their effects[34]. Stability can be influenced by nanoparticle concentration, ionic strength, and stabilizing agents. Numerous studies have shown that AgNPs with zeta potential values of approximately -25 to -30 mV maintain adequate stability for short- to medium-term use,

particularly in controlled environments[35–37]. Rehman et al. reported that most zeta potentials higher than ±30 mV usually offer better long-term stability[38]. Despite being on the lower end for long-term stability, the value remains suitable for applications such as wound dressings, water filtration, and antimicrobial textiles. Further optimization or the addition of additional stabilizers may be needed for enhanced long-term dispersion and stability[39].

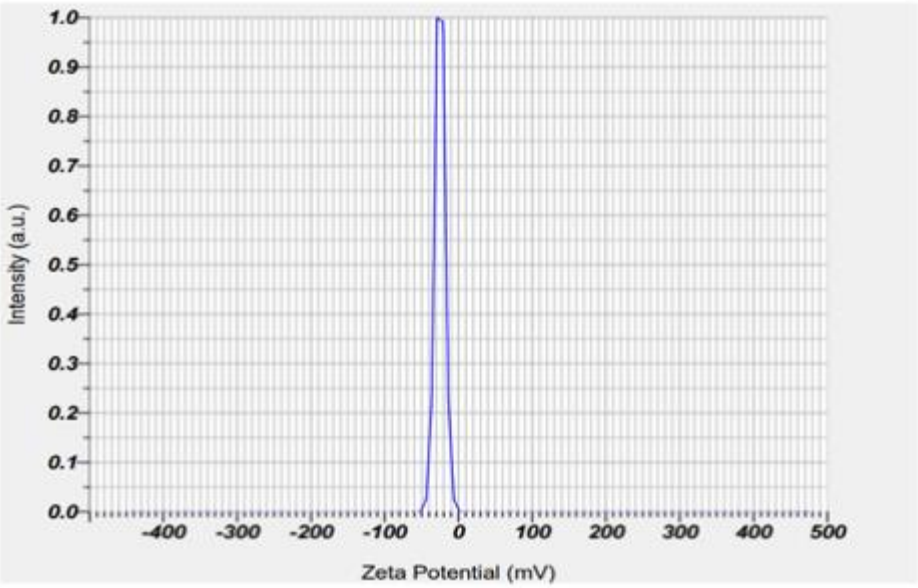

Figure 5. Zeta potential of the AgNPs

4.7. Antibacterial activity

The synthesized AgNPs demonstrated notable antibacterial activity, producing inhibition zones of 18 mm against *S. aureus* and 14 mm against *E. coli* at a concentration of 30 µg. This highlights the strong efficacy of AgNPs, particularly against *S. aureus* (**Table 1**). The antibacterial activity demonstrated that, compared with *E. coli*, *S. aureus* is more susceptible to AgNPs. In contrast, the performance exceeds the antifungal activity of Picoa-AgNPs, which exhibited inhibition percentages of 30.81% against *Pythium* sp. and 16.67% against *Aspergillus niger*. Similarly, although phenol-assisted cubic AgNPs have shown notable antibacterial activity *against Pseudomonas aeruginosa* and *Staphylococcus aureus*, their larger particle size (50.44 nm) may limit their effectiveness in applications that require smaller nanoparticles for enhanced penetration and interaction[26,29]. This finding aligns with previous research indicating that the enhanced susceptibility of gram-positive bacteria, attributed to their thinner peptidoglycan layers and greater vulnerability to membrane perturbation, results in a heightened antibacterial effect of biosynthesized AgNPs against these microorganisms[40–42]. The observed antibacterial effects can be attributed to multiple mechanisms of action. First, AgNPs interact with the bacterial cell membrane, causing destabilization and the formation of pores, which results in leakage of the cellular contents and loss of membrane integrity. Additionally, AgNPs generate ROS, such as superoxide anions, hydrogen peroxide, and hydroxyl radicals, which induce oxidative stress and cause damage to lipids, proteins, and DNA. This oxidative damage disrupts vital cellular processes, including membrane function, enzyme activity, and DNA replication, ultimately leading to cell death. Moreover, AgNPs bind to critical bacterial enzymes and proteins, inhibiting their function by interacting with thiol groups and disrupting metabolic pathways. The combined effects of membrane disruption, ROS generation, and enzyme inhibition contribute to the broad-spectrum antimicrobial action of AgNPs, making them effective against both gram-positive and gram-negative bacteria. These findings suggest that AgNPs synthesized from *C. zeylanicum* bark extract have strong potential as antimicrobial agents for use in medical applications, such as wound dressings and antimicrobial textiles[43,44].

Table 1. Zone of inhibition by *C. zeylanicum* bark extract of AgNPs against bacteria

Microorganisms	Zone of Inhibition in mm		
	10 µg	20 µg	30 µg
Staphylococcus aureus	0	15	18
Escherichia coli	0	14	16

5. Conclusion

The current study effectively illustrated the biosynthesis of AgNPs through the use of *Cinnamomum zeylanicum* bark extract, presenting a promising alternative to traditional chemical synthesis methods. A comprehensive characterization employing UV–vis spectroscopy revealed an absorption peak at 426 nm, whereas FTIR spectroscopy and TEM analysis confirmed the spherical morphology of the synthesized silver nanoparticles, with a calculated average diameter of 5 nm. The crystalline nature was confirmed by the characteristic face-centered cubic structure shown in the XRD analysis, while a zeta potential of -25.0 mV indicated acceptable colloidal stability. In addition, the synthesized AgNPs exhibited excellent antimicrobial potential against *S. aureus* (18 mm) and *E. coli* (14 mm) at a concentration of 30 µg, indicating broad-spectrum antimicrobial activity. The results of the present investigation show excellent promise for applications in medical devices, wound dressings, water purification systems, and antimicrobial textiles. Future research should focus on testing the safety of AgNPs for biomedical applications. The use of cell lines to confirm biocompatibility should specifically aim at assessing cell viability, membrane integrity, apoptosis, and hemolysis. These evaluations will help determine the potential risks associated with AgNPs in clinical settings, including wound dressings and drug delivery systems.

List of abbreviations

AgNPs: Silver Nanoparticles

C. zeylanicum: Cinnamomum zeylanicum

UV–vis: Ultraviolet–visible spectroscopy

FTIR: Fourier transform infrared spectroscopy

TEM: transmission electron microscopy

XRD: X-ray diffraction

DLS: Dynamic light scattering

SPR: surface plasmon resonance

fcc: Face-centered cubic

MHA: Muller–Hinton agar

SAED: Selected area electron diffraction

Ag^{+}: Silver Ion

Ag^{o}: Metallic Silver

S. aureus: Staphylococcus aureus

E. coli: Escherichia coli

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Author contributions

Mariya Banu Sri Rajasekaran and Manoj Kumar Karuppan Perumal were responsible for writing the original draft and contributed to the review and editing process. Guru Prasad Srinivasan contributed to the writing of the manuscript. Muruganandam Nagarajan, Antony Vincent Samrot, Stalin Dhas Tharmalingam, and Angeline Julius developed the conceptualization for the study. Remya Rajan Renuka provided supervision for the manuscript. All the authors participated in the drafting and critical revision of the manuscript. All authors gave final approval of the submitted version of the manuscript.

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Conflict of interest

The authors declare no conflicts of interest.

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