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Potential Application of Silver Nanoparticles Synthesized Using *Cassia abbreviata* Aqueous Extracts in Water Treatment

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Abstract

Nanotechnology is being recognized for its potential in addressing global drinking water issues, managing microbial risks, and meeting stringent water quality standards. However, there is a lack of information on the efficacy of silver nanoparticles synthesized using indigenous African herbal plants in eradicating harmful bacteria in contaminated water. This study introduces, for the first time, the use of the herbal plant *Cassia abbreviata* for the biosynthesis of silver nanoparticles. The biosynthesized silver nanoparticles were characterized using UV-vis spectrophotometer and atomic force microscope (AFM) techniques. The silver nanoparticles exhibited absorption peaks in the 400 to 500 nm range, with an average size ranging from 18 to 33 nm and a rough surface topography. These silver nanoparticles demonstrated potent antibacterial effects against both Gram-positive and Gram-negative pathogenic bacteria, regardless of whether the aqueous extract of leaves, stem barks, or root barks of *C. abbreviata* was utilized. The minimum inhibitory concentration (MIC) values for Gram-positive and Gram-negative bacteria ranged from <0.03 to 1.69 mg/mL. Additionally, the silver nanoparticles efficiently reduced high levels of fecal coliform bacteria (>10^5 cfu/100 mL) in surface water to undetectable levels within 4 hours at a concentration of >9.37 mg/mL, showcasing their potential for water purification. Findings from this study demonstrate that aqueous extracts of *C. abbreviata* leaves, stem barks and root barks are excellent precursors for producing silver nanoparticles with robust antimicrobial and disinfectant properties.

Keywords: Herbal plant; aqueous extract; antimicrobial activity; fecal coliform bacteria; water treatment

Introduction

Cassia abbreviata, a member of the Fabaceae family, is a small-to-medium-sized branched tree that is widely distributed in tropical environments particularly in southeast Africa (Yang et al. 2021, Zheng et al. 2021). For many years, aqueous extracts of *Cassia abbreviata* have been utilized in traditional medicine to treat various microbial infections (Maroyi 2013, Mongalo et al. 2017, Zheng et al. 2021, Yang et al. 2021, Moiketsi et al. 2023). Recent studies have confirmed the presence of a variety of bioactive compounds from different chemical classes such as alkaloids, flavonoids, coumarins, saponins, tannins, phenols and steroids in *C. abbreviata* plants (Yang et al. 2021, Zheng et al. 2021, Raman Ibrahim et

al. 2022) that can react with Ag^+ to produce potent bactericidal nanoparticles (Beyene et al. 2017, Ahmad et al. 2019, Mwakalesi and Mushi 2024). Silver nanoparticles derived from plant extracts have been shown to disrupt bacterial metabolic processes, enhance cytoplasmic membrane permeability, and interact with DNA, leading to cell death (Ahmad et al. 2020). Despite the impact of these nanoparticles, there have been no reported syntheses of bactericidal nanoparticles from *C. abbreviata* (Beyene et al. 2017), limiting our understanding of the plant's potential beyond its traditional medicinal uses. Further research is needed to explore the synthesis of valuable nanoparticles from *C. abbreviata*, which may have significant implications for environmental and public health.

Nanoparticles are produced through a green synthesis method at ambient temperature and pressure, avoiding the use of harmful substances or the generation of harmful by-products (Ahmad et al. 2019). This eco-friendly approach involves the rapid reduction and nucleation of metallic ions using plant metabolites, leading to the formation of reactive crystals that can aggregate and then be stabilized through capping to form metallic nanoparticles (Marchiol et al. 2014). While the synthesis of nanoparticles from plant extracts and metal ions has been well-documented (Ghaffari-Moghaddam and Hadi-Dabanlou 2014, Beyene et al. 2017, Ahmad et al. 2019, Divya et al. 2019) and their antimicrobial properties have been thoroughly examined against various microorganisms, it remains unclear whether metallic nanoparticles derived from the leaves, stem barks, and root barks of *C. abbreviata* demonstrate comparable antimicrobial activity and physico-chemical properties as different parts of the *C. abbreviata* plant contain distinct bioactive compounds (Raman Ibrahim et al. 2022).

The use of green nanoparticles has been applied in various fields (Beyene et al. 2017). However, the application of green nanotechnology in the water treatment sector has not been widely acknowledged by water quality managers, particularly in developing nations, despite the widespread occurrence of waterborne illnesses and the inefficiency and cost-ineffectiveness of existing water treatment technologies (Gwenzi et al. 2015). Previous studies have looked at treating contaminated water using various methods, such as paper embedded with silver nanoparticles (Dankovich and Gray 2011), aminated polyethersulfone-silver nanoparticles composite membranes (Haider et al. 2016), ceramic filters impregnated with silver nanoparticles (Kallman et al. 2011), and woven fabric microfiltration membranes impregnated with silver nanoparticles (Mecha and Pillay 2014). However, the use of synthesized nanoparticles from herbal plants including *C. abbreviata* for water treatment has not been previously examined.

The study focused on the synthesis of bionanoparticles (SBNs) from aqueous extracts of leaves, stem barks, and root barks of *C. abbreviata* plants using an ecofriendly procedure and confirmed through color changes, UV-vis spectroscopy, and atomic force microscopy (AFM). The study also evaluated the antibacterial efficacy of these SBNs against Gram-positive bacteria, specifically *Staphylococcus aureus* (*S. aureus*) and *Enterococcus faecalis* (*E. faecalis*), as well as Gram-negative bacteria, including *Escherichia coli* (*E. coli*) and *Pseudomonas aeruginosa* (*P. aeruginosa*), using zone of inhibition and minimum inhibitory concentration (MIC) assays. Additionally, the study assessed the water disinfection potential of different concentrations of SBNs and exposure times against faecal coliform bacteria in river water. The hypothesis was that SBNs could effectively reduce faecal coliform bacteria in environmental water due to their potent antimicrobial properties. Given the high incidence of waterborne disease outbreaks, especially in low-income countries, this study represents a significant step towards exploring alternative strategies (nano-disinfectants) for water treatment and microbial control.

Materials and Methods

Collection of various parts of *C. abbreviata* and preparation of aqueous extracts

Fresh leaves (CA-FL), stem barks (CA-SB), and root barks (CA-RB) were taken from the *C. abbreviata* plants in the Dar es Salaam region (6° 48′ S, 39° 17′ E), Tanzania, following identification by a plant taxonomist from the Department of Botany at the University of Dar es Salaam. The samples were washed with sterile distilled water, dried in the shade on clean drying tables for three days, and then cut into small pieces (approximately 1 to 2 cm^2). To prepare the aqueous extracts, 10 g of each sample was mixed with 100 mL of sterile distilled water in a 300 mL Erlenmeyer flask and heated at 60 °C for 1 hour. The resulting extracts were filtered through Whatman No. 1 filter paper (Merk) and stored in the refrigerator until needed.

Biosynthesis and characterization of SBNs

SBNs were synthesized by mixing 2 mL of the aqueous extract of *C. abbreviata* with 10 mL of 0.0025 M $AgNO_3$ (Merck, Darmstadt, Germany) to achieve a final concentration of 0.0021 M $AgNO_3$ and 0.95 mg/mL of extract. The mixture was then agitated in a rotary shaker at 120 rpm and left at room temperature until a deep dark brown colloidal suspension formed. Control samples (silver nitrate solution, aqueous extract) did not show any color change when incubated separately under similar conditions as the mixture of silver nitrate and aqueous extracts. The deep brown colloidal suspension was analyzed using a UV-vis spectrophotometer (Elico India Pvt Ltd, Chennai) in the absorbance range of 290 to 790 nm to confirm the presence of SBNs. The SBNs were subjected to five washes through centrifugation at 10,000 rpm for 15 minutes following the procedure described by Mwakalesi and Mushi (2024). The supernatants were discarded, and the dried pellets were weighed before being used to make a stock solution for subsequent experiments. The SBNs were further analyzed using AFM (Agilent Technologies) with a scanning tip (NSC36, Mikro-Masch, Poland). AFM captured two-dimensional images of the dried SBNs (0.4 mg mL^{-1}) placed on freshly cleaned negatively charged mica in non-contact mode with a scanning area of 1 µm × 1 µm. The images were analyzed using Gwyddion 2.51 software to determine the size of the SBNs (Masalu et al. 2020) and the surface topography of the SBN layer (Gulumian et al. 2021).

Testing SBNs for antimicrobial activity

The antimicrobial activity of SBNs was assessed using the well diffusion method (Divya et al. 2019). In brief, *E. coli* (ATCC 25922), *P. aeruginosa* (ATCC 27853), *S. aureus* (ATCC 25923), and *E. faecalis* (ATCC 51299) suspensions adjusted to 0.5 McFarland standard were prepared separately in screw cap test tubes using sterile phosphate-buffered saline. A one-milliliter volume of the standard suspension (≈10^6 cfu/mL) of each reference bacterial strain was spread evenly on separate Muller Hinton agar plates using a sterile cell spreader. Wells of 6 mm diameter were created on 4 mm thick Muller Hinton agar plates with the reference bacterial lawn using a sterile cork borer before adding SBNs (50 µg/mL) into the wells. It is worth mentioning that the plates were filled with an equal volume of Muller Hinton agar, resulting in an agar thickness of 4 mm as measured by a ruler. Gentamicin (50 µg/mL), dimethyl sulfoxide (50 µg/mL), silver nitrate solution (50 µg/mL) and *C. abbreviata* extracts (50 µg/mL) were included as controls. The plates were then incubated at 37 °C for 24 hours after being left at room temperature for 1 hour to allow for the diffusion of SBNs into the agar. Following incubation, the diameter of the clear zone of inhibition was measured in millimeters. The experiment was repeated three times to determine the average diameter of the inhibited zone.

Evaluation of SBNs minimum inhibitory concentration (MIC)

The MIC of synthesized SBNs was determined using a sterile 96-well microtiter plate following the standard broth microdilution method described by Masalu et

al. (2020). In summary, SBNs of various concentrations (ranging from 0.005 to 2 mg/mL) were prepared separately, and 10 µL of a reference bacterial culture with a turbidity of 0.5 McFarland standards was added to the wells of the 96-well microtiter plates. The final volume was adjusted to 100 µL with Muller Hinton broth. The same procedure was followed for evaluating the antibiotic gentamicin, silver nitrate solution, aqueous extracts and dimethyl sulfoxide as controls. Additionally, wells containing only MH broth were used to assess the sterility of the experimental setup. The plates were then incubated at 37 °C for 24 hours. After incubation, the optical density was measured at 600 nm using a UV-Vis spectrophotometer. The MIC value was determined as the lowest concentration of SBNs, aqueous extracts, silver nitrate or gentamicin that completely inhibited the growth of the bacterial species under investigation (Singh et al. 2013).

Water treatment efficacy by SBNs and time-kill assay

The water treatment efficacy of SBNs was tested by separately adding 0, 0.58, 1.17, 2.34, 4.69, 9.37 mg/mL of SBNs to individual water samples (n=3) with a mean faecal coliform bacteria concentration of $1.51\times10^5 \pm 5\times10^3$ cfu/100 mL that were collected from the Ngerengere River (coordinates 6.8S, 37.6E) in Morogoro, Tanzania. The levels of faecal coliform bacteria in the water samples were determined using the method described by Mushi et al. (2021). It should be noted that river water was selected for this experiment because it is one of the main sources of drinking water in Tanzania and contains various organic materials and many microbial species which can enhance our understanding of the antimicrobial activity and suitability of the SBNs for application in drinking water treatment. The mixture was constantly shaken for the specified contact time of two hours at room temperature. One hundred microliters (100 µL) of the mixture were spread in triplicate onto m-Endo agar (DIFCO, Michigan, USA) plates. Plates were incubated at 37 °C for 24 hours. Simultaneously, control plates (triplicate) with m-Endo agar were spread with 100 µL of river water without SBNs and incubated under the same conditions. After incubation, colonies of faecal coliform bacteria were counted and expressed as colony forming units per 100 mL (cfu/100 mL). The resulting data were used to determine the ability of SBNs in reducing the number of faecal coliform bacteria in the investigated river water. On the other hand, we evaluated the bacteria-killing ability of SBNs in which 0.58, 1.17, 2.34, 4.69, 9.37 mg/mL of SBNs were separately added to the river water samples contaminated by faecal coliform bacteria ($1.51\times10^5 \pm 5\times10^3$ cfu/100 mL) and agitated at 150 rpm. One hundred microliters from each of the treated water samples were separately spread on m-Endo agar plates at 10, 20, 30, 60, 120, 180, and 240 minutes. The number of colonies on the m-Endo agar plates was quantified and expressed as cfu/100 mL after incubation at 37 °C for 24 hours. The experiment was carried out in triplicates and the data were used to construct time-kill curves of faecal coliform bacteria in the respective river water samples.

Statistical assays

Triplicate values of the zone of inhibition, MIC, and concentrations of faecal coliform bacteria were presented as mean ± standard deviation (SD). Infographics in this study were generated using Microsoft Excel version 2010 (Redmond, USA). Statistical analysis was performed using SPSS software version 16.0 (SPSS, Inc. Chicago, IL, USA) to compare bactericidal activity levels between SBNs and aqueous extracts of *C. abbreviata* using the Mann-Whitney U test. The Kruskal-Wallis, a non-parametric test, was used to assess the differences in the time of killing of faecal coliform bacteria among SBNs synthesized from CA-FL, CA-SB, and CA-RB extracts. A probability (P) value of <0.05 was considered significant.

Results and Discussion

Biosynthesis of SBNs and their characterisation

The dark brown color of the SBNs observed in this study (Figure 1) align with findings from previous studies where extracts of leaf, stem, and root from plant species other than *C. abbreviata* were mixed with silver nitrate solution (Sigamoney et al. 2016, Saifuddin et al. 2024). This suggests that metabolites from *C. abbreviata* serve as effective bioreductants and capping agents during the synthesis of SBNs (Sigamoney et al. 2016). Analysis of the SBNs using a UV-vis spectrophotometer at room temperature revealed the surface plasmon resonance of silver with maximum absorption peaks at 481 nm, 468 nm, and 490 nm for CA-FL, CA-SB, and CA-RB, respectively (Figure 2). While these absorption peaks fall within the typical range for silver nanoparticles (400 - 500 nm) as reported by Beyene et al. (2017), the differences in their maximum absorption peaks suggest variations in the functional groups of the SBNs among CA-FL, CA-SB, and CA-RB samples. The absorption spectrum of nanoparticles is known to be influenced by surface functionalization (Al Farsi et al. 2021), suggesting differences in the composition of functional groups in the SBNs synthesized from CA-SB, CA-FL and CA-RB extracts. Each sample displayed a single surface plasmon resonance band (Figure 2), confirming the nanoscale nature of the synthesized SBNs with average sizes (total number of particles) of 18 (300) nm for CA-FL, 25 (143) nm for CA-SB, and 33 (158) nm for CA-RB. Furthermore, two-dimensional AFM images of SBNs layers displayed rough surfaces (Figure 3) responsible for enhancing surface area and promoting adhesion (Zhen et al 2021).

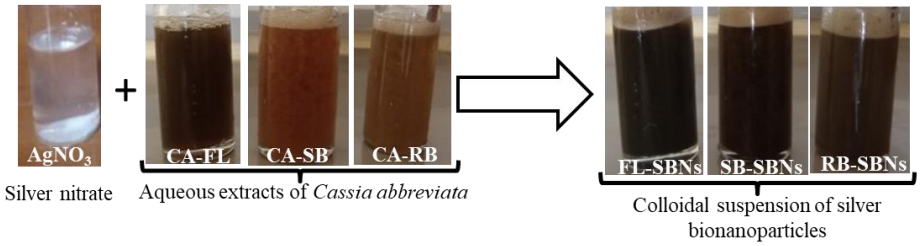

Figure 1: The silver nitrate solution reacted with the aqueous extracts of fresh leaf (CA-FL), stem bark (CA-SB), and root bark (CA-RB) of *C. abbreviata*, resulting in the formation of a dark brown colloidal suspension of silver bionanoparticles (SBNs). FL-SBNs refer to silver bionanoparticles synthesized from leaf extract, SB-SBNs from stem bark, and RB-SBNs from root bark.

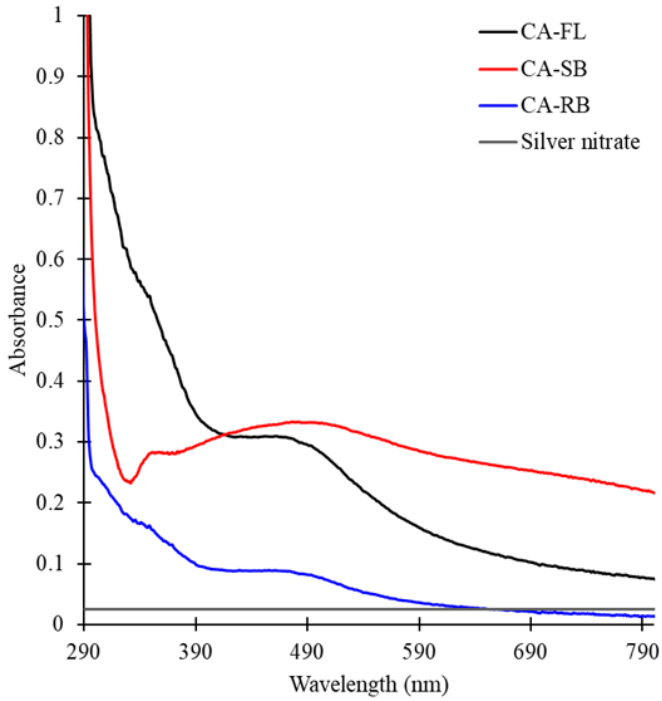

Figure 2: The UV-visible spectra of newly synthesized SBNs from fresh leaf extract (CA-FL), stem bark extract (CA-SB), and root bark extract (CA-RB) are compared with that of a silver nitrate solution.

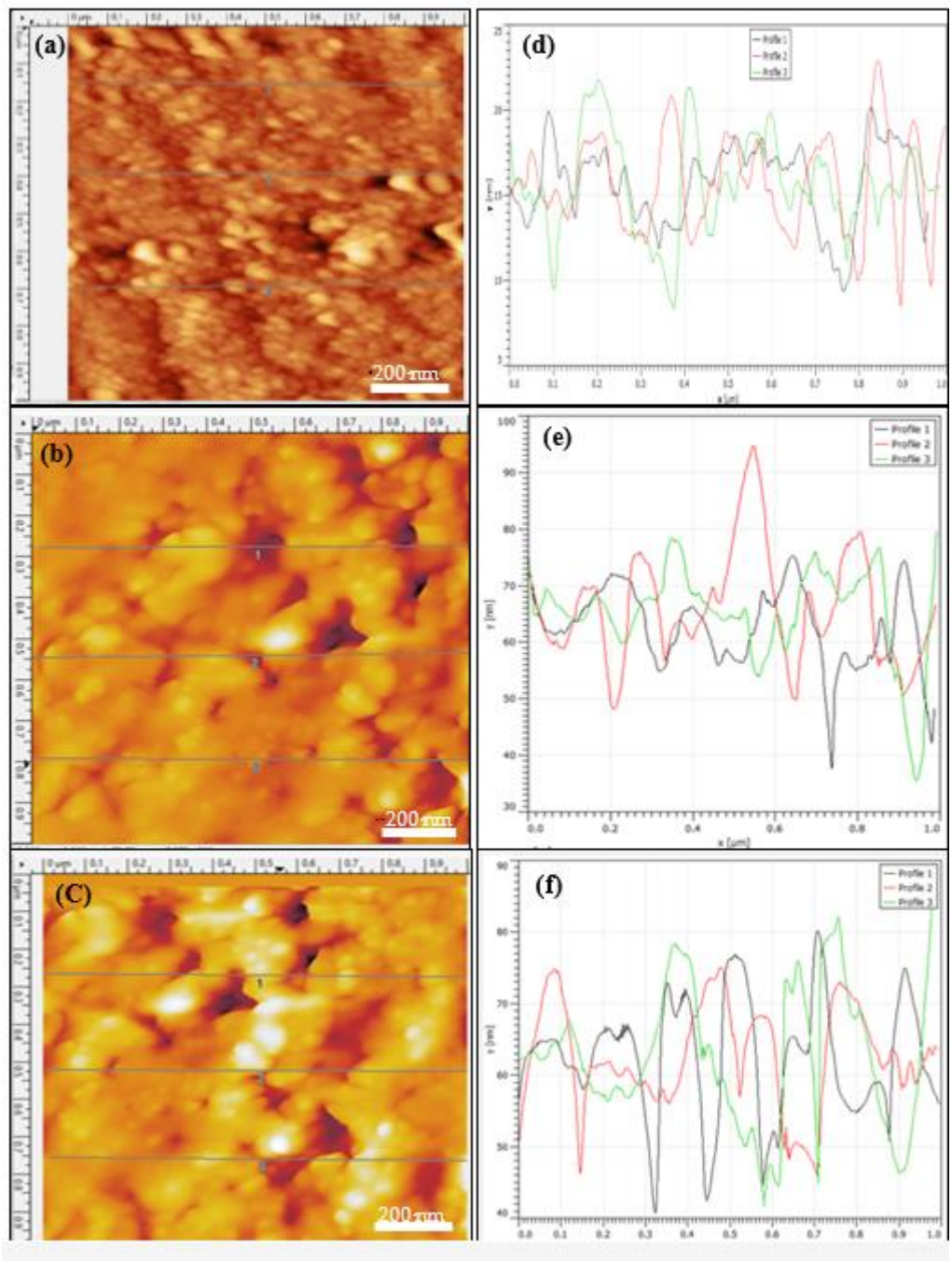

Figure 3: Atomic force microscopy height images were taken at a scanning area of 1 µm × 1 µm, showing the synthesized SBNs from CA-FL (a), CA-SB (b), and CA-RB (c). The corresponding cross-sectional profiles (d, e, f) are also provided. Note that the x-axis and y-axis of the cross-sectional profile represent length (µm) and height (nm), respectively.

Bactericidal activity of SBNs surpassed that of aqueous extracts of *C. abbreviata*

The data on the bactericidal efficacy supported the traditional medicinal use of *C. abbreviata* (Maroyi 2013). Aqueous extracts of CA-FL, CA-SB, and CA-RB exhibited inhibitory effects on *E. coli* (7-10 mm), *P. aeruginosa* (9-10 mm), *S. aureus* (14-18 mm) and *E. faecalis* (11-14 mm) based on the zone of inhibition measurements (Figure 4). Although the extract inhibition zones were smaller than those of the positive control (gentamicin), Gram-positive bacteria were more susceptible to these extracts than Gram-negative bacteria. These results further validate the use of this herbal plant in producing SBNs through a cost-effective, one-step, and environmentally friendly method.

The synthesized SBNs showed significantly higher bactericidal activity compared to the aqueous extracts ($P<0.05$; Figure 4), likely due to the presence of silver in the SBNs complex. This finding aligns with the results reported by Chandrasekharan et al. (2022), despite using different plant species than *C. abbreviata*. The inhibitory effect of SBNs varied among the tested bacterial strains. *E. coli* had smaller inhibition zones (10-13 mm) compared to *P. aeruginosa* (15 – 18 mm), *E. faecalis* (15-17 mm), and *S. aureus* (15–17 mm) regardless of the plant part used in the SBNs production (Figure 4). The susceptibility of *P. aeruginosa*, *E. faecalis*, and *S. aureus* to SBNs was higher than that of silver nitrate, consistent with previous reports by Mwakalesi and Mushi et al. (2024). Additionally, the inhibitory effect of SBNs was comparable to gentamicin for *P. aeruginosa*, *E. faecalis*, and *S. aureus*, but notably lower for *E. coli* compared to gentamicin. Previous studies have shown the bactericidal activity of SBNs against *E. coli*, *P. aeruginosa*, *E. faecalis*, and *S. aureus* (Ghaffari-Moghaddam and Hadi-Dabanlou 2014, Sigamoney et al. 2016, Saravanan et al. 2018). These studies demonstrated that SBNs can adhere to the bacterial cell wall, penetrate it, and cause membrane damage leading to leakage of cellular contents and death or release silver ions that interfere with sulfhydryl groups of proteins and enzymes. Therefore, the investigated bacterial species likely experienced these mechanisms of cell destruction when in contact with the SBNs synthesized from *C. abbreviata* plant parts.

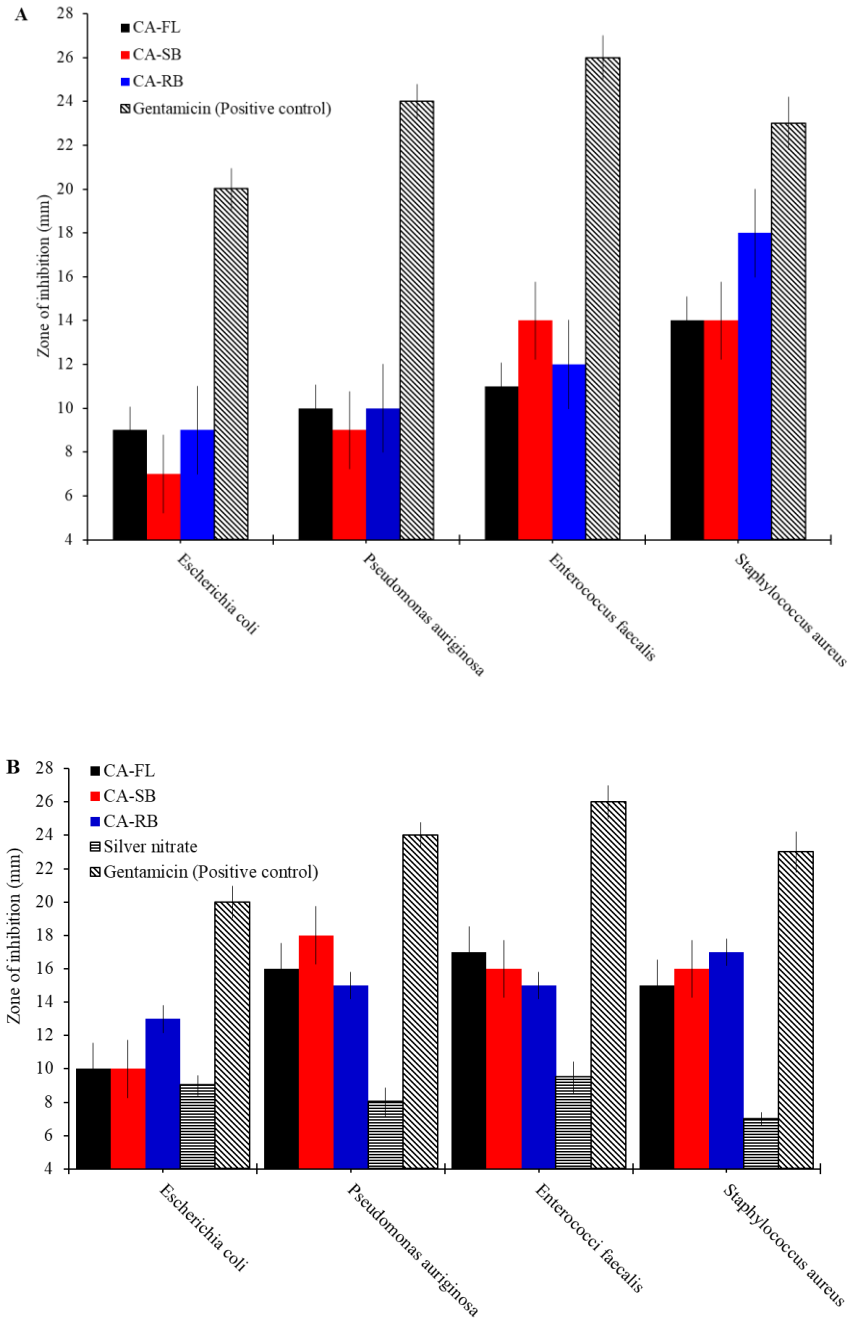

Figure 4: Mean ± standard deviation of the zone of inhibition for aqueous extracts (A) and SBNs (B) derived from fresh leaves (CA-FL), stem barks (CA-SB), and root barks (CA-RB) of the *C. abbreviata* plant under study. It is important to note that the zone of inhibition for the positive control (Gentamicin), negative control (dimethyl sulfoxide), and silver nitrate were also measured for comparison. Notably, all bacterial strains showed no inhibition zone against the negative control, and this data point was not show in Figure 4 for clarity.

The MIC was determined to assess the bactericidal activity of newly synthesized SBNs and the aqueous extract of *C. abbreviata* against the reference pathogenic bacteria (Table 1). Significant differences in MIC values were observed between SBNs and the aqueous extract of *C. abbreviata* ($P<0.05$), consistent with the results of the zone of inhibition experiment (Figure 4). SBNs exhibited lower MIC values (<0.026 to 1.69 µg/mL) against all tested bacterial strains compared to the aqueous extract of *C. abbreviata* (0.36 to 14.5 µg/mL), indicating stronger antimicrobial activity of SBNs. The MIC values for SBNs were lower than those of silver nitrate solution but similar to gentamicin except for SBNs produced from the leaf extract of *C. abbreviata* tested against *E. coli* and *S. aureus* (Table 1). These MIC values were consistent with previous report on silver nanoparticles synthesized from *Opuntia ficus indica* (Ogwuche and Moses 2021) and banana peel (Ibrahim 2015). The enhanced inhibitory activity of the greenly synthesized SBNs may be attributed to their large surface area, facilitating interactions with bacterial cells, and small size, enabling penetration of the bacterial cell wall to inhibit cell growth. The antimicrobial activity of SBNs supports their potential application in controlling pathogenic bacteria in the environment.

Table 1: Minimum inhibitory concentrations of *C. abbreviata* aqueous extracts and SBNs. ND, not determined; SBNs, silver bionanoparticles; CA-FL, *C. abbreviata* fresh leaf; CA-SB, *C. abbreviata* stem bark; CA-RB, *C. abbreviata* root bark

Bacterial strains	Minimum inhibitory concentrations (mg/mL)							
	Aqueous extracts			SBNs			Silver nitrate	Gentamicin
	CA-FL	CA-SB	CA-RB	CA-FL	CA-SB	CA-RB		
E. coli	14.5	11.5	9.5	1.69	<0.034	<0.03	0.086	0.0015
P. aeruginosa	ND	ND	ND	ND	ND	ND	ND	ND
E. faecalis	7.25	1.09	2.37	<0.026	<0.034	<0.03	0.094	0.0013
S. aureus	14.5	0.36	1.19	1.69	<0.034	<0.03	0.066	0.0021

Bacteria-killing ability of SBNs in relation to exposure time

Figure 5 shows the time needed to eliminate faecal coliform bacteria in river water. The presence of SBNs in contaminated surface water resulted in a 3 log unit decrease in the number of cfu/100 mL against the model organisms. The biocidal endpoint for faecal coliform bacteria using CA-FL SBNs was achieved after 1 hour of incubation at room temperature, regardless of the SBNs concentrations used (Fig. 4). Conversely, CA-SB and CA-RB associated SBNs reached the endpoint after 4 hours of incubation, regardless of the SBN concentrations used. There were no significant differences in the reduction of faecal coliform bacteria ($P>0.05$) among the various sources of SBNs tested, indicating that SBNs tested from *C. abbreviata* plant parts can effectively reduce microbes such as faecal coliform bacteria in environmental water before consumption. This finding aligns with the results reported by Chamakura et al. (2011) even though the silver nanoparticles used in their study were sourced from a plant species different from *C. abbreviata*.

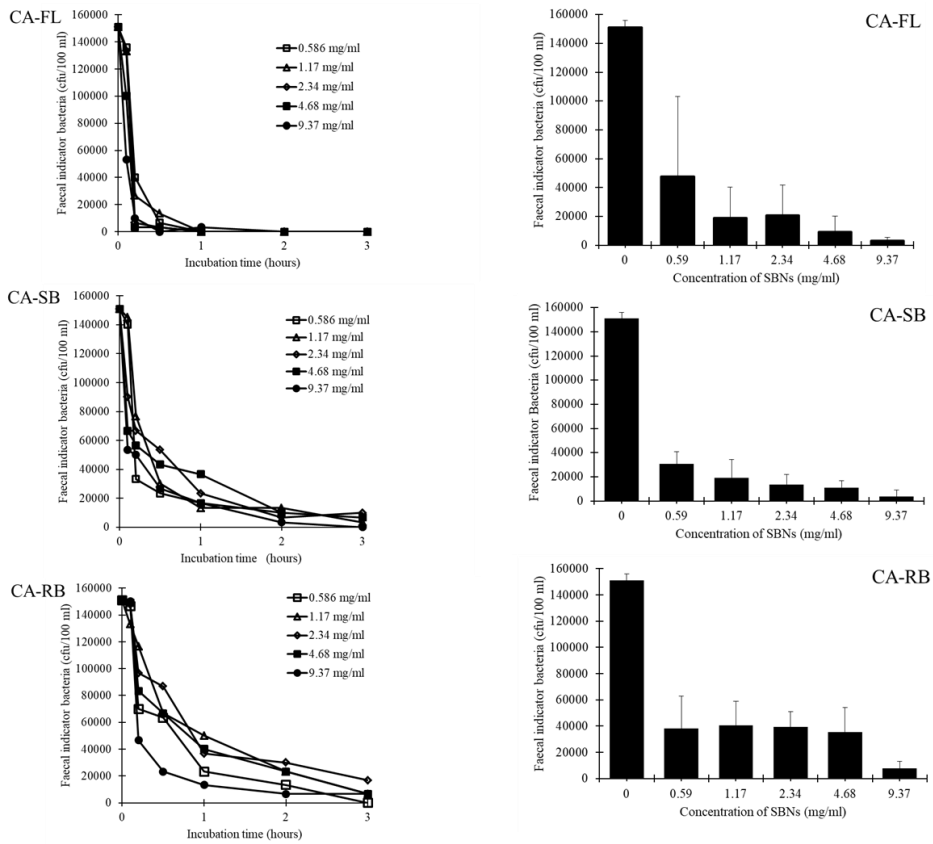

Figure 5: Time-kill plots (left panel) and disinfection efficacy (right panel) following the treatment of faecal coliform bacteria with different concentrations of SBNs. CA-FL, SBNs derived from fresh leaves; CA-SB, SBNs derived from stem barks; CA-RB, SBNs derived from root barks; n=3.

SBNs substantially reduced concentration of faecal coliform bacteria in the river water

The bactericidal activity of SBNs was tested against faecal coliform bacteria, which are used as an indicator of water quality (Cabral et al., 2006, Mushi et al. 2010, Mushi 2020, Mushi et al. 2021) and treatment efficiency (Elmund et al., 1999). It is widely recognised that water contaminated with human and animal faecal matter contains high levels of faecal coliform bacteria (Mushi et al. 2010, Mushi et al. 2021), which are key organisms associated with water quality deterioration. Water samples treated with SBNs exihibited a significant reduction in faecal coliform bacteria concentrations (P<0.05) compared to the control (river water without SBNs). No detectable faecal coliform bacteria were found at concentrations >9.37 mg/L of SBNs derived from the aqueous extract of CA-LF, CA-SB, or CA-RB, indicating that SBNs from any of the *C. abbreviata* organs could be used as a disinfectant. Furthermore, SBNs achieved a 3-log reduction in faecal coliform bacteria in the river water, suggesting their potential as an effective disinfectant. Although this is the first report regarding the application of SBNs—synthesized from *C. abbreviata* extract—in water disinfection, SBNs synthesized from plants other than *C. abbreviata* have previously been demonstrated for drinking water treatment

with inactivation efficacy consistent with that reported herein, although different experimental designs were employed (Dankovich and Gray 2011, Kallman et al. 2011, Mecha and Pillay 2014, Haider et al. 2016,). Therefore, SBNs hold promise as a viable water disinfectant for controlling harmful faecal bacteria, such as faecal coliform in environmental waters. However, the recoverability of SBNs from the treated river water was not assessed in this study, but it is likely that these nanoparticles can be retrieved through centrifugation or sedimentation and become available for re-use.

On the other hand, the newly synthesized SBNs need to be integrated into a matrix that can release the right amount of the bactericide in the finished water, while also enabling for the SBNs to be reused. Unlike chlorine disinfectant, the potential human health risks and ecological impacts of newly synthesized SBNs in this study are currently unknown. Therefore, additional research on the synthesized SBNs is essential to guarantee the overall safety of human and environmental health.

Conclusion

Newly synthesized SBNs from *C. abbreviata* extracts showed strong bactericidal activity against both Gram negative (*E. coli*, *P. aeruginosa*) and Gram positive (*S. aureus* and *E. faecalis*) bacteria. Additionally, SBNs quickly reduced high levels of faecal coliform bacteria in river water to undetectable levels in less than 4 hours, effectively purifying the water. These findings suggest that the plant parts of *C. abbreviata* especially leaf, stem bark, and root bark are excellent precursors for synthesizing nanoparticles with potent antimicrobial and disinfectant properties. However, as SBNs are novel nanoparticles, a cost-effectiveness analysis is needed to compare them with traditional disinfectants like chlorine. This assessment will help determine the suitability of SBNs for treating environmental waters and controlling harmful environmental microorganisms.

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Conflict of interest:

The authors have no conflicts of interest to declare

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