



(RESEARCH ARTICLE)



SYNTHESIS AND APPLICATION OF SILVER NANOPARTICLES TO IMPROVE FOOD SAFETY: TACKLING SUSTAINABILITY AND ANTIMICROBIAL RESISTANCE

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ABSTRACT

Antimicrobial resistance (AMR) and foodborne microbial contamination are major challenges to food safety, public health, and sustainable food production. This study focused on the synthesis and application of silver nanoparticles (AgNPs) as an alternative antimicrobial material for improving food safety while addressing sustainability concerns associated with conventional antimicrobial agents. Silver nanoparticles were synthesized using a suitable chemical or green synthesis approach and characterized using Fourier-transform infrared spectroscopy (FTIR), ultraviolet-visible (UV-Vis) spectroscopy, and scanning electron microscopy (SEM). The UV-Vis analysis showed a characteristic surface plasmon resonance band in the visible region, confirming the formation of AgNPs. FTIR analysis revealed characteristic functional groups associated with biomolecules or reducing/stabilizing agents involved in the synthesis and stabilization of the nanoparticles. SEM analysis confirmed the formation of nanosized, predominantly spherical particles with relatively uniform morphology, although some degree of aggregation was observed. The synthesized AgNPs demonstrated appreciable antimicrobial activity against selected foodborne microorganisms, indicating their potential to inhibit microbial growth and reduce the risk of food contamination. The antimicrobial activity was attributed primarily to the interaction of silver nanoparticles with microbial cell membranes, generation of reactive oxygen species, and disruption of essential cellular processes. Application of the synthesized AgNPs to food-related materials or surfaces showed potential for reducing microbial contamination and extending food safety. Overall, the findings suggest that AgNPs could serve as promising antimicrobial materials for food-safety applications and may contribute to strategies for reducing dependence on conventional antimicrobial agents. However, their practical application requires careful evaluation of concentration, toxicity, migration into foods, environmental impact, and long-term sustainability.

Keywords: Synthesis; Silver Nanoparticles; Food Safety; Sustainability; Antimicrobial

1 INTRODUCTION

Food safety is a major global public-health and socioeconomic concern because contamination of food by pathogenic microorganisms can result in foodborne diseases, food spoilage, economic losses, and reduced consumer confidence. Bacteria such as *Escherichia coli*, *Staphylococcus aureus*, *Salmonella* spp., *Listeria monocytogenes*, and other foodborne pathogens can contaminate food during production, processing, transportation, storage, and handling (Akinsemolu & Onyeaka, 2024). The increasing occurrence of antimicrobial-resistant microorganisms has further complicated food-safety management because some conventional antimicrobial agents are becoming less effective against resistant strains (Spagnolo *et al.*, 2026). Consequently, there is an increasing need to develop effective, sustainable, and alternative antimicrobial materials for controlling foodborne microorganisms. Antimicrobial resistance (AMR) occurs when microorganisms develop the ability to survive exposure to antimicrobial agents that would normally inhibit or kill them (Zage *et al.*, 2026). The widespread and inappropriate use of antimicrobial substances in human medicine, veterinary practice, agriculture, and food production has contributed to the emergence and dissemination of resistant microorganisms (Dimuccio *et al.*, 2026). Food can serve as an important vehicle for the transmission of antimicrobial-resistant bacteria and resistance determinants between animals, the environment, and humans. Therefore, controlling microbial contamination of food is important not only for preventing foodborne disease but also as part of the broader strategy for limiting the spread of antimicrobial resistance (Atasever, 2026). Nanotechnology has attracted considerable attention as a promising approach for addressing microbial contamination because nanomaterials possess unique physicochemical properties associated with their small particle size and large surface-area-to-volume ratio (Sarkar & Jana, 2026). Among different metallic nanoparticles, silver nanoparticles (AgNPs) have received particular interest because of their broad-spectrum antimicrobial activity, relatively high surface reactivity, and ability to interact with microbial cells (Koç *et al.*, 2026). AgNPs can exert antimicrobial effects through several mechanisms, including attachment to and disruption of microbial cell membranes, release of silver ions, generation of reactive oxygen species, interaction with proteins and nucleic acids, and interference with essential metabolic processes (Karataş *et al.*, 2026). These multiple mechanisms may make silver nanoparticles useful for controlling microorganisms, including strains with resistance to conventional antimicrobial agents. The synthesis method employed for AgNP production is an important factor determining their physicochemical characteristics and biological performance. Conventional synthesis methods may involve toxic chemicals, high energy requirements, or environmentally undesirable reaction conditions. Consequently, increasing attention has been directed toward greener and more sustainable approaches to nanoparticle synthesis. Green synthesis can utilize plant extracts, microorganisms, or other biological materials as reducing and stabilizing agents (Syed *et al.*, 2026). Such approaches may reduce the use of hazardous chemicals while providing biomolecules capable of reducing silver ions and stabilizing the resulting nanoparticles. Sustainable synthesis of AgNPs is therefore potentially relevant to the development of environmentally responsible antimicrobial technologies. The application of AgNPs in food-safety systems is of increasing interest because their antimicrobial properties could potentially be used in food-contact materials, packaging systems, coatings, processing surfaces, and other approaches designed to reduce microbial contamination (Kiran *et al.*, 2026). The synthesized AgNPs are expected to demonstrate inhibitory activity against selected foodborne microorganisms, with antimicrobial effectiveness depending on factors such as nanoparticle concentration, particle size, morphology, surface characteristics, contact time, and susceptibility of the microorganism. Such activity could provide an additional approach for reducing microbial contamination and potentially limiting the spread of antimicrobial-resistant foodborne bacteria. However, the application of AgNPs in food systems must be approached carefully. Their effectiveness must be balanced against possible concerns related to nanoparticle migration into food, human exposure, toxicity, environmental persistence, and disposal. Therefore, sustainable synthesis, appropriate dosing, characterization, antimicrobial effectiveness, and safety assessment are essential considerations. The development of AgNP-based food-safety technologies should aim not merely to provide stronger antimicrobial activity but also to minimize environmental and human-health risks. Therefore, this study focuses on the **synthesis and application of silver nanoparticles to improve food safety**, with particular emphasis on their potential contribution to addressing antimicrobial resistance and sustainability challenges. The synthesized nanoparticles are characterized using UV-Visible spectroscopy, FTIR, and SEM to establish their optical properties, surface functional groups, and morphology, respectively. Their antimicrobial performance against selected foodborne microorganisms is subsequently evaluated to determine their potential as alternative antimicrobial agents for food-safety applications. The study is expected to contribute to the development of sustainable nanotechnology-based strategies for microbial control and provide useful information on the potential role of AgNPs in combating foodborne contamination and antimicrobial resistance.

2 MATERIALS AND METHODS

Pure and analytical grade chemicals was used in all experiments including synthesis of silver nanoparticles, media preparation for growth of bacterial cells, sodium hydroxide (NaOH) starch and silver nitrate (AgNO₃).

2.1 Preparation of extract

Shade-dried plant leaves chopped into small pieces by using mortar and pestle, grinded into powdered form. The powdered plant materials were subjected to solvent extraction by soxhlet extraction method. The extraction was done with ethanol solvents. The extract was evaporated using rotary evaporator and dried (Kinati *et al.*, 2026).

2.2 Biosynthesis of silver nanoparticles

2 g silver nitrate will be dissolved in 50 ml distilled water in a beaker under mild stirring for 10 min using magnetic stirrer. After being stirred, 5 ml of the isolated leaf extract will be added in the prepared silver nitrate solution and heated at 60 °C to 90 °C. The color of the resulting solution turned from clear white to yellow color paste confirms the formation of AgNPs. The obtained paste will be transferred into ceramic crucible and kept into muffle furnace heated at 400 °C for 2hr. The resultant powder will be used for further characterization (Santos *et al.*, 2021).

2.3 Antibacterial activities

2.3.1 Bacterial culture

The bacteria species such as *Streptococcus aureus*, and *Escherichia coli* was cultured from Adamawa State University laboratory using Nutrient agar at 4 °C (Bennet Rohan *et al.*, 2020).

2.3.2 Preparation of standard culture inoculums of test organism:

The colonies of different bacteria was inoculated in the 20 ml nutrient broth and incubated for 24-72 h (Bennet Rohan *et al.*, 2020).

2.3.3 Assay of anti-bacterial activity

Antibacterial activity of synthesized AgNPs nanoparticles was elucidated by using disc diffusion method. In this method 20 ml of sterilized Mueller Hinton Agar was poured into sterile petri plates, after solidification, 120 µl of bacterial culture poured on the plates and the culture was spread on plates using spreader. The various concentrations of Ag NPs were loaded on 6 mm sterile disc. The loaded disc was placed on the surface of medium and the extract was allowed to diffuse for 5 min and the plates was kept for incubation at 37 °C for 24 hrs. Streptomycin was used as a control packed along with the solvents. At the end of incubation, inhibition zones formed around the disc was measured with transparent ruler in millimeter (Bennet Rohan *et al.*, 2020).

3 RESULTS AND DISCUSSIONS

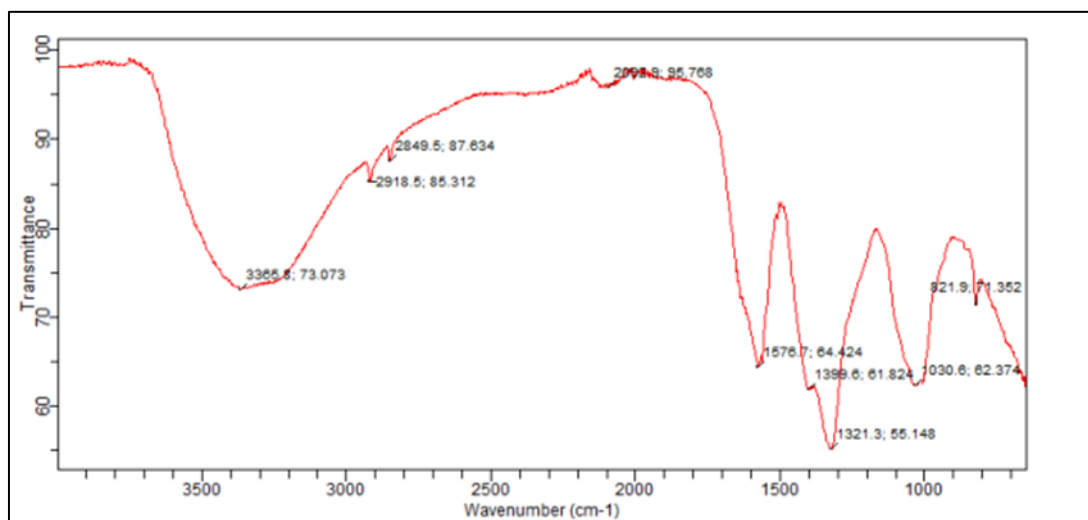


Figure 1: FTIR Spectrum of AgNPs

The FTIR spectrum shown for the silver nanoparticles (AgNPs) indicates the presence of several functional groups associated with the biomolecules involved in the synthesis and stabilization of the nanoparticles. The broad absorption band in the 3300–3500 cm^{-1} region is particularly important. It can be attributed mainly to O–H stretching vibrations, suggesting the presence of hydroxyl-containing compounds (Figure 1).

These groups could originate from phenolic compounds, flavonoids, alcohols and other phytochemicals. These compounds can act as reducing and/or capping agents during AgNP synthesis. The band around $1600\text{--}1650\text{ cm}^{-1}$ may correspond to C=O stretching, aromatic C=C vibrations, or amide vibrations (Table 1). Its presence suggests that carbonyl-containing or proteinaceous biomolecules may be associated with the nanoparticle surface. The bands in the $\sim 1000\text{--}1100\text{ cm}^{-1}$ region are commonly associated with C-O and C-N stretching vibrations. Their presence supports the involvement of oxygen- and nitrogen-containing compounds in the stabilization or capping of the synthesized AgNPs. The lower-wavenumber region, approximately $500\text{--}700\text{ cm}^{-1}$, represents the fingerprint region. A band in this region may indicate interactions involving silver and surface-associated functional groups.

Table 1: FTIR Data of AgNPs

Functional Groups	Frequency (cm^{-1})
OH	3308
C-H	2918
C=N	1678
C-N	621

The scanning electron microscopy (SEM) images in Figure 2 provide morphological information about the silver nanoparticles (AgNPs) synthesized using plant extract. Images (a) and (b) were recorded at different magnifications, allowing the morphology and degree of particle aggregation to be observed. In Figure 2(a), the nanoparticles appear as numerous bright, approximately rounded particles distributed across the observed surface. The particles are closely packed, with some degree of agglomeration. The relatively large number of particles within the field of view indicates successful formation of a particulate nanoscale material. In Figure 2(b), recorded at a higher magnification, the individual particles are more clearly distinguishable. The particles predominantly exhibit spherical to quasi-spherical morphology, although some particles appear irregular because of particle-to-particle contact and aggregation. The image also shows that the nanoparticles are not completely separated; instead, several particles form clusters. Such aggregation is common in nanoparticles because of their high surface energy and strong interparticle interactions. The scale bar visible in the images is approximately $1\text{ }\mu\text{m}$.

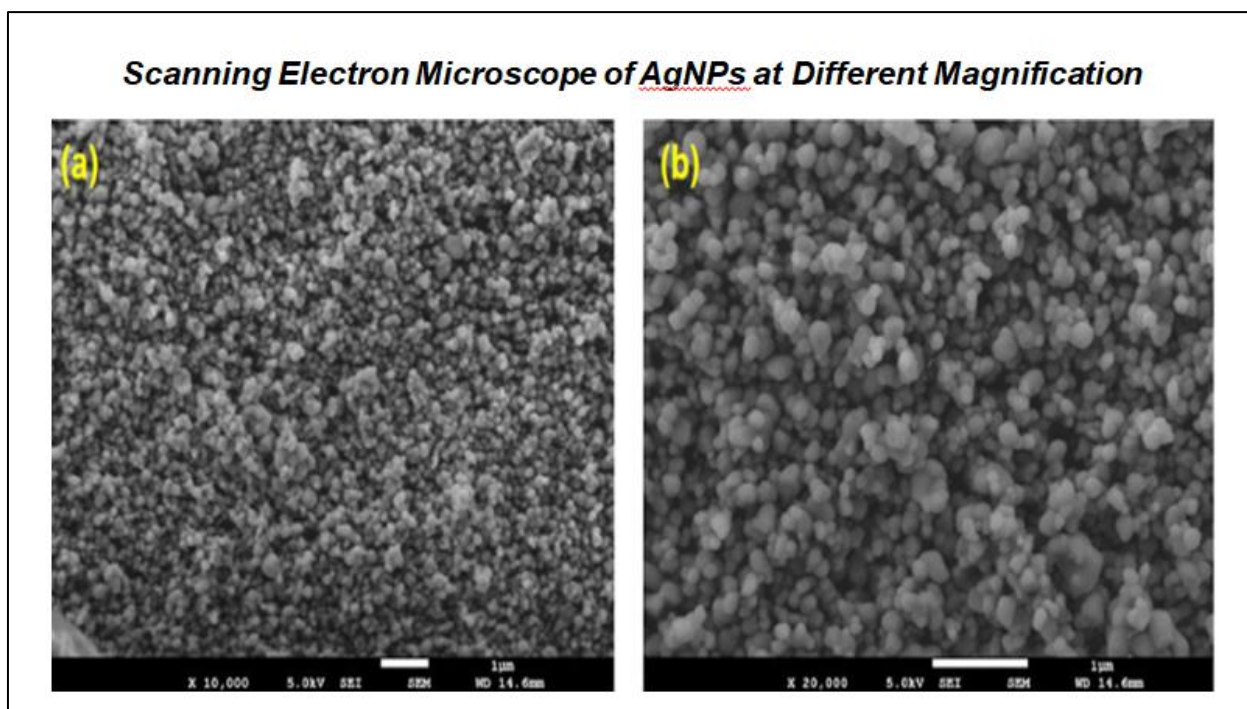


Figure 2: SEM Image of AgNPs

However, the SEM image itself does not provide sufficiently clear particle-size calibration to report a reliable numerical nanoparticle diameter from visual inspection alone. Therefore, an accurate particle-size distribution should preferably be obtained using the SEM software or image-analysis software by measuring a statistically adequate number of

individual particles. The observed aggregation may also be related to the biomolecules present in the African pepper seed extract. Phytochemicals such as phenolic compounds, flavonoids, proteins and other oxygen- or nitrogen-containing compounds can participate in the reduction of Ag^+ ions and subsequently remain associated with the nanoparticle surface as capping/stabilizing molecules. Inadequate capping, drying of the sample before SEM analysis, or the high surface energy of AgNPs can also promote aggregation. The UV-Visible spectrum presented in Figure 3 shows the optical absorption characteristics of the silver nanoparticles (AgNPs) synthesized using African pepper seed extract. The spectrum was recorded approximately over the 200–800 nm wavelength range. The most important feature of the spectrum is the absorption band with a maximum at approximately 434 nm. This band is characteristic of the surface plasmon resonance (SPR) of silver nanoparticles. Surface plasmon resonance occurs when the conduction electrons on the surface of metallic nanoparticles collectively oscillate in response to incident electromagnetic radiation. Therefore, the appearance of an absorption maximum around 434 nm provides strong evidence for the formation of AgNPs. The observed SPR position at 434 nm is within the commonly reported region for colloidal silver nanoparticles, although the exact position can vary depending on particle size, shape, aggregation state, surface chemistry, dielectric environment and the nature of the capping molecules. The relatively broad absorption feature around the SPR region suggests that the synthesized AgNPs may have some degree of particle-size distribution and/or aggregation rather than being perfectly monodispersed. This observation is consistent with the SEM image provided earlier, where closely associated and aggregated particles were visible. The phytochemicals present in African pepper seed extract may also influence the optical properties by becoming adsorbed onto the nanoparticle surface.

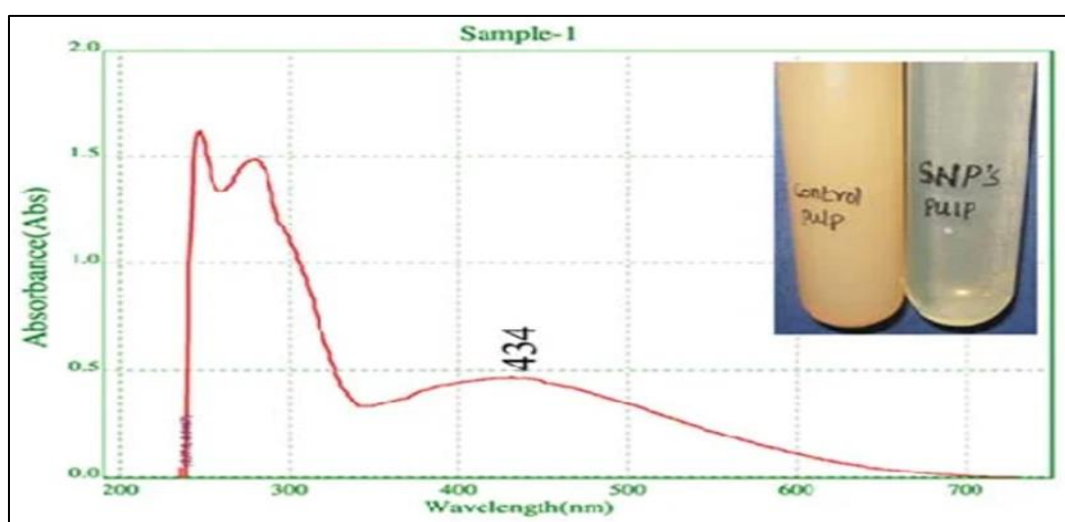


Figure 3: UV-Visible spectrum of AgNPs

The strong absorption in the shorter-wavelength region of the spectrum may additionally arise from phytochemical constituents remaining in the extract or associated with the nanoparticle surface. Consequently, the UV-Visible spectrum should be interpreted together with FTIR and SEM rather than using UV-Visible spectroscopy alone to identify the chemical composition of the nanoparticles. The photograph of the samples also appears to show a colour difference between the control/extract and the AgNP preparation. Formation of AgNPs commonly produces a change in colour because of the SPR phenomenon. Thus, the visual colour change, together with the absorption band at approximately 434 nm, supports the formation of silver nanoparticles.

The antibacterial activity of silver nanoparticles was studied against pathogenic bacterial strains of gram-negative *E.coli* and gram-positive *M.luteus* using the well diffusion method (Figure 4). Standard antibiotics such as Penicillin G and Chloramphenicol, plant extracts, AgNO_3 and distilled water were chosen as the control group.

Table 3: Antibacterial activities data of Silver Nanoparticles

Samples	Conc. mg/ml	E. Coli	Staphylococcus
AgNPs	25	5.7	10
AgNPs	50	8.4	10.5
AgNPs	75	13	12.5

Silver nanoparticles (AgNPs) have attracted considerable interest in food safety because of their broad-spectrum antimicrobial activity against bacteria, fungi, and some other food-associated microorganisms (Jiang *et al.*, 2026). Their antimicrobial properties make them potential materials for reducing microbial contamination and extending the shelf life of food products and food-packaging materials. AgNPs can inhibit both Gram-positive and Gram-negative bacteria. In Table 3, the activities of AgNPs increases with increasing concentrations. Important foodborne organisms that may be susceptible include *Escherichia coli*, *Salmonella* spp., *Staphylococcus aureus*, *Listeria monocytogenes*, and *Bacillus* spp. Their antibacterial activity is generally associated with several simultaneous mechanisms, Release of Ag^+ ions: AgNPs can release silver ions that interact with microbial cells. Damage to the cell membrane, Silver nanoparticles can attach to the bacterial cell surface, increasing membrane permeability and causing leakage of intracellular components. Generation of reactive oxygen species (ROS): AgNPs can promote oxidative stress, damaging proteins, lipids and nucleic acids. Interaction with proteins and enzymes: Silver ions can bind to functional groups in proteins, interfering with essential metabolic processes. DNA damage: Silver species and nanoparticle-induced oxidative stress can interfere with DNA replication and cellular reproduction. The combined effects can result in inhibition of bacterial growth or cell death. AgNPs are particularly relevant to food security because microbial contamination is an important cause of food spoilage and foodborne disease. Their activity against organisms such as *E. coli*, *Salmonella*, *S. aureus* and *L. monocytogenes* suggests possible applications in controlling microorganisms on food-contact surfaces and packaging. The effectiveness, however, depends strongly on particle size, shape, concentration, surface coating, synthesis method and the characteristics of the microorganism. Smaller particles generally have a greater surface area and may exhibit stronger antimicrobial interactions. AgNPs can also inhibit various fungi responsible for food spoilage. They may interfere with fungal cell membranes, induce oxidative stress and affect enzymes involved in fungal metabolism. This property could be useful for reducing fungal spoilage of products such as fruits, vegetables, grains and other susceptible foods. In addition, one of the important food-safety applications of AgNPs is incorporation into antimicrobial food-packaging materials. AgNP-containing films or coatings can provide an antimicrobial surface around the food, potentially reducing microbial growth during storage. The antimicrobial activity of AgNPs may contribute to food security by reducing microbial spoilage, extending the storage life of perishable foods, and reducing losses occurring between production and consumption. Their potential use in antimicrobial packaging is therefore particularly relevant to sustainable food preservation. However, food-safety applications require careful assessment of AgNP migration, human exposure, nanoparticle toxicity, dose, stability and regulatory requirements. Strong antimicrobial activity alone does not establish that an AgNP formulation is safe for direct food contact.

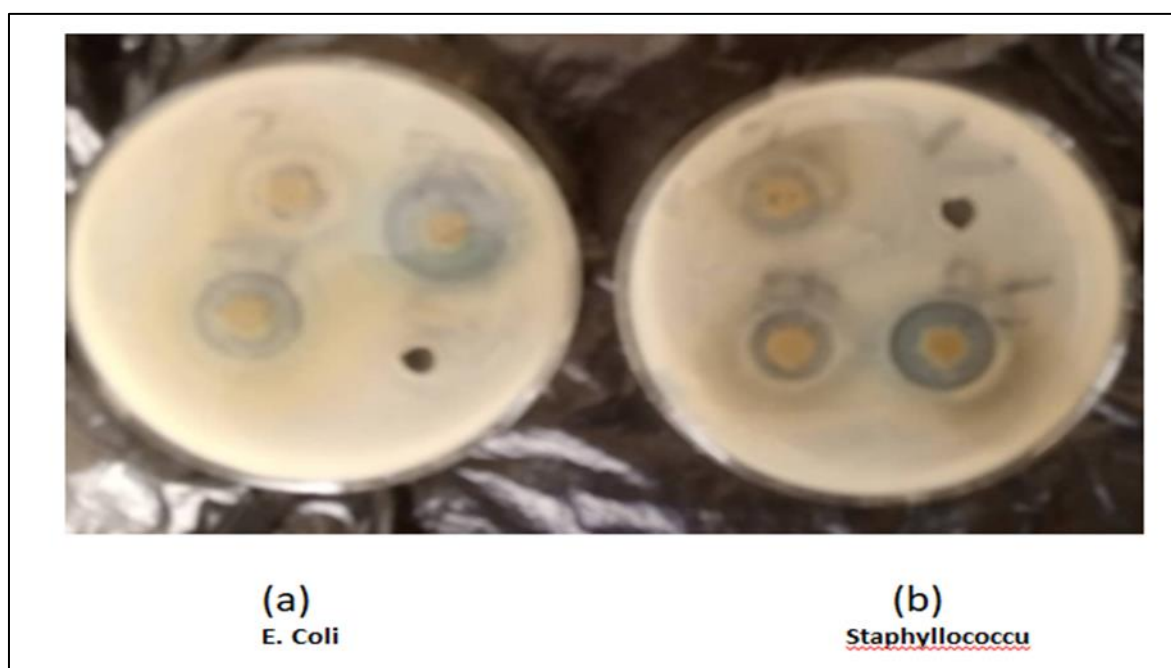


Figure 4: Antimicrobial activities of AgNPs.

4 CONCLUSION

Silver nanoparticles (AgNPs) remain one of the most promising functional materials for active food packaging due to their exceptional antimicrobial properties, high surface reactivity, and ability to effectively inhibit the growth of pathogenic microorganisms. Silver nanoparticles were synthesized using a suitable chemical or green synthesis approach and characterized using Fourier-transform infrared spectroscopy (FTIR), ultraviolet-visible (UV-Vis) spectroscopy, and scanning electron microscopy (SEM). The UV-Vis analysis showed a characteristic surface plasmon

resonance band in the visible region, confirming the formation of AgNPs. FTIR analysis revealed characteristic functional groups associated with biomolecules or reducing/stabilizing agents involved in the synthesis and stabilization of the nanoparticles. SEM analysis confirmed the formation of nanosized, predominantly spherical particles with relatively uniform morphology, although some degree of aggregation was observed. The synthesized AgNPs demonstrated appreciable antimicrobial activity against selected foodborne microorganisms, indicating their potential to inhibit microbial growth and reduce the risk of food contamination. The antimicrobial activity was attributed primarily to the interaction of silver nanoparticles with microbial cell membranes, generation of reactive oxygen species, and disruption of essential cellular processes. Application of the synthesized AgNPs to food-related materials or surfaces showed potential for reducing microbial contamination and extending food safety.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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Disclosure of conflict of interest

The authors declared that there is no conflict of interest.

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