

UTILIZING BANANA PEEL WASTE EXTRACT FOR GREEN SYNTHESIS OF SILVER NANOPARTICLES AND THEIR ANTIBACTERIAL APPLICATION

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Abstract

Silver nanoparticles (AgNPs) were successfully produced through a green synthesis method involving the utilization of waste banana peel waste (BPW) extract. BPW has attracted considerable attention for its attributes as a straightforward, environmentally friendly, and non-toxic material. To facilitate this process, BPW powder was created by boiling, blending, and air-drying, serving as both a reducing and capping agent. The biosynthesized AgNPs underwent characterization via UV-visible spectroscopy, Fourier transform infrared (FTIR) spectroscopy, X-ray diffraction (XRD), and Field Emission scanning electron microscopy (FE-SEM). Furthermore, antibacterial activity tests were conducted on cotton fabrics to optimize the process and assess its effectiveness. The results revealed a distinct absorption peak at 420 nm corresponding to AgNPs, a finding corroborated by FE-SEM and energy dispersive spectrometry (EDS). The application of AgNPs from BPW on fabrics exhibited outstanding antibacterial activity by inhibiting the growth of *Staphylococcus aureus* and *Escherichia coli*. Overall, the present findings support the use of BPW extraction as a cost-effective, environmentally friendly, and efficient approach for the green synthesis of AgNPs with promising antibacterial properties on fabrics.

Keywords: Antibacterial activity; banana peel; green synthesis; silver nanoparticles

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Introduction

Nanoscience, nanoengineering, and nanotechnology represent highly promising scientific areas with the potential to revolutionize applications on an incredible scale (Cuevas *et al.*, 2017; Ferreira and Filipe, 2018). The unique properties of nanoparticles, like their small size, large surface area to surface volume ratio and optical, magnetic, chemical, and biomechanical properties, position them as candidates for novel applications in the textile field (Yetisen *et al.*, 2016; Hemlata *et al.*, 2020). These applications include water and oil repellence (Bae *et al.*, 2009; Synytska *et al.*, 2011), UV blocking (Yang *et al.*, 2004), antistatic properties (Zhang and Yang, 2009; Textor and Mahltig, 2010), and antibacterial effects (Yeo *et al.*, 2003), all well-documented.

Traditional Thai textiles represent more than just fabric. They bring together cultural heritage, craftsmanship and symbols that have been passed down for centuries. This makes them highly valuable not only in Thailand but also around the world. Although traditional Thai textiles have many desirable qualities, there are areas where improvements can increase usability, sustainability and market attractiveness, especially integrating the use of antibacterial substances with traditional Thai textiles. Combining traditional craftsmanship with modern innovations in antibacterial technology, allows Thai textiles to continue to develop to meet the changing needs of consumers while preserving their cultural heritage and original identity. Silver nanoparticles (AgNPs), as noble metals, have received much attention in textile applications due to their multifunctional theranostic abilities (Behboodi *et al.*, 2019; Hemlata *et al.*, 2020). Moreover, it has been revealed that silver nanoparticles are non-toxic to the human body and highly effective against bacteria, viruses and other microorganisms at low concentrations without any adverse side effects (Kokila *et al.*, 2015; Fahimirad *et al.*, 2019). Green synthesis has been considered one of the promising approaches for the synthesis of silver nanoparticles because of its simple, one-step process, cost-effectiveness, biocompatibility, low toxicity, and environmentally friendly (Saratale *et al.*, 2018; Khatami and Iravani, 2021; Samuel *et al.*, 2022). Green nanoparticle synthesis methods use microorganisms, enzymes, fungi, plants, or plant extracts; therefore, it has been proposed as possible eco-friendly alternatives to chemical and physical methods. The synthesis of nanoparticles using plants can offer benefits to other green syntheses by eliminating the complicated processes of maintaining microbial culture (Dikshit *et al.*,

2021; Ahmed *et al.*, 2022). Many plants contain various bioactive compounds such as polyphenols, flavonoids, terpenoids, alkaloids, and proteins, which can be used as both reducing and capping agents during nanoparticle synthesis. It is an important component in the synthesis of silver nanoparticles. They play an important role in controlling the size, shape, stability, and functionality of nanoparticles.

Bananas are among the most popular fruits, rich in nutrients (Goh *et al.*, 2023). However, after consuming the pulp, banana peels are typically discarded as general waste, causing potential environmental problems. In Thailand, like the Bang Krathum district in Phitsanulok province, significant quantities of banana peel waste result from processing banana products, such as dried bananas, banana preserves, and banana chips. Banana peels contain numerous biopolymers, including cellulose, hemicellulose, lignin, and pectin. These biopolymers have the capability to act as ligands, coordinate with metal ions, and form metal nanoparticles (Das *et al.*, 2017; Hameed *et al.*, 2019). Using banana peel waste as a reducing and capping agent may offer an economic and environmental way forward and provide an innovative way to repurpose fruit waste and achieve a zero-waste production system.

In this work, green synthesis of AgNPs using banana peel waste extract was conducted, and the synthesized nanoparticles were characterized through UV-vis spectroscopy, Field Emission Scanning Electron Microscopes (FE-SEM) equipped with EDX, the X-ray diffraction (XRD), and Fourier transform infrared spectroscopy (FTIR) analysis. Additionally, the study explored the textile application of the synthesized nanoparticles, specifically investigating their antibacterial activity.

Materials and Methods

Banana Peel Waste (BPW) Extract

Banana (*Musa paradisiaca*) peel waste was collected from the Banana Bang Krathum state enterprise community. BPW was thoroughly washed with distilled water to eliminate surface dirt and adhering impurities and then cut them into small pieces. Subsequently, the small pieces of BPW were dried under sunlight conditions for three days. After the drying process, the BPW underwent milling and grinding to obtain powder form. A 100 g of BPW powder was mixed in 200 ml of distilled water and

subjected to boiling at 90°C for 30 min. The mixture was then filtered twice through Whatman No.1 filter paper. The resultant filtrate from BPW was stored at 4°C and employed as a reducing agent.

Synthesis of Silver Nanoparticles (AgNPs) using BPW

In all experimental procedures, the silver source utilized was silver nitrate (AgNO_3) purchased from RCI Labscan™. 1 ml of BPW extract was added to the 100 ml of a 1 mM silver nitrate solution (Goh *et al.*, 2023). The reaction mixture was incubated in the absence of light to avoid the photoactivation of AgNO_3 under static conditions. To optimize the synthesis condition for producing the silver nanoparticles, the BPW concentrations were systematically varied, including 1, 2, 3, and 4 ml. Moreover, the impact of pH was also investigated by adjusting the pH of the reaction mixtures to 4, 6, 8, and 12, respectively. All experiments were measured in triplicates. Centrifuge at 6,000 rpm was applied to separate the silver nanoparticles from the solution. The gained AgNPs were subsequently subjected to freeze-drying, also known as lyophilization. This technique associates the elimination of water, which exists in the form of ice, from a material through sublimation under low-pressure (Nowak and Jakubczyk, 2020).

Characterization of AgNPs

The UV-visible spectra of silver nanoparticles were obtained based on wavelength variations using a UV-Vis spectrophotometer (Perkin Elmer LAMBDA™, Waltham, Massachusetts, USA). To understand the functional groups within the phytoconstituents responsible for the reduction and capping of AgNPs were examined using a Fourier Transform Infrared (FTIR) spectrophotometer (Nicolet™ iS™5 FT-IR spectrometer, Thermo Scientific, USA.) using the AgNPs powder. The scanning range of the FTIR spectrophotometer was covered from 4,000 to 400 cm^{-1} with a spectral resolution of 1 cm^{-1} . To investigate the crystal structure and phase of AgNPs powder, the X-ray diffraction (XRD) characterization was performed on an X-ray diffractometer (XRD, Philip PW 3040/60 X'Pert Pro, Eindhoven, Netherlands) using $\text{Cu K}\alpha$ radiation over a 2θ range from 10° to 80° with a step size of 0.04° at a scanning speed of 3°/min. Field Emission Scanning Electron Microscopes (FE-SEM) equipped with EDX were employed to determine the surface morphology, shape, size and atomic content of the silver nanoparticles. The AgNPs powder was mounted on a metal stub using a copper tape-style adhesive which increases conductivity. The microscope operated at 10 kV in high-vacuum (HV) mode with

an ETD detector beam current set to 0.05 nA. The FESEM morphological examination at 50,000 magnification was analyzed.

Antibacterial Activity of Synthesized Silver Nanoparticles

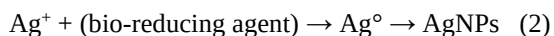
The antibacterial activity of AgNPs and BPW was evaluated against both Gram-negative and Gram-positive bacteria to provide a more comprehensive understanding of an antimicrobial agent's effectiveness. Practically, a Gram-negative bacterium (*Escherichia coli*: *E. coli*) and a Gram-positive bacterium (*Staphylococcus aureus*: *S. aureus*) were selected because of their significance as a common human pathogen. They involved with skin and soft tissue infections, as well as more severe conditions such as pneumonia, endocarditis, and sepsis (Mohamed *et al.*, 2021). The qualitative evaluation of the antibacterial properties of the fabrics was subjected to the ATCC147 test standard, using the disc diffusion method (El-Aziz *et al.*, 2020; El-Bendary *et al.*, 2021). For bacterial strains and culture conditions, *E. coli* and *S. aureus* were maintained on a nutrient agar medium (NAM) at 35°C for 24 h. Then, *E. coli* and *S. aureus* were prepared by taking a single colony from the stock bacterial culture with a loop and inoculating 20 ml of sterile nutrient broth (NB) in a 100 ml Erlenmeyer flask. The flask was then incubated in a shaking incubator at 120 rpm at 35°C for 24 h. The liquid cultures were diluted to obtain bacterial cell concentrations of approximately 1.5×10^8 colony-forming units (CFU/mL) for an antibacterial test. The bacterial cell concentration matched McFarland standard No. 0.5 (Mohamed *et al.*, 2021). Thai cotton fabrics uncoated and coated with AgNPs at different pH of 5 mm diameter were placed on a nutrient agar layer in a Petri-dish. The Petri-dish was kept in an incubator at 35°C for 24 h to determine inhibition zones. The growth of the tested microorganisms was limited to a circular area or clear zone around the fabrics which contained tested material.

Results and Discussion

UV-visible Spectroscopy Analysis

The green synthesis of silver nanoparticles is an eco-friendly approach (Saratale *et al.*, 2018; Khatami and Iravani, 2021; Samuel *et al.*, 2022). It has been substantiated as efficient and environmentally friendly. This method can reduce generated waste and contribute to sustainable processes. At the time of the addition of the aqueous extract derived from banana peel waste to a silver nitrate solution, the color of the solution changed from yellow to reddish-brown during 45 min.

The phenomenon responsible for the color of nanoparticles is called surface plasmon resonance (SPR). When exposed to incident light, the collective oscillations of free electrons in the metal interact with the light field, generating surface plasmon resonances (Wen *et al.*, 2020). These resonances lead to the absorption or emission of certain wavelengths of light, resulting in distinct colors observable to human vision. The frequency of surface plasmon resonance highly relies on the structure and size of the AgNPs. Therefore, the reduction of silver ions to nano size is the main cause of the color change of the solution. The exposure of BPW extract to AgNO₃ solution indicated AgNP formation by color change over time. A possible reaction mechanism might be as follows.



The color transition process of the solution was attributed to the reduction process of silver ion (Ag⁺) to Ag⁰ nanoparticles, as Figure 1.

To confirm the formation of silver nanoparticles and to explore their plasmonic resonance, UV-Vis spectroscopy was used to analyze the absorbance data. The validation of silver nanoparticle generation was assessed through the UV-Vis spectra ranging from wavelength 300–800 nm. Silver nanoparticles showed a distinctive absorption peak at 420 nm because of the excitation of surface plasmon resonance (SPR), as shown in Figure 2(a) (Pérez-Marroquín *et al.*, 2022). Our

UV-Vis spectra data of silver nanoparticles is similar to the previous report (Ibrahim, 2015; Kokila *et al.*, 2015).

The effect of BPW concentration is illustrated in Figure 2(b). The reaction mixtures containing 1, 2, 3, and 4 ml of BPW displayed a dark brown color. The SPR peaks showed a proportion increase in intensity, with the maximum peak intensity observed at a BPW content of 3 ml due to the formation of more AgNPs. Nevertheless, when the concentration is increased further, there is a decrease in the intensity of the SPR band, which can be explained by the interactions between the nanoparticles in the solution. At higher concentrations of BPW, there might be an increased chance of aggregation among the silver nanoparticles (AgNPs) formed. Aggregation leads to a broadening and weakening of the SPR peak. When nanoparticles aggregate, the collective

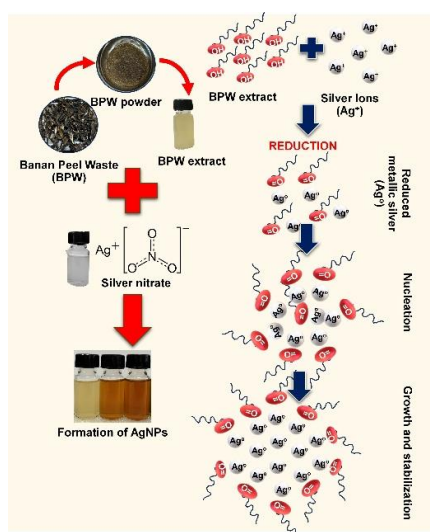


Figure 1. Proposed mechanism of green synthesis of silver nanoparticles from banana peel waste

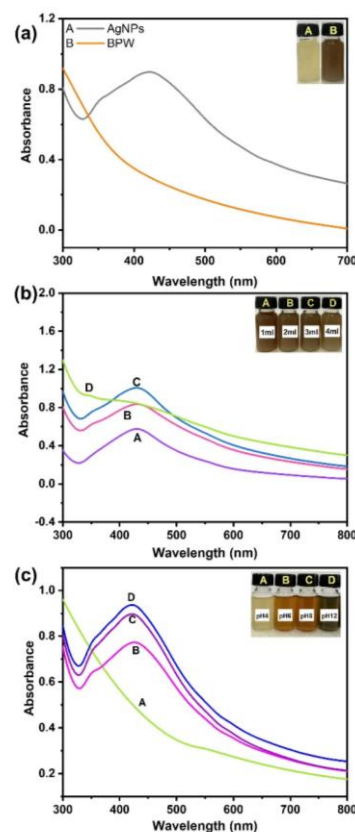


Figure 2. Visual observations and UV-visible absorption spectra of synthesized silver nanoparticles; (a) BPW extract and the reaction mixtures containing 100 ml of a 1 mM silver nitrate solution, (b) synthesized silver nanoparticles at various concentrations of BPW and (c) synthesized silver nanoparticles at various pH

oscillations of electrons are affected, causing a decrease in intensity.

As Figure 2(c), the color and the intensity of the peaks were pH dependent. At pH 4, there was neither a change in color nor a characteristic peak (Figure 2(c)), tube and curve A). Varying shades of reddish-brown color was observed at pH values 6-8 (Figure 2(c), tube and curve B, C). The maximum color intensity was obtained at pH 12 (Figure 2(c), tube and curve D). Consistent with this previous observation by (Kokila *et al.*, 2015) presented that no reaction occurred in acidic pH, while at alkaline pH, the rate of formation of AgNPs is high. The color changes observed in the pH range during the synthesis of silver nanoparticles can be attributed to differences in the dissociation constants (pKa) of the functional groups present in the relevant phytochemicals. The pKa values of functional groups define their ionization states in response to changes in pH (Brezoiu *et al.*, 2020).

X-ray Diffraction (XRD) Analysis

The crystalline nature of AgNPs was further proved by X-ray diffraction (XRD) analysis. The XRD patterns of synthesized AgNPs are presented in Figure 3. Silver nanoparticles synthesized from BPW extract revealed Bragg Reflection peaks at 38.15, 44.48, 64.84, and 77.55 within the 2θ range of 10-80 degrees. These peaks correspond to the lattice planes (111), (200), (220), and (311), respectively. These XRD pattern have a good agreement with the standard diffraction pattern of the Joint Committee on Powder Diffraction Standards (JCPDS) file No. 03-0921, indicating the pure crystalline nature of the synthesized silver nanoparticles. Particularly, the intensity of the peak corresponding to the (111) plane is higher than other planes, suggesting a predominant orientation along the (111) plane (Kokila *et al.*, 2015). The XRD patterns shown in our study are consistent with previous findings (Kokila *et al.*, 2015; Mickymaray, 2019; Ali *et al.*, 2023). Using the Scherrer equation, the average crystalline size of AgNPs was determined from the diffractogram to be 25 nm.

FTIR Analysis

To identify the main functional groups of banana peel waste potentially involved in the synthesis of AgNPs, FTIR measurements were carried on. Figure 4 illustrates the FTIR spectra of BPE before and after the reaction with silver nitrate. The vibrational bands at 3,343-3,287 cm^{-1} are associated with inter and intra O-H stretching (Dubey *et al.*, 2017; Khan *et al.*, 2023). A small peak appears at 2,918 and 2,850 cm^{-1} (CH stretching vibration, specifically related to methyl groups

(CH_2 and CH_3), and at 1,637 cm^{-1} , indicating H-O-H bending of absorbed water. Moreover, the peak located at 1,031 cm^{-1} corresponds to C-O-C pyranose ring stretching. During the synthesis of AgNPs, the slight shifts of peaks indicate the electrostatic interactions between the hydroxyl and ether groups of BPW and the Ag^+ . The absence of any band at around 1,387 cm^{-1} corresponding to nitrate in the BPW/AgNPs, confirms the removal of NO_3^- groups from the material (Khan *et al.*, 2023). Banana peels mainly consist of pectin, cellulose and hemicelluloses, and the functional groups associated with these biopolymers as well as the proteinaceous matter, may play a role in reducing the silver salt to Ag^0 .

The Morphology Study

The morphology of the silver nanoparticles (AgNPs) synthesized through the green approach utilizing BPW was investigated employing a Field Emission Scanning Electron Microscope (FE-SEM). Figure 5 illustrates representative FE-SEM micrographs and the EDS spectra of the reaction mixtures between 3 ml of BPW solution and 1.0 mM of silver nitrate, incubated at varying pH levels for

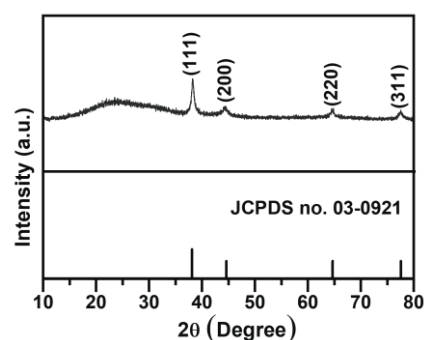


Figure 3. XRD spectra for the silver nanoparticles synthesized from 1mM aqueous AgNO_3 solution with 3 ml BPW

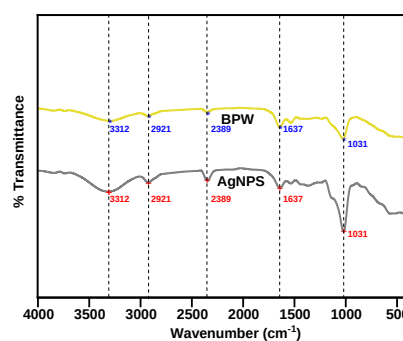


Figure 4. FTIR spectra of banana peel waste (BPW) (Dark grey line) and silver nanoparticles (AgNPS) in BPW (Yellow line)

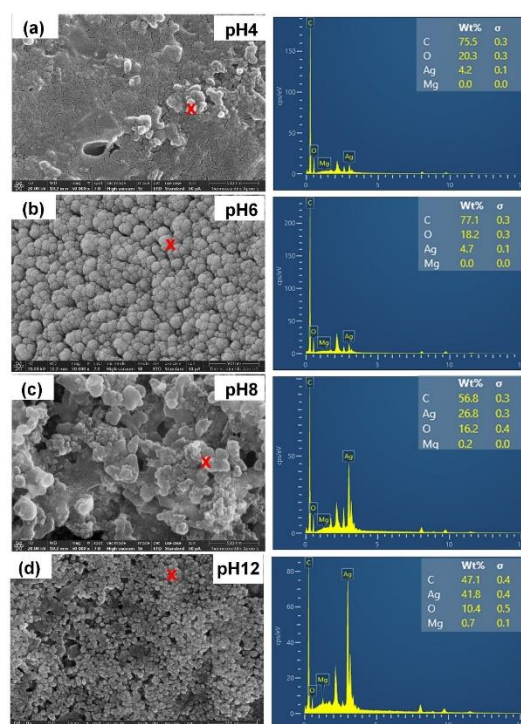


Figure 5. FE-SEM images of surface morphology and EDS spectrum of the synthesized silver nanoparticles at various pH values: (a) pH4, (b) pH6, (c) pH8, and (d) pH12, respectively, with magnification 50,000

Table 1. Atomic percentage of silver nanoparticles prepared at different pH

pH Values	Element	Weight percentage
4	Ag	4.2%
	C	75.5%
	O	20.3%
6	Ag	4.7%
	C	77.1%
	O	18.2%
8	Ag	26.8%
	C	56.8%
	O	16.2%
12	Ag	41.8%
	C	47.1%
	O	10.4%

45 min. The pH of the reaction mixture significantly influences the size, shape, and morphology of the silver nanoparticles, and the growth of nanoparticles varies according to the pH of the solution. Various shapes of agglomerated particles were noted at pH 6 and 8. Upon increasing the pH to 12, almost spherical particles were formed and the diameter of AgNPs is in the range of 26-44 nm. The pH variations play a role in preventing agglomeration between particles and influencing the shaping of the morphology of AgNPs. The EDS attachment present with the FE-SEM is known to provide

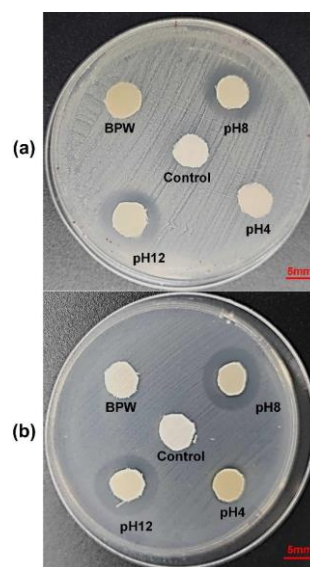


Figure 6. Clear zone inhibition of silver nanoparticles against, (a) Gram-Positive (*S. aureus*) and (b) Gram-Negative Bacteria (*E. coli*) of AgNps from BPW at different pH

Table 2. Clear zone of inhibition of Gram-Positive (*S. aureus*) and Gram-Negative Bacteria (*E. coli*) of AgNps from BPW at different pH

Sample test	Clear zone of inhibition of <i>S. aureus</i> (mm)	Clear zone of inhibition of <i>E. coli</i> (mm)
Control	0	0
BPW	0	0
pH4	0	13.6±0.10
pH8	19.00±0.04	22.90±0.06
pH12	20.80±0.02	23.50±0.04

information on the elemental analysis. Elemental analysis by EDS results showed displayed the presence of carbon (C), oxygen (O) and magnesium (Mg). Moreover, the EDS microscopy of AgNPs at different pH levels has revealed carbon (C), oxygen (O), and silver (Ag) on the nanoparticle surface. The percentage atomic ratios of these elements are summarized in Table 1.

Antibacterial Activity

The antibacterial activity of the aqueous BPW extract and the green-synthesized AgNPs at different pH levels were investigated by employing the disc diffusion method against *S. aureus* (Gram-positive) and *E. Coli* (Gram-negative) bacteria. The clear zones of inhibition of AgNPs at different pH values are displayed in Figure 6, and the inhibition diameter is summarized in Table 2. Figure 6 shows a distinct zone of inhibition around cotton fabric coated with AgNPs, whereas the control fabric

(uncoated with AgNPs) and BPW show no signs of inhibition. As indicated in Table 2, AgNPs at pH12 showed high antibacterial activity with a larger zone of inhibition against *S. aureus* and *E.coli* when compared to AgNPs at pH 4. The maximum clear zone of inhibition of AgNPs at pH 12 was 20.80 and 23.50 mm against *S.aureus* (Figure 6(a)) and *E.coli*, respectively (Figure 6(b)). The cotton fabric coated with AgNPs exhibited higher antibacterial activity against *E.coli* as compared to *S. aureus*. which may be because of the variation in cell wall composition. The cell membrane of Gram-positive bacteria is composed of multiple layers of peptidoglycan layer, thus forming a more rigid structure leading to difficult penetration of the silver nanoparticles, while in Gram-negative bacteria, the cell membrane has a thinner peptidoglycan layer resulting in an easier penetration of the nanoparticles (Cavassin *et al.*, 2015).

As illustrated in Figure 7, the mechanisms underlying the antimicrobial actions of silver nanoparticles, the antimicrobial activity of silver nanoparticles is primarily attributed to their capability to release silver ions (Ag^+) which can attach to the negatively charged cell surface leading to a change in the composition of the cell membrane and the cell wall and disturb their vital functions such as loss of cell membrane integrity and ultimately cell death (Babele *et al.*, 2018; Fang *et al.*, 2018). The antimicrobial action of AgNPs involves a multi-step mechanism, as shown in Figure 7; (1) silver nanoparticles come into contact with the negative charge of the bacterial cell wall, (2) cell wall destabilization causes increasing in bacterial permeability and release of silver ions, (3) the released silver ions contribute to the production of reactive oxygen species (ROS) and free radicals, which can induce extreme oxidative stress inside the cell wall. The oxidative stress effects, such as cell apoptosis, protein destruction, and DNA damage, lead to bacterial cell death. (4) The silver nanoparticles can modulate signal transduction pathways within the bacterial cell. The modulation further contributes to the antimicrobial effect (Rosli *et al.*, 2021).

Conclusions

To achieve a zero-waste production system and create waste to wealth, discarded banana peels were used as a reductant and stabilizer in the synthesis of silver nanoparticles. This study silver nanoparticles successfully synthesized silver nanoparticles using banana peel waste extract. The average size of the silver nanoparticles was approximately 32.57 ± 8.84 nm, and their size could be adjusted through simple

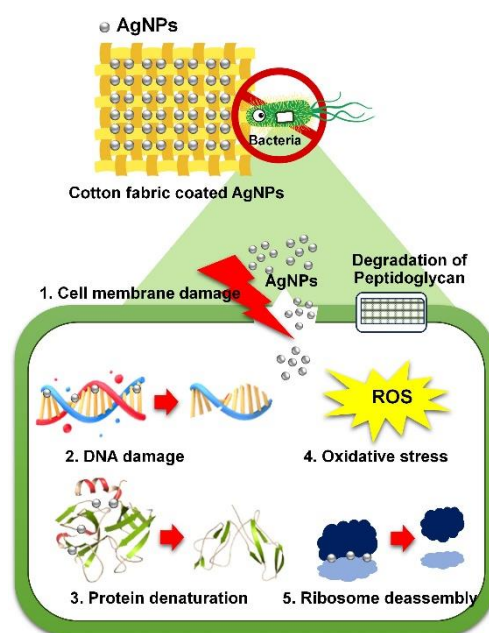


Figure 7. The mechanisms underlying the antimicrobial actions of silver nanoparticles

modifications of the extract concentration and the pH of the reactions. The silver particles presented a more spherical morphology. The synthesized silver nanoparticles revealed good antimicrobial activity against the selected pathogenic microorganisms. Our findings approve the utilization of banana peel waste extraction as a cost-effective, environmentally friendly, and efficient approach for the green synthesis of AgNPs with promising antibacterial properties on fabrics.

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References

- Ahmed, S.F., Mofijur, M., Rafa, N., Chowdhury, A.T., Chowdhury, S., Nahrin, M., Islam, A.B.M., and Ong, S.H.C. (2022). Green approaches in synthesising nanomaterials for environmental nanobioremediation: Technological advancements, applications, benefits and challenges. *Environmental Research*, 204(Part A):111967. <https://doi.org/10.1016/j.envres.2021.111967>
- Ali, M.H., Azad, M.A.K., Khan, K.A., Rahman, M.O., Chakma, U., and Kumer, A. (2023). Analysis of crystallographic structures and properties of silver nanoparticles synthesized using PKL extract and nanoscale

- characterization techniques. *ACS Omega*, 8(31):28133-28142. <https://doi.org/10.1021/acsomega.3c01261>
- Babele, P.K., Thakre, P.K., Kumawat, R., and Tomar, R.S. (2018). Zinc oxide nanoparticles induce toxicity by affecting cell wall integrity pathway, mitochondrial function and lipid homeostasis in *Saccharomyces cerevisiae*. *Chemosphere*, 213:65-75. <https://doi.org/10.1016/j.chemosphere.2018.09.028>
- Bae, G.Y., Min, B.G., Jeong, Y.G., Lee, S.C., Jang, J.H., and Koo, G.H. (2009). Superhydrophobicity of cotton fabrics treated with silica nanoparticles and water-repellent agent. *Journal of colloid and interface science*, 337(1):170-175. <https://doi.org/10.1016/j.jcis.2009.04.066>
- Behboodi, S., Baghbani-Arani, F., Abdalan, S., and Shandiz, S.A.S. (2019). Green engineered biomolecule-capped silver nanoparticles fabricated from *Cichorium intybus* extract: in vitro assessment on apoptosis properties toward human breast cancer (MCF-7) cells. *Biological trace element research*, 187:392-402. <https://doi.org/10.1007/s12011-018-1392-0>
- Brezoiu, A.-M., Bajenaru, L., Berger, D., Mitran, R.-A., Deaconu, M., Lincu, D., Guzun, A.S., Matei, C., Moisesescu, M.G., and Negreanu-Pirjol, T. (2020). Effect of nanoconfinement of polyphenolic extract from grape pomace into functionalized mesoporous silica on its biocompatibility and radical scavenging activity. *Antioxidants*, 9(8):696. <https://doi.org/10.3390/antiox9080696>
- Cavassin, E.D., de Figueiredo, L.F.P., Otoch, J.P., Seckler, M.M., de Oliveira, R.A., Franco, F.F., Marangoni, V.S., Zucolotto, V., Levin, A.S.S., and Costa, S.F. (2015). Comparison of methods to detect the in vitro activity of silver nanoparticles (AgNP) against multidrug resistant bacteria. *Journal of Nanobiotechnology*, 13(1):1-16. <https://doi.org/10.1186/s12951-015-0120-6>
- Cuevas, J.C. and Scheer, E. (2017). *Molecular Electronics: An Introduction To Theory and Experiment*. World Scientific Series in Nanoscience and Nanotechnology, Volume 15, 848p. <https://doi.org/10.1142/10598>
- Das, R.K., Pachapur, V.L., Lonappan, L., Naghdi, M., Pulicharla, R., Maiti, S., Cledon, M., Dalila, L.M.A., Sarma, S.J., and Brar, S.K. (2017). Biological synthesis of metallic nanoparticles: plants, animals and microbial aspects. *Nanotechnology for Environmental Engineering*, 2:1-21. <https://doi.org/10.1007/s41204-017-0029-4>
- Dikshit, P.K., Kumar, J., Das, A.K., Sadhu, S., Sharma, S., Singh, S., Gupta, P.K., and Kim, B.S. (2021). Green synthesis of metallic nanoparticles: Applications and limitations. *Catalysts*, 11(8):902. <https://doi.org/10.3390/catal11080902>
- Dubey, S., Sharma, R.K., Agarwal, P., Singh, J., Sinha, N., and Singh, R.P. (2017). From rotten grapes to industrial exploitation: *Komagataeibacter europaeus* SGP37, a micro-factory for macroscale production of bacterial nanocellulose. *International Journal of Biological Macromolecules*, 96:52-60. <https://doi.org/10.1016/j.ijbiomac.2016.12.016>
- El-Aziz, M.A.A., Ibrahim, H.M., El-Roos, N.A., Anis, B., and Elsabagh, R. (2020). Antibacterial efficacy of zinc oxide and titanium dioxide nanoparticles against *Escherichia coli* in minced meat. *World's Veterinary Journal*, 10(3):267-275. <https://doi.org/10.36380/scil.2020.wvj35>
- El-Bendary, M.A., Afifi, S.S., Moharam, M.E., El-Ola, S.M.A., Salama, A., Omara, E.A., Shaheen, M.N.F., Hamed, A.A., and Gawdat, N.A. (2021). Biosynthesis of silver nanoparticles using isolated *Bacillus subtilis*: characterization, antimicrobial activity, cytotoxicity, and their performance as antimicrobial agent for textile materials. *Preparative Biochemistry and Biotechnology*, 51(1):54-68. <https://doi.org/10.1080/10826068.2020.1789992>
- Fahimirad, S., Ajallouei, F., and Ghorbanpour, M. (2019). Synthesis and therapeutic potential of silver nanomaterials derived from plant extracts. *Ecotoxicology and Environmental Safety*, 168:260-278. <https://doi.org/10.1016/j.ecoenv.2018.10.017>
- Fang, R.H., Kroll, A.V., Gao, W., and Zhang, L. (2018). Cell membrane coating nanotechnology. *Advanced Materials*, 30(23):1706759. <https://doi.org/10.1002/adma.201706759>
- Ferreira, M.A.M. and Filipe, J.A. (2018). Nanotechnology Applications-The Future Arrived Suddenly. In: *Computational Approaches in Biomedical Nano-Engineering*. Sohail, A. and Li, Z. (eds), p. 23-41. <https://doi.org/10.1002/9783527344758.ch2>
- Goh, H.T., Cheok, C.Y., and Yeap, S.P. (2023). Green synthesis of silver nanoparticles using banana peel extract and application on banana preservation. *Food Frontiers*, 4(1):283-288. <https://doi.org/10.1002/fft2.206>
- Hameed, R.S., Fayyad, R.J., Nuaman, R.S., Hamdan, N.T., and Maliki, S. (2019). Synthesis and characterization of a novel titanium nanoparticles using banana peel extract and investigate its antibacterial and insecticidal activity. *Journal of Pure and Applied Microbiology*, 13(4):2241-2249. <https://doi.org/10.22207/JPAM.13.4.38>
- Hemlata, Meena, P.R., Singh, A.P., and Tejavath, K.K. (2020). Biosynthesis of silver nanoparticles using *Cucumis prophetarum* aqueous leaf extract and their antibacterial and antiproliferative activity against cancer cell lines. *ACS Omega*, 5(10):5520-5528. <https://doi.org/10.1021/acsomega.0c00155>
- Ibrahim, H.M.M. (2015). Green synthesis and characterization of silver nanoparticles using banana peel extract and their antimicrobial activity against representative microorganisms. *Journal of Radiation Research and Applied Sciences*, 8(3):265-275. <https://doi.org/10.1016/j.jrras.2015.01.007>
- Khan, H., Raghuvanshi, S., Saroha, V., Singh, S., Baba, W.N., Mudgil, P., and Dutt, D. (2023). Biotransformation of banana peel waste into bacterial nanocellulose and its modification for active antimicrobial packaging using polyvinyl alcohol with in-situ generated silver nanoparticles. *Food Packaging and Shelf Life*, 38:101115. <https://doi.org/10.1016/j.fpsl.2023.101115>
- Khatami, M. and Iravani, S. (2021). Green and eco-friendly synthesis of nanophotocatalysts: an overview. *Comments on Inorganic Chemistry*, 41(3):133-187. <https://doi.org/10.1080/02603594.2021.1895127>
- Kokila, T., Ramesh, P., and Geetha, D. (2015). Biosynthesis of silver nanoparticles from Cavendish banana peel extract and its antibacterial and free radical scavenging assay: a novel biological approach. *Applied Nanoscience*, 5:911-920. <https://doi.org/10.1007/s13204-015-0401-2>
- Mickymaray, S. (2019). One-step synthesis of silver nanoparticles using Saudi Arabian desert seasonal plant *Sisymbrium irio* and antibacterial activity against multidrug-resistant bacterial strains. *Biomolecules*, 9(11):662. <https://doi.org/10.3390/biom9110662>
- Mohamed, H., Zaki, A., El-Ela, F.I.A., and El-dek, S. (2021). Effect of hydrothermal time and acid-washing on the antibacterial activity of Sodium titanate nanotubes. *IOP conference series: materials science and engineering*, <https://doi.org/10.1088/1757-899X/1046/1/012025>
- Nowak, D. and Jakubczyk, E. (2020). The freeze-drying of foods-The characteristic of the process course and the effect of its parameters on the physical properties of food materials. *Foods*, 9(10):1488. <https://doi.org/10.3390/foods9101488>
- Pérez-Marroquín, X.A., Aguirre-Cruz, G., Campos-Lozada, G., Callejas-Quijada, G., León-López, A., Campos-Montiel, R.G., García-Hernández, L., Méndez-Albores, A., Vázquez-Durán, A., Aguirre-Álvarez, G. (2022). Green synthesis of silver nanoparticles for preparation of gelatin films with antimicrobial activity. *Polymers*, 14(17):3453. <https://doi.org/10.3390/polym14173453>

- Rosli, N.A., Teow, Y.H., and Mahmoudi, E. (2021). Current approaches for the exploration of antimicrobial activities of nanoparticles. *Science and Technology Of Advanced Materials*, 22(1):885-907. <https://doi.org/10.1080/14686996.2021.1978801>
- Samuel, M.S., Ravikumar, M., John J. A., Selvarajan, E., Patel, H., Chander, P.S., Soundarya, J., Vuppala, S., Balaji, R., and Chandrasekar, N. (2022). A review on green synthesis of nanoparticles and their diverse biomedical and environmental applications. *Catalysts*, 12(5):459. <https://doi.org/10.3390/catal12050459>
- Saratale, R.G., Saratale, G.D., Shin, H.S., Jacob, J.M., Pugazhendhi, A., Bhaisare, M., and Kumar, G. (2018). New insights on the green synthesis of metallic nanoparticles using plant and waste biomaterials: current knowledge, their agricultural and environmental applications. *Environmental Science and Pollution Research*, 25:10164-10183. <https://doi.org/10.1007/s11356-017-9912-6>
- Szynyska, A., Khanum, R., Ionov, L., Cherif, C., and Bellmann, C. (2011). Water-repellent textile via decorating fibers with amphiphilic Janus particles. *ACS applied materials and interfaces*, 3(4):1216-1220. <https://doi.org/10.1021/am200033u>
- Textor, T. and Mahltig, B. (2010). A sol-gel based surface treatment for preparation of water repellent antistatic textiles. *Applied Surface Science*, 256(6):1668-1674. <https://doi.org/10.1016/j.apsusc.2009.09.091>
- Wen, K., Jiang, X., He, J., Li, G., and Yang, J. (2020). Color-adjustable devices based on the surface plasmons effect. *Applied Sciences*, 10(6):1960. <https://doi.org/10.3390/app10061960>
- Yang, H., Zhu, S., and Pan, N. (2004). Studying the mechanisms of titanium dioxide as ultraviolet-blocking additive for films and fabrics by an improved scheme. *Journal of Applied Polymer Science*, 92(5):3201-3210. <https://doi.org/10.1002/app.20327>
- Yeo, S.Y., Lee, H.J., and Jeong, S.H. (2003). Preparation of nanocomposite fibers for permanent antibacterial effect. *Journal of Materials Science*, 38:2143-2147. <https://doi.org/10.1023/A:1023767828656>
- Yetisen, A.K., Qu, H., Manbachi, A., Butt, H., Dokmeci, M.R., Hinestroza, J.P., Skorobogatiy, M., Khademhosseini, A., and Yun, S.H. (2016). Nanotechnology in textiles. *ACS nano*, 10(3):3042-3068. <https://doi.org/10.1021/acsnano.5b08176>
- Zhang, F. and Yang, J. (2009). Preparation of nano-ZnO and its application to the textile on antistatic finishing. *International Journal of Chemistry*, 1(1):18. <https://doi.org/10.5539/ijc.v1n1p18>