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## Green Synthesis of Silver Nanoparticles Using Aqueous Extracts of Fruit Peel: Antioxidant, Antimicrobial and Photocatalytic Activities

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### ABSTRACT

The increasing threat of multidrug-resistant pathogens and the growing environmental burden of agricultural waste have prompted the search for sustainable solutions. Green synthesis utilizing fruit peel extracts offers an environmentally benign approach for producing biologically active nanomaterials with therapeutic and environmental remediation potential. Herein, silver nanoparticles (AgNPs) were fabricated using aqueous extracts derived from pomegranate, lemon, and orange peels. The synthesized nanomaterials were subsequently characterized through UV-Vis, FTIR, and SEM. Characteristic absorption maxima between 425-450 nm confirmed nanoparticle formation, while SEM micrographs revealed predominantly spherical morphologies. FTIR analysis identified characteristic O-H, C-H, C=O, and C-O bands, indicating that polyphenols and flavonoids in the fruit peel extracts served dual functions as both reducing and capping agents during nanoparticle synthesis. The antioxidant property measured through the DPPH free radical scavenging assay showed the highest antioxidant ability for pomegranate AgNPs (62.92%). The biosynthesized AgNPs displayed noteworthy antimicrobial efficacy against both gram positive (*S. aureus* and *B. subtilis*) and gram negative (*E. coli* and *P. aeruginosa*) bacteria. Moreover, the maximum inhibition zone of 19.6 mm (against *S. aureus*) was achieved using pomegranate-derived AgNPs (P-AgNPs). In addition, the AgNPs efficiently degraded crystal violet under sunlight, achieving maximum degradation efficiencies of 89.91%, 93.62%, and 93.55% for P-AgNPs, O-AgNPs, and L-AgNPs, respectively. Sustainable valorization of agricultural waste via the proposed method results in nanoparticles with multifaceted applications while simultaneously contributing to the reduction of solid waste.

**KEYWORDS:** Green synthesis, Silver nanoparticles, Fruit peel, Antimicrobial activity, Antioxidant activity, Photocatalytic degradation

### INTRODUCTION

Nanotechnology is an expansive discipline whose applications continue to grow in various areas of study, including medicine, pharmacy, electronics, agriculture, and environmental remediation. This entails the manipulation of materials and devices at the nanoscale to create new solutions and improve existing technologies. Nanotechnology has the potential to impact a wide range of industries (Kafshgari *et al.*, 2015; Farouk *et al.*, 2023; Formoso *et al.*, 2016; Mekuye and Abera, 2023). In relation to nanomaterials, AgNPs have received much attention owing to their exceptional physicochemical characteristics, including a high surface area-to-volume ratio, localized surface plasmon resonance (LSPR), catalytic behavior, and antimicrobial action. AgNPs have demonstrated efficacy against a wide range of pathogens, making them useful in biomedical applications such as wound treatment and drug delivery (Rybka *et al.*, 2022; Jangra *et al.*, 2025; Pawar *et al.*, 2025). Our group has

previously demonstrated that bimetallic nanoparticles, including FeAg supported on graphene, exhibit potent antibacterial activity, which is attributed to both reactive oxygen species (ROS) generation and the oxidation of cellular antioxidants (Ahmad *et al.*, 2016). Moreover, AgNPs (silver nanoparticles) have gained importance because of their increased stability and photocatalysis properties (Shahzadi *et al.*, 2025). Our previous work on reduced graphene oxide-supported bimetallic nanoparticles demonstrated the efficient photocatalytic degradation of organic pollutants, including methylene blue, through the activation of sodium percarbonate (Ahmad *et al.*, 2024). Several synthesis methods for producing silver nanoparticles (AgNPs) fall into either the physical (evaporation condensation, laser ablation) or chemical categories (chemical reduction and electrochemical deposition). These methods are effective but possess certain drawbacks (Duman *et al.*, 2024; Pacioni *et al.*, 2015; Yaqoob *et al.*, 2020). Physical methods involve

significant energy consumption and sophisticated equipment, whereas chemical methods typically use harmful reducing agents, organic solvents, and stabilizers, which are detrimental to the environment and pose health risks to humans (Duman *et al.*, 2024; Abady *et al.*, 2025; Oliveira & Lenzi, 2023). The use of sodium borohydride, hydrazine, and other chemicals as reducing agents results in the formation of hazardous substances (Khatoon *et al.*, 2023; Duman *et al.*, 2024). To address the problems outlined above, green synthesis has been proposed as a viable and eco-friendly solution (Akhter *et al.*, 2024; Oliveira & Lenzi, 2023; Husain & Nasibullah, 2024). Green nanotechnology involves the use of biological sources, including plant extracts, microbes, and agricultural waste, as natural reducers and capping agent in the process of creating nanoparticles (Girotra *et al.*, 2024; Veer *et al.*, 2025; Shahzadi *et al.*, 2025). The application of biologically active compounds extends beyond nanoparticle synthesis; for instance, antimicrobial peptides have been successfully employed to control microbial contamination in industrial fermentation processes (Qureshi *et al.*, 2017), highlighting the broader potential of biological agents in sustainable technologies. Plant-based synthesis is advantageous for several reasons: it is affordable, scalable, eco-friendly, and eliminates the need for hazardous chemicals. Phytochemicals found in plant extracts, such as flavonoids, phenolic acids, terpenoids, alkaloids, and proteins, are natural reducers of metal ions and capping agents for nanoparticles (Akhter *et al.*, 2024; Farouk *et al.*, 2023; Khan *et al.*, 2026; Zhafira & Sajidah, 2025). Mechanistic studies on bimetallic nanoparticles have revealed that the antibacterial activity is mediated through both reactive oxygen species (ROS) generation and glutathione (GSH) oxidation pathways, with GSH oxidation playing a more dominant role (Ahmad *et al.*, 2016). The use of plant-based resources has been extensively studied because of their availability, cost-effectiveness, and sustainability of such natural sources. However, the fruit peels stand out because they represent one of the most abundant sources of natural antioxidants. Fruit peels represent millions of tons of waste that is generated annually as a result of the activity of the global fruit-processing industry (Dubey *et al.*, 2023; Toppo, 2024; Hussain *et al.*, 2022; Sharma *et al.*, 2022). To quantify this in quantitative perspective, pomegranate peels constitute 40–50% of the total fruit weight, which translates to approximately 9 million tons of waste per 1 million tons of pomegranate juice (Gaharwar *et al.*, 2024). In the European Union, over 74 million tons of fruit are produced every year, resulting in 17 million tons of waste (Manakas *et al.*, 2025). Globally, the citrus fruit processing industry produces approximately 63.75 million metric tons of waste annually (Kiteto *et al.*, 2025). Some of the most widely grown fruits include pomegranates (*Punica granatum*), lemons (*Citrus limon*), and oranges (*Citrus sinensis*). They are rich in polyphenols, flavonoids,

ascorbic acid, and other antioxidants (Siddiqui *et al.*, 2024; Rodriguez *et al.*, 2025; Huang *et al.*, 2025; Nayana and Wani, 2024). The use of such waste materials for the synthesis of nanoparticles can help solve the waste management problem, along with providing new opportunities for the synthesis of nanomaterials (Monika *et al.*, 2024; Farouk *et al.*, 2023; Abdelbasir *et al.*, 2020; Saratale *et al.*, 2018; Sharma *et al.*, 2024).

Pomegranate peels are rich in phytochemicals that are excellent reducing and capping agents. Various studies have successfully synthesized silver nanoparticles using pomegranate peel extract, demonstrating good antimicrobial and antioxidant effects (Mostafa *et al.*, 2026; Rani *et al.*, 2024; Saad *et al.*, 2021). Lemon peels contain citric acid, ascorbic acid, flavonoids (mainly hesperidin and eriocitrin), and several phenolic acids, all of which help make lemon peels a powerful reducing agent. With the help of these biologically active molecules, silver ions can be easily reduced by donating electrons, and hence silver nanoparticles are formed. Furthermore, the antioxidant activity of these components can stabilize the nanoparticles and prevent aggregation, resulting in increased functional activity. Together, these reducing and stabilizing characteristics make lemon peel an important natural source for use in green synthesis technology (Abdelrazik *et al.*, 2023; Fadhil *et al.*, 2024; Jahan & Işildak, 2021; Nasr *et al.*, 2019). Orange peels contain numerous bioactive compounds, such as flavonoids, including hesperidin and naringin, phenolic acids, carotenoids, and vitamin C. The presence of these compounds in orange peels provides significant reducing and stabilizing capabilities that facilitate the neutralization of free radicals and the prevention of oxidative stress. Thus, orange peel can be considered a useful natural antioxidant and stabilizer in various industries. The high content of bioactive compounds in orange peels makes them suitable for application in food preservation, pharmacology, and cosmetology (Ahmed *et al.*, 2023; Shrinath *et al.*, 2023). Moreover, owing to the content of bioactive substances, orange peels have been used for the eco-friendly synthesis of nanoparticles (Mickky *et al.*, 2024; Gupta *et al.*, 2025). The selection of these three peels was done purposefully considering the fact that their phytochemical composition is different but overlaps in some properties; tannin/ellagitannin-rich (pomegranate peel) vs. flavanone glycosides and organic acids-rich (citrus). The distinct phytochemical profiles of these three peels allow for a comparative evaluation of their reducing, capping, and bioactivity potentials. Although separate studies have reported on the production of silver nanoparticles (AgNPs) from pomegranate and citrus fruit peels, no studies have compared the three types of peels under identical conditions during both synthesis and assay testing. Moreover, there is no clear consensus in the literature on which peel results in the most active nanoparticles. This deficiency of a like-for-like comparison is bridged through this research. The

key innovations of the current study include the following: (i) this is the first systematic comparison of pomegranate, lemon, and orange peels for AgNP synthesis under strictly identical experimental conditions, enabling direct assessment of how peel phytochemistry influences nanoparticle properties; (ii) we provide a comprehensive comparative evaluation of antioxidant, antibacterial, and photocatalytic activities, revealing previously unreported performance trade-offs between biological and catalytic functions; and (iii) we demonstrate the effective use of natural sunlight for photocatalytic dye degradation using these biosynthesized AgNPs, offering a sustainable approach for wastewater treatment.

## MATERIALS AND METHODS

**Chemicals and Reagents:** Silver Nitrate ( $\text{AgNO}_3$ ), DPPH, and Ascorbic acid were procured from Sigma-Aldrich. Peptone, yeast extract, MHA, and nutrient broth were supplied by Oxoid Ltd.

**Collection and Preparation of Fruit Peels:** Fresh pomegranate (*Punica granatum*), lemon (*Citrus limon*), and orange (*Citrus sinensis*) peels were obtained from domestic kitchen waste and local fruit-juice vendors in Jamshoro, Sindh, Pakistan. The fruits were cleaned using tap water and distilled water to eliminate any surface contaminants. Drying was performed under ambient conditions and finally under oven conditions at 55 °C for 24 h. Subsequently, the dry peels were ground into a fine powder using a mill and sieved using a #40 mesh (0.42 mm openings). The sieve particles were stored in an airtight container at 4 °C (Laiba et al., 2026).

**Preparation of Peel Extracts:** Exactly 20 g of dried peel of each fruit was mixed with 60 mL of deionized water in a conical flask. This was further followed by incubation of the mixture in the shaking incubator at 60 °C and 150 rpm for 2 hours. After incubation, the mixture was cooled to room temperature. The cooled mixture of the plant extract was further centrifuged at

6000 rpm for 10 minutes and filtered using Whatman no. 1 filter paper (Farouk et al., 2023).

**Synthesis of Silver Nanoparticles:** AgNPs were synthesized by combining 50 mL of each fruit peel extract with 50 mL of 1 mM silver nitrate solution in 250 mL conical flasks. The reaction mixtures were incubated in a shaking water bath at 90 °C for 4 hours, followed by overnight standing at room temperature. After the reaction, the colloidal suspensions were centrifuged at 10,000 rpm for 20 min. The resulting nanoparticle pellets were washed three times with double-distilled water and once with absolute ethanol, then dried in an oven at 60 °C for 6 hours (Farouk et al., 2023; Niluxsshun et al., 2021). For all bioassays, the dried AgNPs were re-dispersed in sterile distilled water with brief sonication (5 min) to achieve the required concentrations.

**Characterization of Nanoparticles:** Formation and characterization of nanoparticles were confirmed using UV-Visible absorption spectroscopy. FTIR spectroscopic analysis was carried out in the wavelength region of 400-4000  $\text{cm}^{-1}$ . Analysis was performed to identify the functional groups involved in the reduction, capping, and stabilization processes. SEM was performed for size and morphological confirmation of the synthesized nanoparticles. Particle size and size distribution were estimated from the SEM micrographs using ImageJ software ( $n \geq 100$  particles per sample) (Abro et al., 2026; Khuhro et al., 2025).

**Antioxidant Activity:** The free radical scavenging capacity of the AgNPs was evaluated using the DPPH assay method described by Khuhro et al. (2025). Different concentrations of nanoparticle suspensions (20-100  $\mu\text{g/mL}$ ) were combined with 2 mL of 0.1 mM DPPH methanolic solution. The reaction mixtures were incubated in darkness for 30 minutes, after which absorbance readings were recorded at 517 nm. The DPPH radical scavenging activity (inhibition percentage) was calculated using the following equation:

$$\% \text{ Inhibition} = \frac{[Ab \text{ control} - Ab \text{ sample}]}{Ab \text{ control}} \times 100$$

where Ab control is the absorbance of the DPPH reagent, and Ab sample is the absorbance of the sample at time

**Antimicrobial Activity:** The antimicrobial efficacy of the nanoparticles was assessed using the agar well diffusion method. *Staphylococcus aureus*, *Bacillus subtilis*, *Escherichia coli*, and *Pseudomonas aeruginosa* were obtained from the culture collection of the Institute of Biotechnology and Genetic Engineering at the University of Sindh, Jamshoro, Pakistan. These strains have been used in previous studies (Rahu et al., 2021). Overnight cultures were adjusted to a 0.5 McFarland standard ( $\approx 1.5 \times 10^8$  CFU/mL) in sterile saline prior to inoculation. Briefly, fresh bacterial cultures were evenly spread onto Mueller-Hinton agar plates. Wells measuring 6–8 mm in diameter were created, and 50  $\mu\text{L}$  of the test sample (adjusted to 50  $\mu\text{g/mL}$ ) was introduced into each well.

A standard antibiotic disc (ciprofloxacin, 5  $\mu\text{g}$ ) served as the positive control, while wells loaded separately with sterile distilled water, the corresponding aqueous peel extract, and 1 mM  $\text{AgNO}_3$  served as negative/comparator controls. The plates were then incubated at 37 °C for 24 h.

**Minimal Inhibition Concentration:** The MIC was measured using the broth microdilution technique in Mueller–Hinton broth by preparing two-fold serial dilutions of each AgNP suspension (5 -200  $\mu\text{g/mL}$ ), where the same amount of bacteria (approximately  $5 \times 10^5$  CFU/mL) was added to all wells for testing. The MIC was defined as the lowest concentration that caused no growth in the presence of test organisms at 37°C after 24 h.

**Photocatalytic Dye Degradation:** The model contaminant was crystal violet (CV). AgNPs were greenly fabricated using pomegranate, lemon, and orange extracts (P-AgNPs, L-AgNPs, and O-AgNPs, respectively). For photocatalysis, 10 mg of the NPs was mixed into 50 mL of 30 mg/L CV solution, allowed to mix in the dark for 60 min to attain adsorption-desorption equilibrium, and then placed under natural solar light. CV samples were drawn at intervals of 1-80 minutes. After centrifugation, UV-Visible spectrophotometry was used to determine the absorbance of the remaining CV at 590 nm. A batch study was performed at 30 °C using 50 mL of CV solution to determine the optimal conditions for

adsorption equilibrium. Various parameters were changed in one run at a time, such as dye concentration (10-100 mg/L), agitation speed (0-300 rpm), photocatalyst dosage (10-60 mg), pH (3-10), and contact time (1-80 minutes). The standard conditions were 30 mg/L CV, 200 rpm, 30 min, and 30 °C. Two parallel control experiments were carried out: one was a dark absorption control (CV + catalyst kept in the dark) for determining the amount of adsorption, and the other was a photolysis control (CV subjected to sunlight in the absence of catalyst) for determining the amount of photolysis. The degradation efficiency was calculated as follows:

$$\text{Dye Degradation \%} = \frac{[C_0 - C_t]}{C_0} \times 100$$

where  $C_0$  is the initial dye concentration, and  $C_t$  is the dye concentration at time  $t$ .

**Statistical Analysis:** All experimental procedures were performed in triplicate, and the data are presented as mean values with corresponding standard deviations (SD). The statistical significance between the experimental groups was evaluated using one-way analysis of variance (ANOVA) followed by Tukey's post-hoc test, with statistical significance set at  $p < 0.05$  (Abro *et al.*, 2026; Laiba *et al.*, 2026).

## RESULTS

**Synthesis of silver nanoparticles:** The synthesized silver nanoparticles using fruit peels were preliminarily indicated by observing their color change. With the introduction of fruit peels to the silver nitrate solution, a color change, pomegranate peel extract color change from yellow to dark brown, lemon fruit peel extract caused a color change from yellow to reddish-brown and orange fruit peel extract-based synthesis, the color changed from yellow to dark brown was immediately noted, suggesting that the  $\text{Ag}^+$  ions were reduced to  $\text{Ag}^0$  nanoparticles. However, it is important to observe that the above color change in the visual spectrum is just an initial qualitative confirmation; therefore, it was verified through UV-VIS spectroscopy, FTIR, and SEM.

**Characterization of Silver Nanoparticles:** The UV-Vis spectroscopy studies of the fabricated nanoparticles provided evidence of the synthesis of silver nanoparticles owing to the presence of specific peaks. The AgNPs prepared from pomegranate demonstrated a peak at 425 nm, which is in agreement with the findings of other studies. The maximum absorption of AgNPs obtained from lemon peels was observed at 435 nm. A peak for AgNPs obtained from the orange peel was observed at 450 nm. FTIR was used to determine

the biomolecules in lemon, orange, and pomegranate extracts responsible for the reduction of  $\text{Ag}^+$  ions and the subsequent capping and stabilization of the formed silver nanoparticles. All three IR spectra exhibited similarities in terms of a similar overall shape with characteristic peaks in the O-H, C-H, and carbonyl regions, with a group of low-frequency bands below  $\sim 700 \text{ cm}^{-1}$ . The principal bands and their assignments for the three samples are summarized in Table 1 and are described in detail below. However, they differ in terms of their positions on the spectrum and intensity. FTIR spectroscopy was used to characterize the biomolecules responsible for the reduction of  $\text{Ag}^+$  ions and capping of the nanoparticles. All three FTIR spectra possessed the typical O-H, C-H, and carbonyl functional groups in addition to low frequency regions below approximately  $700 \text{ cm}^{-1}$ ; however, the specific frequencies and intensities were different from one sample to another. The complete list of frequencies is presented in Table 1. Figure 1a shows the FTIR spectra along with the assigned frequencies (Figure 1a). The structural morphology of the AgNPs was studied using SEM, which demonstrated that the particles were spherical with a variable size distribution (Figure 1b). Morphological studies of silver nanoparticles (AgNPs) were performed using scanning electron microscopy (SEM). The main form of AgNPs was spherical particles with an inconstant size distribution (Figure 1b). The size measurement was carried out by image analysis using ImageJ ( $n \geq 100$  particles per sample), and the average diameter values were found to be approximately 150–750 nm for all samples under study; the mean diameters of P-AgNPs, L-AgNPs, and O-AgNPs were  $632.07 \pm 72 \text{ nm}$ ,  $328.15 \pm 32 \text{ nm}$ , and  $197.70 \pm 16 \text{ nm}$ , respectively.

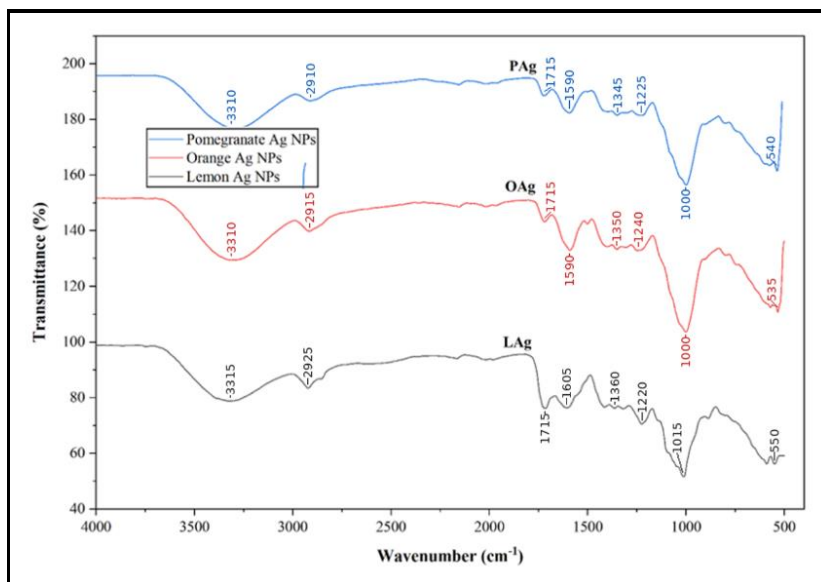


**Figure 1a.** FTIR spectra of green-synthesized AgNPs (pomegranate, orange, and lemon peel), with the principal peak positions annotated on each trace.

**Table 1.** Major FTIR band positions (cm⁻¹) and their assignments for silver nanoparticles synthesized from lemon (L-AgNPs), orange (O-AgNPs), and pomegranate (P-AgNPs) peel extracts.

| Peaks (Functional Groups)                             | L-AgNPs       | O-AgNPs          | P-AgNPs       |
|-------------------------------------------------------|---------------|------------------|---------------|
| O-H stretch (phenols, alcohols, carboxylic acids)     | 3325.66       | 3325.24          | 3280.77       |
| C-H stretch (aliphatic -CH₂/-CH₃)                     | 2919.25       | 2922.01          | 2917.73       |
| C-H overtone / combination band                       | 1979.75       | 2161.74          | —             |
| C=O stretch (carboxylic acids, esters, ketones)       | 1716.88       | 1733.43          | 1733.24       |
| Aromatic C=C / conjugated C=O / N-O                   | 1608.25       | 1603.08          | 1607.99       |
| Aromatic C=C / C-H bending                            | —             | 1516.41, 1367.37 | 1366.55       |
| C-O stretch (phenols, ethers, esters)                 | 1225.63       | 1266.30          | 1235.02       |
| C-O-C (polysaccharides / glycosides)                  | 1014.23       | 1015.66          | 1015.68       |
| Metal-oxygen (Ag-O) / low-frequency fingerprint bands | 614.52–528.06 | 606.98–533.83    | 595.09–533.38 |

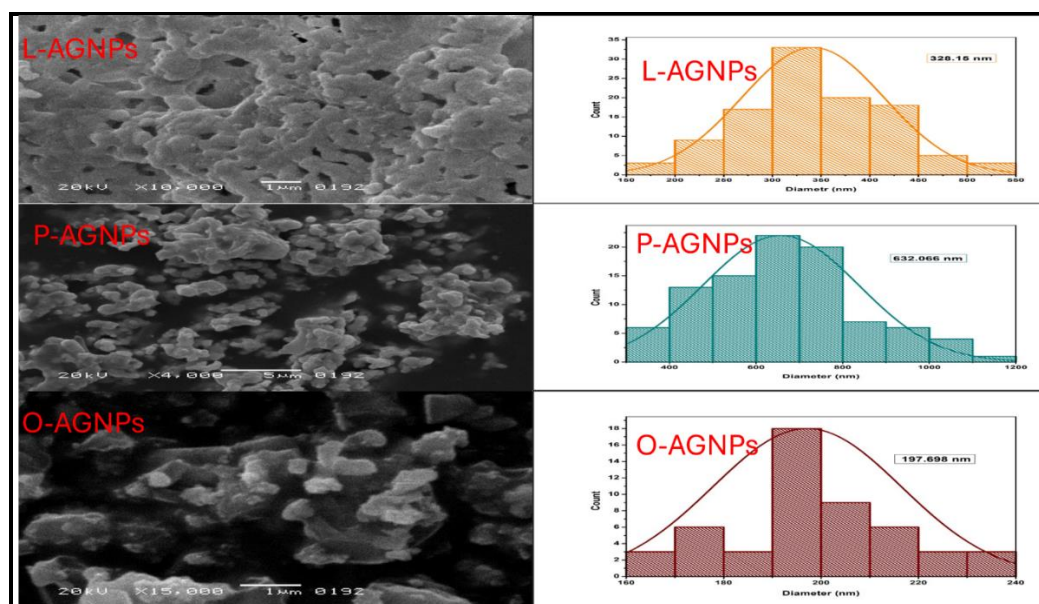


**Figure 1b.** SEM images of AgNPs. L-AgNPs (lemon), P-AgNPs (pomegranate), O-AgNPs (orange) peel nanoparticles. Each SEM image was analyzed for size distribution using the ImageJ software. Bar graphs with lines show the size distribution.

**Antioxidant Activity:** The AgNPs from pomegranate peel had a very good scavenging ability for DPPH radicals, with inhibition values varying from 36.86% to 62.92% within 20 to 100 µg/mL of concentration. The

AgNPs from orange peel exhibited DPPH scavenging activity that was dependent on concentration, with an inhibition of 58.53% within 100  $\mu\text{g/mL}$  of concentration. The antioxidant activity followed the order P-AgNPs > L-AgNPs > O-AgNPs (Table 2). This

pattern is consistent with the phenolic-rich nature of these peels, as observed in the published literature. However, because the amount of phenolics was not measured in the current study, the relation is inferred but not explicitly proven.

**Table 2.** Antioxidant, DPPH % scavenging activities of silver nanoparticles and ascorbic acid. Values represent the mean  $\pm$  SD (n=3). Different superscript letters (a–c) within a column indicate statistically significant differences among the three AgNP types (Tukey's HSD,  $p < 0.05$ ); superscript letters are added to indicate the significance of the difference.

| Concentration ( $\mu\text{g/mL}$ ) | Ascorbic Acid                 | Pomegranate-AgNPs             | Lemon-AgNPs                   | Orange-AgNPs                  |
|------------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
| 20                                 | 33.66 $\pm$ 0.68 <sup>a</sup> | 36.86 $\pm$ 0.15 <sup>a</sup> | 33.30 $\pm$ 0.17 <sup>a</sup> | 31.89 $\pm$ 1.67 <sup>a</sup> |
| 40                                 | 35.78 $\pm$ 0.85 <sup>a</sup> | 39.22 $\pm$ 0.90 <sup>a</sup> | 35.98 $\pm$ 0.70 <sup>a</sup> | 35.37 $\pm$ 0.68 <sup>a</sup> |
| 60                                 | 43.39 $\pm$ 0.79 <sup>b</sup> | 46.80 $\pm$ 0.55 <sup>b</sup> | 43.60 $\pm$ 0.75 <sup>b</sup> | 42.25 $\pm$ 1.29 <sup>b</sup> |
| 80                                 | 53.32 $\pm$ 1.32 <sup>c</sup> | 56.44 $\pm$ 0.49 <sup>c</sup> | 53.16 $\pm$ 2.30 <sup>c</sup> | 52.59 $\pm$ 2.03 <sup>c</sup> |
| 100                                | 58.61 $\pm$ 0.75 <sup>d</sup> | 62.92 $\pm$ 0.33 <sup>d</sup> | 59.54 $\pm$ 0.89 <sup>d</sup> | 58.53 $\pm$ 1.06 <sup>d</sup> |

**Antimicrobial Activity:** AgNPs synthesized using pomegranate peel exhibited the most effective antibacterial action against all tested bacteria, particularly *S. aureus* (ZOI = 19.6 mm) and *P. aeruginosa* (ZOI = 19.0 mm). Lemon peel-derived AgNPs were the most effective in their antibacterial action against *P. aeruginosa*, with a ZOI of 19 mm. All fruit peel-derived AgNPs demonstrated remarkable antimicrobial activity, with minimum zone of inhibition values ranged between 13-16 mm for *B.*

*subtilis* (Figure 2). The trend in antimicrobial activity was the same as that of antioxidants: P-AgNPs > L-AgNPs > O-AgNPs. This is consistent with the phenol-rich nature of pomegranate peels, as reported; however, it should be noted that the quantity of phenols was not actually measured in the current study, and thus the correlation is based on an inference drawn from the data. The negative controls, which contained either only the extract or only AgNO<sub>3</sub>, did not exhibit any activity.

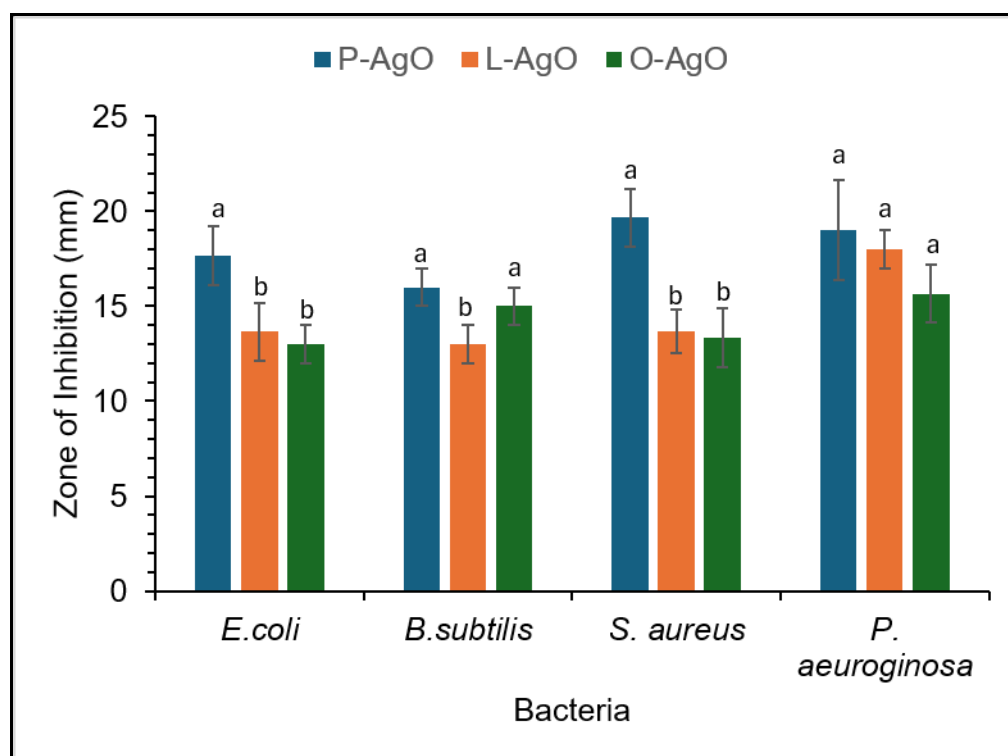


**Figure 2.** Antibacterial activity of L-AgNPs, O-AgNPs, and P-AgNPs zone of inhibition (mm) and AgNPs synthesized using different fruit peels. Error bars represent the standard deviation (n=3). Bars represent mean  $\pm$  SD (n = 3); the y-axis represents the zone of inhibition in mm. Different superscript letters (a, and b) above the bars indicate statistically significant differences among the groups. A for non-significant and b for significant difference (one-way ANOVA, Tukey's HSD,  $p < 0.05$ ).

**Photocatalytic Dye Degradation:** Crystal violet dye photocatalytic degradation reaction took place by using AgNPs. First of all, an initial sample consisting of 10

mg of AgNPs and 50 mL of crystal violet dye solution (30 mg/L) was kept in dark for 60 minutes to reach adsorption-desorption equilibrium state. Afterwards,

the mixture was irradiated with natural sunlight and then decolorization was noted at different pH values from 3-10 (Figure 3). The removal efficiency increased with an increase in the pH of the solution from acidic to neutral-alkaline conditions, with individual maxima

for pomegranate AgNPs at pH 7, lemon AgNPs at pH 8, and orange AgNPs at pH 10 (the highest single-condition value observed, peak efficiency 91%; Figure 3)

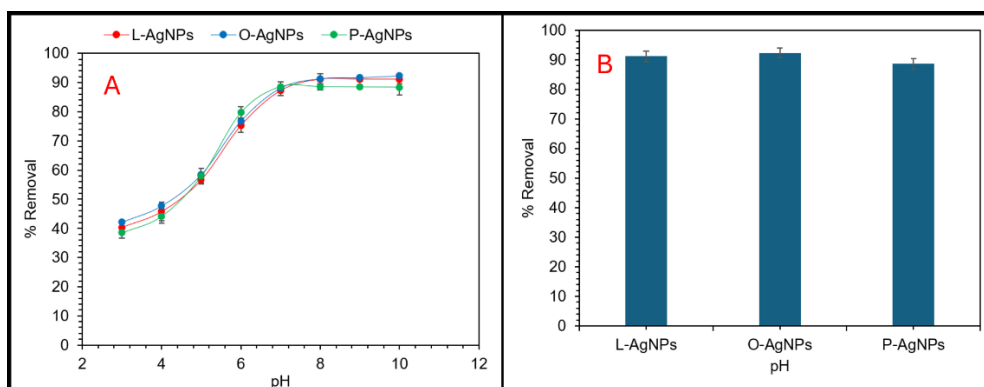


**Figure 3.** (a) Effect of pH on crystal violet degradation using three AgNPs. (b) Maximal dye degradation at specific pH for each nanoparticle. Axes: degradation efficiency (%) vs pH; mean  $\pm$  SD,  $n = 3$ ,  $p < 0.05$ .

Degradation spectra were obtained at different time intervals (Figure 4). Under optimized conditions, the maximum degradation efficiencies were 89.91%, 93.62%, and 93.55% for P-AgNPs, O-AgNPs, and L-AgNPs, respectively. For clarity, these per-nanoparticle maxima (rather than the standalone  $\sim 91\%$  pH-optimization value for O-AgNPs) are the definitive degradation figures reported in this study. The adsorption of CV occurred rapidly during the first few minutes, after which a plateau of effective removal occurred at 30 min, after which the efficiency did not change significantly (Figure 4) (removal at equilibrium). The absorbance peaks decreased progressively with increasing exposure duration, indicating enhanced photocatalytic degradation (Figure 4). The results from the control experiment, in which the CV under light was not catalyzed, showed very little decolorization; however, the dark adsorption

control achieved equilibrium in approximately 30 min with little decolorization. Therefore, it can be concluded that the decolorization effect is mainly due to photocatalytic decolorization and not adsorption or photolysis.

Although P-AgNPs demonstrated the highest antioxidant and antibacterial properties, O-AgNPs and L-AgNPs showed slightly better photodegradation performance for crystal violet (CV). This observation is expected because the photocatalysis process is mainly influenced by the LSPR-mediated formation of reactive oxygen species and the electrostatic interaction of the cationic dye, and not by the antioxidative effect of the capping shell. The presence of a more compact polyphenol shell on the P-AgNPs, which increases the efficiency of scavenging reactions and bacterial interactions, may partially mask the metal surface.

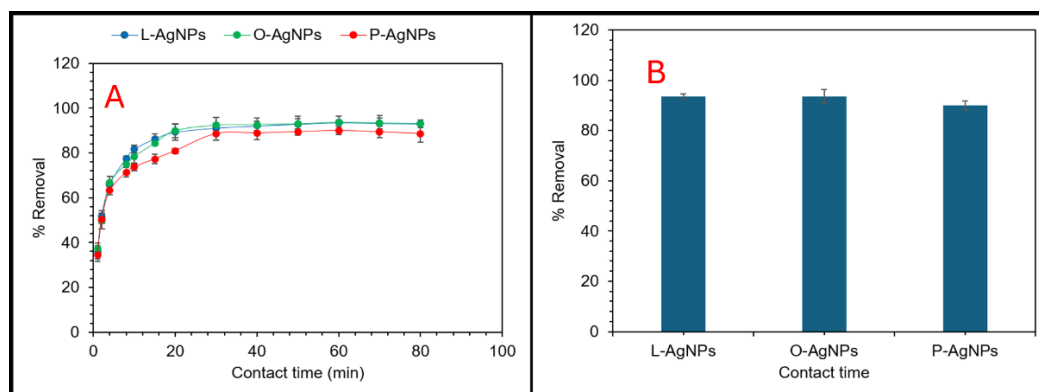


**Figure 4.** (a) Crystal violet degradation using three AgNPs. Effect of time from 1-80 min. (b) Maximal CV degradation at 30 min. Axes: degradation efficiency (%) vs. time (min); mean  $\pm$  SD,  $n = 3$ ,  $p < 0.05$ .

In experiments on agitation rate, exposure time to sunlight was 30 min, pH was optimized in previous experiments, and shaking speed varied from 0-300 rpm. It was found that the higher agitation rate of up to

200 rpm increased the removal efficiency from 50% at 0 rpm to 93% at 200 rpm, after which no changes were observed (Figure 5).

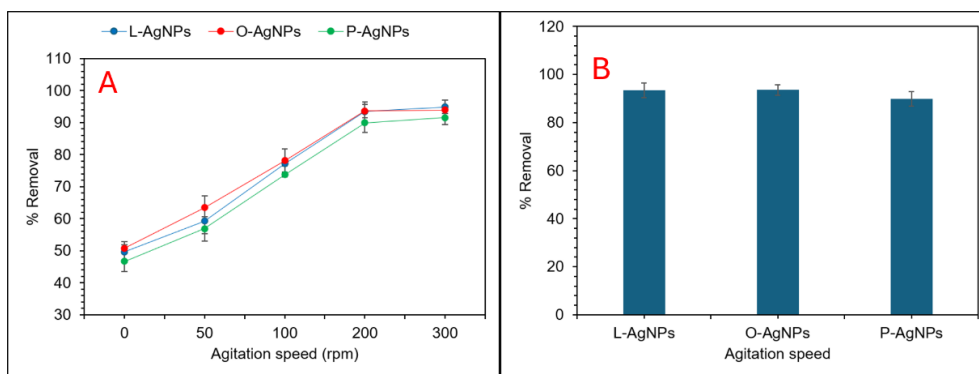


**Figure 5.** (a) Effect of shaking on CV photocatalysis using three nanoparticles. (b) CV degradation at 200 rpm. Axes: degradation efficiency (%) vs agitation speed (rpm); mean  $\pm$  SD,  $n = 3$ ,  $p < 0.05$ .

An experiment was conducted to determine the effect of photocatalyst dosage on CV degradation. The experiment was performed using nanoparticle dosages of 10-60 mg under constant experimental conditions, such as exposure to sun rays for 30 min and speed of agitation at 200 rpm with optimized pH (Figure 6). The effects of the initial CV concentrations were

investigated between 10 and 100 mg/L. The degradation effectiveness decreased from 95% at 10 mg/L to 63% at 100 mg/L. This decrease can be attributed to the saturation of catalyst binding sites, decreased transmission of light through the darker solution, and competition for catalyst sites from the dye and its breakdown products (Figure 7).

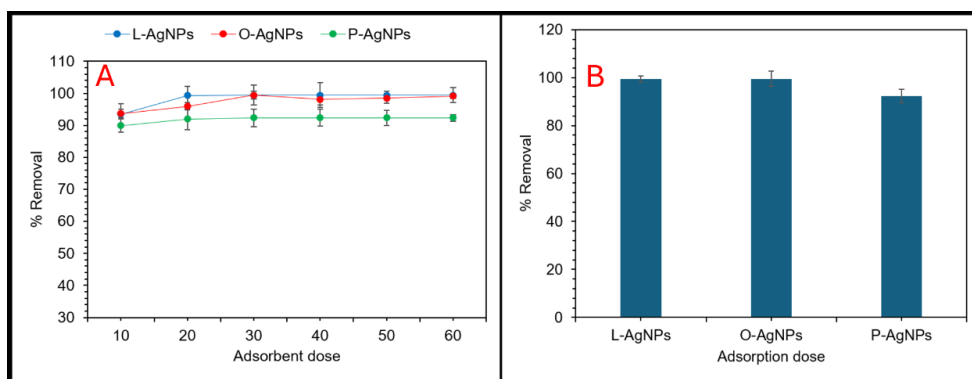


**Figure 6.** (a) Impact of photocatalyst dosage on CV degradation. (b) Maximal CV degradation at 30 mg of AgNPs. Axes: degradation efficiency (%) vs dosage (mg); mean  $\pm$  SD,  $n = 3$ ,  $p < 0.05$ .

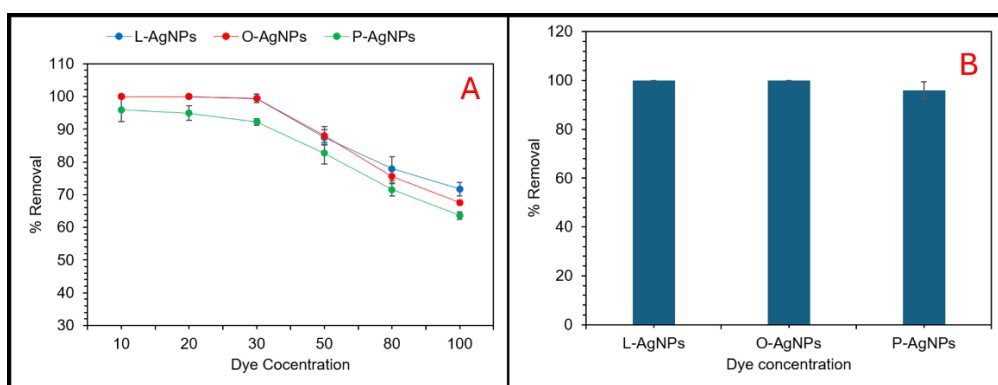


**Figure 7.** (a) Effect of CV concentration of 10-100 mg/L. (b) Maximal CV degradation at 10 mg/L. Axes: degradation efficiency (%) vs. initial CV concentration (mg/L); mean  $\pm$  SD,  $n = 3$ ,  $p < 0.05$ .

## DISCUSSION

The current study presents the successful green production of AgNPs using extracts obtained from the peels of pomegranates, lemons, and oranges, with

subsequent characterization and evaluation of their biological activities. These findings correlate well with the available literature related to the biogenesis of metal nanoparticles with plants. When added to an aqueous solution of silver nitrate, the extracts from the fruits peels immediately changed the color of the solution, indicating the conversion of  $\text{Ag}^+$  to  $\text{Ag}^0$ , that

is, from yellow to dark brown in the case of pomegranates (Farouk *et al.*, 2023), from yellow to reddish-brown in the case of lemons (Khane *et al.*, 2022), and from yellow to dark brown in the case of oranges (Gupta *et al.*, 2025; Mostafa *et al.*, 2021). This color change is a known indicator of silver nanoparticle synthesis based on the excitation of the SPR of the nanoparticles (Gupta *et al.*, 2025).

The presence of nanoparticles was confirmed using UV-Visible spectroscopy, with surface plasmon resonance (SPR) peaks at 425, 435, and 450 nm for pomegranate, lemon, and orange peel. This agrees with previous studies, where it was noted that green-synthesized AgNPs from the peels of citrus fruits and pomegranates have SPR peaks between 420 and 454 nm (Gupta *et al.*, 2025; Farouk *et al.*, 2023; Saad *et al.*, 2021; Weng *et al.*, 2022; Mostafa *et al.*, 2021). The variation in the SPR peaks of the three sources may be due to differences in their phytochemical compositions.

Citric and ascorbic acids, along with flavanone glycosides such as hesperidin and eriocitrin, are found in abundance in lemon peels (Nasr *et al.*, 2019; Srividhyaa *et al.*, 2023). While ascorbate and citrate act as fast-reducing agents but have smaller capping ligands (Santos *et al.*, 2015), the fast reduction kinetics of the ligands and the thin and weakly bound organic capping layer correlate well with the slightly shifted surface plasmon resonance (SPR) peak at 435 nm and with somewhat larger nanoparticle sizes than P-AgNPs (Nasr *et al.*, 2019). With a less thick layer of the capping ligands, more of the metal surface is exposed, and this agrees with the somewhat better photocatalytic activity seen in L-AgNPs compared to the poor ranking of the nanoparticles as antioxidants and antibacterial agents compared to P-AgNPs (Srividhyaa *et al.*, 2023).

Orange peels are known to contain flavanone glycosides, hesperidin, and naringin, in addition to carotenoids and vitamin C. Large-sized glycosylated flavonoids act as efficient capping agents; however, these agents prefer to form larger particles, which is also observed in our results in terms of the red-shifted SPR peak obtained at 450 nm and is supported by the size range of 20–100 nm obtained for orange-peel-derived AgNPs (AgNPs) (Gupta *et al.*, 2025). The prevalence of carbohydrate/glycoside functional groups, visible in the form of strong C-O and C-O-C FTIR peaks, ensures good colloidal stability of the particles as well as an efficient surface for the adsorption of the cationic crystal violet dye.

The biomolecules involved in the reduction, capping, and stabilization of the nanoparticles were

identified using FTIR spectroscopy (summarized in Table 2). The broad O-H band near  $3300\text{ cm}^{-1}$  reflects polyphenols, flavonoids, and ascorbic acid acting as the principal electron donors that reduce  $\text{Ag}^+$  to  $\text{Ag}^0$  (Khane *et al.*, 2022). Therefore, the intensity of the observed band corresponds to this process. C-H stretching vibrations of aliphatic groups can be seen in the area of  $2900\text{ cm}^{-1}$ . Bands at  $1716\text{--}1733\text{ cm}^{-1}$  (C=O of carboxylic acids, esters, and ketones) and at  $1600\text{ cm}^{-1}$  (conjugated C=O, aromatic C=C, and N-O) correspond to oxygen-containing molecules, which form a coordination layer on the surface of a nanoparticle, thereby preventing its agglomeration. Bands at  $1516.41$ ,  $1367.37$ , and  $1366.55\text{ cm}^{-1}$  in the orange and pomegranate spectra, which correspond to aromatic C=C/C-H bending, prove the presence of a rich polyphenolic content in these fruits according to their chemistry. Bands in the range  $1000\text{--}1270\text{ cm}^{-1}$  (C-O and C-O-C of phenols, ethers, esters, and polysaccharides) confirm the retention of carbohydrate and phenolic compounds on the particle surface. The cluster of sharp bands in the area below  $700\text{ cm}^{-1}$  ( $614.52\text{--}528.06\text{ cm}^{-1}$  for lemon;  $606.98\text{--}533.83\text{ cm}^{-1}$  for orange;  $595.09\text{--}533.38\text{ cm}^{-1}$  for pomegranate) indicates the metal-oxygen (Ag-O) stretching, which proves the formation of silver nanoparticles (Khane *et al.*, 2022; Albukhari *et al.*, 2019). The differences in binding at the surface affect the activity levels that have been witnessed: the increased binding to polyphenols will make it easier for the compound to scavenge radicals and interact with bacteria, but can also affect charge transfer at the interface.

The similarity between the three spectra proves that all three extracts play the role of reduction and capping agents by means of functional groups; however, some differences, such as the O-H band at  $3280.77$  vs.  $\sim 3325\text{ cm}^{-1}$  for pomegranate, and a shift in the carbonyl band from  $1716.88\text{ cm}^{-1}$  (lemon) to  $\sim 1733\text{ cm}^{-1}$  (orange, pomegranate) are the classic FTIR signatures of a functional group binding directly to the particle surface rather than remaining free in solution.

Variations in the properties of the nanoparticles were observed based on the fruit type, which was attributed to the differences in the phytochemical composition (Yaqoob *et al.*, 2020). The nanoparticles produced from pomegranate peel, which had the highest amount of phenolic compounds, were smaller and more stable than those produced from other sources (Mostafa *et al.*, 2021), while those produced from orange peel had a size between 20–100 nm (Gupta *et al.*, 2025).

The synthesized silver nanoparticles (AgNPs) exhibited concentration-dependent scavenging of DPPH radicals, with the highest scavenging effects observed with pomegranate-extract-based nanoparticles (36.86-62.92 % at 20-100 µg/mL) and lower with lemon and orange nanoparticles (P-AgNPs>L-AgNPs>O-AgNPs). This is consistent with the total phenolic content in the corresponding extracts, as polyphenols and flavonoids are the primary sources of electrons/hydrogens that act as radical scavengers (Laghari *et al.*, 2023), although, as noted, phenolic content was not quantified here. Consistent results were obtained in studies with pomegranate peel AgNPs by Saad *et al.* (2021) and citrus peel AgNPs, when the nanoparticles were shown to possess higher antioxidant activity than the free extract due to their surface phytochemical coat (Khane *et al.*, 2022; Gupta *et al.*, 2025).

All the AgNPs synthesized from the fruit peels exhibited a wide spectrum of antibacterial activity against gram-positive bacteria, such as *S. aureus* and *B. subtilis*, and gram-negative bacteria, such as *E. coli* and *P. aeruginosa*, as shown by the zones of inhibition between 13 and 16 mm in the case of *B. subtilis*, while the highest value was obtained for *S. aureus*, which amounted to 19.6 mm. The order of antibacterial activity observed (P AgNPs > L AgNPs > O AgNPs) agrees with the reported phenolic content. The minimum inhibitory effect of the aqueous extracts and silver nitrate individually suggests that the antibacterial property depends on the nanoparticles themselves and not on any other component of the precursor or extract (Khane *et al.*, 2022; Mai-Prochnow *et al.*, 2016). The intrinsic bactericidal properties of polyphenols and flavonoids present in the extract act together when the nanoparticles are coated with these compounds (Khane *et al.*, 2022; Haida *et al.*, 2022; Aazam & Zaheer, 2016).

The antibacterial mechanism of AgNPs is multifactorial. It involves the release of Ag<sup>+</sup> ions that bind to thiol (-SH) groups in vital bacterial enzymes, leading to protein inactivation. Concurrently, nanoparticle-surface interactions generate ROS, which induce oxidative stress, damage the cell membrane, and interfere with DNA replication. The pathways involving oxidative processes such as ROS and GSH oxidation were used herein through analogy with earlier experiments on the mechanistic study of similar nanoparticles (bimetallic nanoparticles); however, they have not been observed experimentally in relation to the current AgNPs derived from fruit peels and are thus discussed as the inferred mechanism (future research

involving specific ROS scavenging and GSH oxidation experiments is suggested—see Limitations). Notably, the layer of phytochemicals not only serves as a stabilizer but also provides bactericidal action. Surface-bound polyphenols and flavonoids have antibacterial properties and can induce oxidative stress on the cell membrane, leading to higher bacterial membrane disruption than bare AgNPs (Khane *et al.*, 2022; Haida *et al.*, 2022; Aazam & Zaheer, 2016; Ahmed *et al.*, 2016). The different sensitivities to Gram-positive and Gram-negative strains are related to differences in cell wall composition, mainly the thickness of the peptidoglycan layer and the outer lipopolysaccharide cell membrane in gram-negative strains (Mikhailova, 2020). The different sensitivities to Gram-positive and Gram-negative bacteria depend on the cell wall properties. In gram-positive bacteria, the thick peptidoglycan layer and teichoic acids may serve as a protective layer, whereas in gram-negative bacteria, the negative charges of lipopolysaccharides attract cationic nanoparticles and Ag<sup>+</sup> ions, promoting ion accumulation and cell damage (Slavin *et al.*, 2017; Guimarães *et al.*, 2010). However, since susceptibility depends not only on nanoparticle charge and size but also on the capping reagent and strain properties, there have been reports of higher activity against both Gram-negative and Gram-positive bacteria (Morones *et al.*, 2005; Sathiyavimal *et al.*, 2018). For instance, Rahman *et al.* (2017) observed greater bactericidal activity against gram-negative strains in AgNPs produced by *A. flavum*. In the current study, the largest zone of inhibition was observed for Gram-positive *S. aureus*. The activity of AgNPs is similar to that of common antibiotics because of their high nanoparticle penetration and accumulation in cells (Mu *et al.*, 2016). These results are consistent with previous findings concerning AgNPs produced from the leaves of *Cordia dichotoma*, *Diospyros montana*, and other plants (Bharathi *et al.*, 2018a; Bharathi *et al.*, 2018b; Seerangaraj *et al.*, 2021).

Removal efficiency for photocatalytic degradation of crystal violet (CV) via natural sunlight varied depending on pH level, improving from acidic to neutral-alkaline media, and attained maximums for pomegranate-based AgNPs at pH 7, lemon-based AgNPs at pH 8, and orange-based AgNPs at pH 10, which amounted to 91% efficiency. This dependency is explained by the positive character of crystal violet: at lower pH, a high amount of H<sup>+</sup> ions competes with negative active sites, while a neutral-alkaline environment facilitates electrostatic attraction and adsorption of the dye. The differences in the optimal

pH levels for various materials were caused by the differences in the surface functional groups and charges provided by the extracts of different peels. Equilibrium for dye adsorption was reached rather quickly (in 30 min), which proves the limited capacity of the active sites for the dye. Increased agitation rate (up to 200 rpm, which increases mass transfer and decreases boundary layer thickness) and dosage of photocatalyst (which provides more area for dye adsorption) improved the efficiency. Increasing the initial dye concentration (10–100 mg/L; from 95% to 63%) decreased the efficiency due to adsorbent saturation.

With sunlight illumination, silver nanoparticles (AgNPs) exhibit localized surface plasmon resonance (LSPR) properties. The oscillations of the conduction band electrons lead to the formation of hot electrons that can be transferred to the absorbed molecular oxygen and water. Plasmon-induced charge transfer leads to the formation of reactive oxygen species (ROS), mainly superoxide anions ( $O_2^{\bullet-}$ ) and hydroxyl radicals ( $\bullet OH$ ). These reactive species oxidize the chromophore moieties of crystal violet, resulting in the cleavage of the rings, leading to their mineralization to  $CO_2$  and  $H_2O$ . This is the known plasmon-induced process in metallic nanoparticles, which differs completely from semiconductor photocatalysis, which relies on bandgap excitation (Ashkar *et al.*, 2023; Al-Thabaiti & Khan, 2020). Similar photocatalytic mechanisms have been reported in our previous work on reduced graphene oxide-supported FeCu bimetallic nanoparticles, where the activation of sodium percarbonate generated hydroxyl radicals for the efficient degradation of methylene blue (Ahmad *et al.*, 2024). The oxidation of CV and pyronin Y occurs via these radicals, leading to their mineralization to  $CO_2$ ,  $H_2O$ , and other small organic fragments (Shaikh *et al.*, 2020; Ashkar *et al.*, 2023; Vanaamudan *et al.*, 2016). Photons are absorbed by the nanoparticles, followed by the generation and trapping of charges, which react with  $O_2$  and  $H_2O$  to generate radicals (Ashkar *et al.*, 2023; Al-Thabaiti & Khan, 2020).

The photodegradation efficiency obtained for the peel-extracted AgNPs, determined from absorbance measurements at 590 nm, ranged from 89% to 93%, as shown by the gradual decrease in the absorbance value with an increase in the exposure time. No degradation occurred in the absence of the nanocatalyst in the control test (Seerangaraj *et al.*, 2021). With respect to the other fruit peel-derived AgNP systems, the current efficiencies seem to be in line: the maximum values of approximately 89-94% found here are similar to those

obtained for AgNPs derived from citrus peels and radish microgreens that were evaluated for their activity towards crystal violet (Ashkar *et al.*, 2023) and for AgNPs derived from *Citrus grandis* (Arunachalam *et al.*, 2012). Likewise, the inhibition zones obtained (up to 19.6 mm) were in the same range as those obtained for pomegranate peel- and lemon peel-derived AgNPs (Abdelrazik *et al.*, 2023; Khane *et al.*, 2022). However, waste-derived copper nanoparticles were active against *Staphylococcus aureus* and *Escherichia coli* (Khatri *et al.*, 2024). The degradation efficiency observed in this study is comparable to that reported for rGO-FeCu bimetallic nanoparticles, which achieved over 99% removal of methylene blue through the activation of sodium percarbonate (Ahmad *et al.*, 2024). The present results are consistent with those of previous studies on CuONPs isolated from *Sida acuta* (Sathiyavimal *et al.*, 2018), AgNPs extracted from *Carissa carandas* (Anupama and Madhumitha, 2017), and AgNPs isolated from *Citrus grandis* (Arunachalam *et al.*, 2012), which have shown high efficiency of photo-decolorization of dyes due to reactive oxygen species mediated mechanism.

The fruit-peel route offers several advantages over alternative synthesis strategies. Compared with other synthesis routes, the use of fruit peel extracts offers clear advantages. Plant-mediated synthesis is simpler and more cost-effective than microbial-mediated synthesis, which requires pure strains and sterile conditions (Kuppusamy *et al.*, 2016). It eliminates toxic reagents and reduces environmental pollution compared to conventional chemical synthesis (Gudikandula & Maringanti, 2016; Kumar *et al.*, 2020). Uniquely, it valorizes an abundant waste stream in the same step, aligning the method with circular-economy goals.

## CONCLUSION

In conclusion, this work establishes an eco-friendly, waste-valorizing route for producing silver nanoparticles from pomegranate, lemon, and orange peels, which have been identified via unique surface plasmon resonance peaks at 425, 435, and 450 nm, respectively. Bioactivity tests revealed significant concentration-dependent antioxidant activity, with pomegranate silver nanoparticles exhibiting the strongest free radical scavenging ability (62.92% at 100  $\mu g/mL$ ). Lemon and orange silver nanoparticles displayed lower but almost comparable activities (59.54% and 58.53%, respectively). Finally, the photocatalytic analysis demonstrated maximum crystal violet degradation efficiencies of 89.91%, 93.62%, and

93.55% for P-AgNPs, O-AgNPs, and L-AgNPs, respectively, with performance depending on pH and surface charge. As far as the application of these results is concerned, it is possible to conclude about a complimentary distribution of usage: P-AgNPs become the most attractive for use in biomedical areas due to their high effectiveness in antioxidant and antibacterial properties, while O-AgNPs and L-AgNPs, demonstrating slightly higher photocatalytic efficiency, can be used in the field of environmental cleanup. Since no quantification of the total phenolics or flavonoids was performed in this study, the correlations between bioactivity and phenolic content can only be speculated from the literature and should be considered with caution. Similarly, the role of ROS and GSH in bacterial inhibition cannot be proven by experiments in this case; instead, special tests of ROS scavenging and GSH oxidation are recommended for such studies. For the antibacterial test, only the well-diffusion assay was used. To evaluate the relative effectiveness of the inhibitors in quantitative terms, MIC determination against each bacterium with reference to a standard antibiotic is required. In addition, the cytotoxicity/biocompatibility, reusability of the catalyst, and stability of the colloids have not been tested. In a translational sense, batch-to-batch variations in the extracts, costs and scalability of the process, and reusability of the nanoparticles should be considered before application. Future research should include quantitative analyses of phytochemicals, ROS/GSH, MIC tests, cytotoxicity at different concentrations, tests of reusability and stability, and preliminary techno-economic and scale-up analyses. Taken together, these quantitative data confirm that AgNPs derived from fruit peels are multifunctional agents with antioxidant, antibacterial, and photocatalytic activities that can be used in biomedical applications and environmental pollution problems within a circular-economy approach.

## CONFLICT OF INTEREST

The authors declare no conflict of interest.

## AUTHORS' CONTRIBUTION

Conceptualization: A.N.J., S.B.R., I.K., A.S.Q. Methodology: S.B.R., I.K., G.M.K., M.S.K. Analysis: S.B.R., I.K., A.N.J., A.A.D., M.S.K. Writing, Review, Editing: S.B.R., I.K., A.S.Q., A.N.J. The manuscript has been reviewed and endorsed by all the authors.

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## REFERENCES

- Aazam, E. S., & Zaheer, Z. (2016). Growth of Ag-nanoparticles in an aqueous solution and their antimicrobial activities against Gram positive, Gram negative bacterial strains and Candida fungus. *Bioprocess and biosystems engineering*, **39**(4), 575-584. <https://doi.org/10.1007/s00449-016-1539-3>
- Abady, M. M., Mohammed, D. M., Soliman, T. N., Shalaby, R. A., & Sakr, F. A. (2025). Sustainable synthesis of nanomaterials using different renewable sources. *Bulletin of the National Research Centre*, **49**(1). <https://doi.org/10.1186/s42269-025-01316-4>
- Abdelbasir, S. M., Mccourt, K. M., Lee, C. M., & Vanegas, D. C. (2020). Waste-Derived Nanoparticles: Synthesis Approaches, Environmental Applications, and Sustainability Considerations. *Frontiers in Chemistry*, **8**, 782. <https://doi.org/10.3389/fchem.2020.00782>
- Abdelrazik, M., Elkotaby, H. H., Yousef, A., El-Sayed, A. F., & Khedr, M. (2023). Green synthesis of silver nanoparticles derived from lemon and pomegranate peel extracts to combat multidrug-resistant bacterial isolates. *Journal of Genetic Engineering and Biotechnology*, **21**(1), 97. <https://doi.org/10.1186/s43141-023-00547-0>
- Abro, F. M., Mir-Jatt, A. N., Sattar Qureshi, A., Khand, A. A., Khanzada, B., Soomro, Q. A., ... & Patrick, A. (2026). Green Synthesis of Nickel Oxide Nanoparticles using pea peel extract for Attenuation of Quorum Sensing and Biofilm Formation in *Pseudomonas aeruginosa* QS107. *Journal of Microbiological Sciences*, **5**(01), 74-83. <https://doi.org/10.38211/jms.2026.05.210>
- Ahmad, A., Li, L., Bao, J., Jia, X., Xu, Y., & Guo, X. (2016). Antibacterial activity of graphene supported FeAg bimetallic nanocomposites. *Colloids and Surfaces B: Biointerfaces*, **143**, 490-498. [10.1016/j.colsurfb.2016.03.065](https://doi.org/10.1016/j.colsurfb.2016.03.065)
- Ahmad, A., Qureshi, A.S., Hassan, A., Arshad, M., Khurshid, H., Mehmood, U., & Guo, X. (2024). Synthesis of reduced graphene oxide supported FeCu and its environmental applications. *Environmental Science and Pollution Research*. <https://doi.org/10.1007/s11356-024-34965-5>
- Ahmed, S. A., Taie, H. A., & Wahab, W. A. A. (2023). Antioxidant capacity and antitumor activity of the bioactive protein prepared from orange peel residues as a by-product using fungal protease. *International Journal of Biological Macromolecules*, **234**
- Albukhari, S. M., Ismail, M., Akhtar, K., & Danish, E. Y. (2019). Catalytic reduction of nitrophenols and dyes using silver nanoparticles@ cellulose polymer paper for the resolution of wastewater treatment challenges. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, **577**, 548-561. [10.1016/j.colsurfa.2019.05.058](https://doi.org/10.1016/j.colsurfa.2019.05.058)
- Al-Thabaiti, S. A., & Khan, Z. (2020). Biogenic synthesis of silver nanoparticles, sensing and photo catalytic activities for bromothymol blue. *Journal of Photochemistry and Photobiology*, **3**, 100010. <https://doi.org/10.1016/j.jpap.2020.100010>
- Anupama, N., & Madhumitha, G. (2017). Green synthesis and catalytic application of silver nanoparticles using Carissa

- carandas fruits. *Inorganic and Nano-Metal Chemistry*, **47**(1), 116-120. <https://doi.org/10.1080/15533174.2016.1149731>
- Arunachalam, R., Dhanasingh, S., Kalimuthu, B., Uthirappan, M., Rose, C., & Mandal, A. B. (2012). Phytosynthesis of silver nanoparticles using *Coccinia grandis* leaf extract and its application in the photocatalytic degradation. *Colloids and Surfaces B: Biointerfaces*, **94**, 226-230. [10.1016/j.colsurfb.2012.01.040](https://doi.org/10.1016/j.colsurfb.2012.01.040)
- Ashkar, M. A., Babu, A., Joseph, R., Rani, S. K., & Vasimalai, N. (2023). Ecofriendly synthesis of silver nanoparticles using Radish microgreens extract and their potential photocatalytic degradation of toxic crystal violet and pyronin Y dyes and antibacterial studies. *Inorganic Chemistry Communications*, **156**, 111225. <https://doi.org/10.1016/j.inoche.2023.111225>
- Bharathi, D., Diviya Josebin, M., Vasantharaj, S., & Bhuvaneshwari, V. (2018a). Biosynthesis of silver nanoparticles using stem bark extracts of *Diospyros montana* and their antioxidant and antibacterial activities. *Journal of Nanostructure in Chemistry*, **8**(1), 83-92. <https://doi.org/10.1007/s40097-018-0256-7>
- Bharathi, D., Vasantharaj, S., & Bhuvaneshwari, V. (2018b). Green synthesis of silver nanoparticles using *Cordia dichotoma* fruit extract and its enhanced antibacterial, anti-biofilm and photocatalytic activity. *Materials Research Express*, **5**(5), 055404. [10.1088/2053-1591/aac2ef](https://doi.org/10.1088/2053-1591/aac2ef)
- Dubey, P., Tripathi, G., Mir, S. S., & Yousuf, O. (2023). Current scenario and global perspectives of citrus fruit waste as a valuable resource for the development of food packaging film. *Trends in Food Science & Technology*, **141**, 104190. <https://doi.org/10.1016/j.tifs.2023.104190>
- Duman, H., Eker, F., Akdaşçı, E., Witkowska, A. M., Bechelany, M., & Karav, S. (2024). Silver nanoparticles: A comprehensive review of synthesis methods and chemical and physical properties. *Nanomaterials*, **14**(18), 1527. <https://doi.org/10.3390/nano14181527>
- Fadhil, Z., Naser, H. G., Hasan, A. A., Jwad, R. S., Alshareef, S. A., Kommanaboyina, S., & Al-Mashhadani, M. H. (2024). Green Chemistry of Lemon Peels, Extracting Components for Sustainability: A Review. *Journal of University of Anbar for Pure Science*, **18**(2). [10.37652/juaps.2024.148332.1226](https://doi.org/10.37652/juaps.2024.148332.1226)
- Farouk, S.M., Abu-Hussien, S.H., Abd-Elhalim, B.T., Mohamed, R.M., Arabe, N.M., Hussain, A.A.T., Mostafa, M.E., Hemdan, B., El-Sayed, S.M., Bakry, A., Ebeed, N.M., Salah, M., Elhariry, H., & Galal, A. (2023). Biosynthesis and characterization of silver nanoparticles from *Punica granatum* (pomegranate) peel waste and its application to inhibit foodborne pathogens. *Scientific Reports*, **13**, 19469. <https://doi.org/10.1038/s41598-023-46355-x>
- Formoso, P., Muzzalupo, R., Tavano, L., De Filipo, G., & Pasquale Nicoletta, F. (2016). Nanotechnology for the environment and medicine. *Mini reviews in medicinal chemistry*, **16**(8), 668-675. <https://doi.org/10.2174/1389557515666150709105129>
- Gaharwar, S. S., Kumar, A., Mandavgane, S. A., Rahagude, R., Gokhale, S., Yadav, K., & Borua, A. P. (2024). Valorization of *Punica granatum* (pomegranate) peels: a case study of circular bioeconomy. *Biomass Conversion and Biorefinery*, **14**(6), 7707-7724. <https://doi.org/10.1007/s13399-022-02744-2>
- Girotra, V., Kaushik, P., & Vaya, D. (2024). Exploring sustainable synthesis paths: a comprehensive review of environmentally friendly methods for fabricating nanomaterials through green chemistry approaches. *Turkish Journal of Chemistry*, **48**(5), 703-725. <https://doi.org/10.55730/1300-0527.3691>
- Gudikandula, K., & Maringanti, S.C. (2016). Synthesis of silver nanoparticles by chemical and biological methods and their antimicrobial properties. *Journal of Experimental Nanoscience*, **11**(9), 714-721. <https://doi.org/10.1080/17458080.2016.1139196>
- Guimarães, P. M., Teixeira, J. A., & Domingues, L. (2010). Fermentation of lactose to bio-ethanol by yeasts as part of integrated solutions for the valorisation of cheese whey. *Biotechnology advances*, **28**(3), 375-384. [10.1016/j.biotechadv.2010.02.002](https://doi.org/10.1016/j.biotechadv.2010.02.002)
- Gupta, S., Choudhary, D.K., & Sundaram, S. (2025). Green synthesis and characterization of silver nanoparticles using *Citrus sinensis* (Orange peel) extract and their antidiabetic, antioxidant, antimicrobial and anticancer activity. *Waste and Biomass Valorization*, **16**, 1101-1114. <https://doi.org/10.1007/s12649-024-02782-z>
- Haida, Z., Ab Ghani, S., Nakasha, J. J., & Hakiman, M. (2022). Determination of experimental domain factors of polyphenols, phenolic acids and flavonoids of lemon (*Citrus limon*) peel using two-level factorial design. *Saudi Journal of Biological Sciences*, **29**(1), 574-582. <https://doi.org/10.1016/j.sjbs.2021.09.022>
- Hoffmann, M.R., Martin, S.T., Choi, W., & Bahnmann, D.W. (1995). Environmental applications of semiconductor photocatalysis. *Chemical Reviews*, **95**(1), 69-96.
- Huang, J., Xu, X., Liu, C., & Liu, L. (2025). Exploring the potential of lemon peel extracts in cosmetics: Chemical composition and bioactive properties. *Journal of Microbiology and Biotechnology*, **35**, e2412042. <https://doi.org/10.4014/jmb.2412.12042>
- Husain, A., & Nasibullah, M. (2024). A Brief History of the Green Synthesis of Nanomaterials. In *Sustainable Nanoremediation* (pp. 187-200). Apple Academic Press.
- Hussain, H., Mamadalieva, N. Z., Hussain, A., Hassan, U., Rabnawaz, A., Ahmed, I., & Green, I. R. (2022). Fruit peels: Food waste as a valuable source of bioactive natural products for drug discovery. *Current issues in molecular biology*, **44**(5), 1960-1994. <https://doi.org/10.3390/cimb44050134>
- Jahan, I., & Işildak, İ. (2021). Lemon Peel Extract for Synthesizing Non-Toxic Silver Nanoparticles through One-Step Microwave-Accelerated Scheme. *Kahramanmaraş Sütçü İmam Üniversitesi Tarih ve Doğa Dergisi*, **24**(1), 1-10. <https://doi.org/10.18016/ksutarimdogavi.737063>
- Jangra, M., Saini, G., Sheoran, P., Gahlaut, A., & Raj, V. (2025). Advances in Silver Nanoparticles: Synthesis, Characterization, and Diverse Applications in Medicine, Environment, Antimicrobial and Antiviral Research. *Critical Reviews in Analytical Chemistry*, **1**-25. <https://doi.org/10.18016/ksutarimdogavi.737063>
- Kafshgari, M. H., Voelcker, N. H., & Harding, F. J. (2015). Applications of zero-valent silicon nanostructures in biomedicine. *Nanomedicine*, **10**(16), 2553-2571. <https://doi.org/10.2217/nmm.15.91>
- Khan, M. A., Shafiq, A., Asaad, M., & Zhu, H. (2026). Green synthesis of nanoparticles: a comprehensive review of biogenic methods and their applications. *Sustainable & Green Materials*, **2687133**. <https://doi.org/10.1080/29965292.2026.2687133>
- Khane, Y., Benouis, K., Albukhaty, S., Sulaiman, G.M., Abomughaid, M.M., Al Ali, A., Aouf, D., Fenniche, F., Khane, S., Chaibi, W., Henni, A., Bouras, H.D., & Dizge, N. (2022). Green synthesis of silver nanoparticles using aqueous *Citrus limon* zest extract: Characterization and evaluation of their antioxidant and antimicrobial properties. *Nanomaterials*, **12**(12), 2013. <https://doi.org/10.3390/nano12122013>
- Khatoun, U. T., Velidandi, A., & Rao, G. N. (2023). Sodium borohydride mediated synthesis of nano-sized silver particles:

- Their characterization, anti-microbial and cytotoxicity studies. *Materials Chemistry and Physics*, **294**, 126997. <https://doi.org/10.1016/j.matchemphys.2022.126997>
- Khatr, F. A., Solangi, I. B., Memon, G. Z., Khattak, M. I., Bhatti, M. A., Keerio, F. A., & Farooque, M. (2024). Antibacterial Application of Copper Nanoparticles Biosynthesized by Water Caltrop Pod. *Journal of Applied Research in Plant Sciences*, **5**(02), 288-296. <https://doi.org/10.38211/joarps.2024.05.282>
- Khuhro, G. M., Aqeel Bhutto, M., & Rahaman, T. (2025). Investigating the antibacterial and antioxidant properties of chemically synthesized zinc oxide nanoparticles. *Analytical Chemistry Letters*, **15**(1), 129-137. <https://doi.org/10.1080/22297928.2025.2449724>
- Kiteto, M. K., Vidija, B. M., & Mecha, C. A. (2025). Production of bioethanol from citrus peel waste: a techno-economic feasibility study. *Energy Conversion and Management: X*, **26**, 100916. <https://doi.org/10.1016/j.ecmx.2025.100916>
- Kumar, H., Bhardwaj, K., Sharma, R., Nepovimova, E., Kuča, K., Dhanjal, D.S., Verma, R., Bhardwaj, P., Sharma, S., & Kumar, D. (2020). Fruit and vegetable peels: Utilization of high value horticultural waste in novel industrial applications. *Molecules*, **25**(12), 2812. <https://doi.org/10.3390/molecules25122812>
- Kuppusamy, P., Yusoff, M.M., Maniam, G.P., & Govindan, N. (2016). Biosynthesis of metallic nanoparticles using plant derivatives and their new avenues in pharmacological applications—An updated report. *Saudi Pharmaceutical Journal*, **24**(4), 473-484. <https://doi.org/10.1016/j.jsps.2014.11.013>
- Laghari, M. H., Mangi, J. U., Gorar, M., Sohu, S., Hayat, A., Zahid, S., & Sidhu, A. R. (2023). Identification and quantification of phenolic compounds by HPLC-DAD and antioxidant activity from Cordia Gharaf Plant. *Journal of Applied Research in Plant Sciences*, **4**(02), 653-661. <https://doi.org/10.38211/joarps.2023.04.02.159>
- Laiba, S., Khushk, I., Khushik, F. A., Jatt, A. N., Chisti, Y., & Qureshi, A. S. (2026). Production of hydrolytic enzymes from crop waste for bioconversion of lignocellulosic biomass to ethanol. *3 Biotech*, **16**(7), 255. <https://doi.org/10.1007/s13205-026-04900-1>
- Mai-Prochnow, A., Clauson, M., Hong, J., & Murphy, A. B. (2016). Gram positive and Gram negative bacteria differ in their sensitivity to cold plasma. *Scientific reports*, **6**(1), 38610. <https://doi.org/10.1038/srep38610>
- Manakas, P., Balafoutis, A. T., Kottaridi, C., & Vlysidis, A. (2025). Sustainability assessment of orange peel waste valorization pathways from juice industries. *Biomass Conversion and Biorefinery*, **15**(5), 6525-6544. <https://doi.org/10.1007/s13399-024-05626-x>
- Maruthupandy, M., Qin, P., Muneeswaran, T., Rajivgandhi, G., Quero, F., & Song, J. M. (2020). Graphene-zinc oxide nanocomposites (G-ZnO NCs): Synthesis, characterization and their photocatalytic degradation of dye molecules. *Materials Science and Engineering: B*, **254**, 114516. <https://doi.org/10.1016/j.mseb.2020.114516>
- Mekuye, B., & Abera, B. (2023). Nanomaterials: An overview of synthesis, classification, characterization, and applications. *Nano select*, **4**(8), 486-501. <https://doi.org/10.1002/nano.202300038>
- Mickky, B., Elsaka, H., Abbas, M., Gebreil, A., & Shams Eldeen, R. (2024). Orange peel-mediated synthesis of silver nanoparticles with antioxidant and antitumor activities. *BMC biotechnology*, **24**(1), 66. <https://doi.org/10.1186/s12896-024-00892-z>
- Mikhailova, E.O. (2020). Silver nanoparticles: Mechanism of action and probable bio-application. *Journal of Functional Biomaterials*, **11**(4), 84. <https://doi.org/10.3390/jfb11040084>
- Monika, P., Chandrababha, M. N., Hari Krishna, R., Vittal, M., Likhitha, C., Pooja, N., ... & C. M. (2024). Recent advances in pomegranate peel extract mediated nanoparticles for clinical and biomedical applications. *Biotechnology and Genetic Engineering Reviews*, **40**(4), 3379-3407. <https://doi.org/10.1080/02648725.2022.2122299>
- Morones, J. R., Elechiguerra, J. L., Camacho, A., Holt, K., Kouri, J. B., Ramirez, J. T., & Yacaman, M. J. (2005). The bactericidal effect of silver nanoparticles. *Nanotechnology*, **16**(10), 2346-2353. <https://doi.org/10.1088/0957-4484/16/10/059>
- Mostafa, S. A., Ahmed, O. S., Mahmoud, W. H., Eldesouky, M., & El-Sherif, A. A. (2026). Green synthesis of silver nanoparticles using red peel waste of Pomegranate and its antibacterial and cytotoxic activities. *Egyptian Journal of Chemistry*, **69**(7), 599-610.
- Mostafa, Y.S., Alamri, S.A., Alrumman, S.A., Hashem, M., & Baka, Z.A. (2021). Green synthesis of silver nanoparticles using pomegranate and orange peel extracts and their antifungal activity against *Alternaria solani*, the causal agent of early blight disease of tomato. *Plants*, **10**(11), 2363. <https://doi.org/10.3390/plants10112363>
- Mu, H., Tang, J., Liu, Q., Sun, C., Wang, T., & Duan, J. (2016). Potent antibacterial nanoparticles against biofilm and intracellular bacteria. *Scientific reports*, **6**(1), 18877. <https://doi.org/10.1038/srep18877>
- Nasr, H. A., Nassar, O. M., El-Sayed, M. H., & Kobisi, A. A. (2019). Characterization and antimicrobial activity of lemon peel mediated green synthesis of silver nanoparticles. *International Journal of biology and chemistry*, **12**(2), 56-63. <https://doi.org/10.26577/ijbch-2019-v2-7>
- Nasr, H. A., Nassar, O. M., El-Sayed, M. H., & Kobisi, A. A. (2019). Characterization and antimicrobial activity of lemon peel mediated green synthesis of silver nanoparticles. *International Journal of Biology & Chemistry*, **12**(2), 56. <https://doi.org/10.26577/ijbch-2019-v2-7>
- Nayana, P., & Wani, K. M. (2024). Unlocking the green potential: sustainable extraction of bioactives from orange peel waste for environmental and health benefits. *Journal of Food Measurement and Characterization*, **18**(10), 8145-8162. <https://doi.org/10.1007/s11694-024-02779-1>
- Niluxsshun, M. C. D., Masilamani, K., & Mathiventhan, U. (2021). Green synthesis of silver nanoparticles from the extracts of fruit peel of Citrus tangerina, Citrus sinensis, and Citrus limon for antibacterial activities. *Bioinorganic chemistry and applications*, **2021**(1), 6695734. <https://doi.org/10.1155/2021/6695734>
- Oliveira, J. R., & Lenzi, G. G. (2023). Advances in the use of green and sustainable synthesis to obtain nanomaterials. In *Green Chemistry for Environmental Sustainability-Prevention-Assurance-Sustainability (PAS) Approach*. IntechOpen. <https://doi.org/10.5772/intechopen.1002866>
- Pacioni, N. L., Borsarelli, C. D., Rey, V., & Veglia, A. V. (2015). Synthetic routes for the preparation of silver nanoparticles: a mechanistic perspective. In *Silver nanoparticle applications: in the fabrication and design of medical and biosensing devices* (pp. 13-46). Cham: Springer International Publishing. [https://doi.org/10.1007/978-3-319-11262-6\\_2](https://doi.org/10.1007/978-3-319-11262-6_2)
- Pawar, S. P., Ahire, M. S., Shewale, V. V., Jadhav, S., Mahajan, K. S., & Sonawane, D. D. (2025). Silver nanoparticles: A comprehensive review on synthesis, properties and applications. *Research Journal of Pharmaceutical Dosage Forms and Technology*, **17**(4), 279-285. <https://doi.org/10.52711/0975-4377.2025.00039>
- Qureshi, A. S., Zhang, J., da Costa Sousa, L., & Bao, J. (2017). Antibacterial peptide secreted by *Pediococcus acidilactici*

- enables efficient cellulosic open L-lactic acid fermentation. *ACS Sustainable Chemistry & Engineering*, **5**(10), 9254-9262. <https://doi.org/10.1021/acssuschemeng.7b02212>
- Rahman, A. U., Khan, A. U., Yuan, Q., Wei, Y., Ahmad, A., Ullah, S. & Ahmad, W. (2019). Tuber extract of *Arisaema flavum* eco-benignly and effectively synthesize silver nanoparticles: Photocatalytic and antibacterial response against multidrug resistant engineered *E. coli* QH4. *Journal of Photochemistry and Photobiology B: Biology*, **193**, 31-38. <https://doi.org/10.1016/j.jphotobiol.2019.01.018>
- Rahu, M. I., Naqvi, S. H. A., Memon, N. H., Idrees, M., Kandhro, F., Pathan, N. L., ... & Bhutto, M. A. (2021). Determination of antimicrobial and phytochemical compounds of *Jatropha curcas* plant. *Saudi journal of biological sciences*, **28**(5), 2867-2876. <https://doi.org/10.1016/j.sjbs.2021.02.019>
- Rani, J., Singh, S., Beniwal, A., Kakkar, S., Moond, M., Sangwan, S., & Kumari, S. (2024). Pomegranate peel mediated silver nanoparticles: antimicrobial action against crop pathogens, antioxidant potential and cytotoxicity assay. *Discover nano*, **19**(1), 160.
- Rodriguez, S., Kaur, K., & Sharma, M. (2025). Extraction methods and bioactive compounds from pomegranate peels: A comprehensive review for sustainable packaging applications. *Food Biomacromolecules*, **2**(1), 42-68.
- Rybka, M., Mazurek, L., & Konop, M. (2022). Beneficial effect of wound dressings containing silver and silver nanoparticles in wound healing—from experimental studies to clinical practice. *Life*, **13**(1), 69.
- Saad, P. G., Castelino, R. D., Ravi, V., Al-Amri, I. S., & Khan, S. A. (2021). Green synthesis of silver nanoparticles using Omani pomegranate peel extract and two polyphenolic natural products: characterization and comparison of their antioxidant, antibacterial, and cytotoxic activities. *Beni-Suef University Journal of Basic and Applied Sciences*, **10**(1), 29.
- Santos, E. D. B., Madalossi, N. V., Sigoli, F. A., & Mazali, I. O. (2015). Silver nanoparticles: green synthesis, self-assembled nanostructures and their application as SERS substrates. *New Journal of Chemistry*, **39**(4), 2839-2846.
- Saratale, R. G., Saratale, G. D., Shin, H. S., Jacob, J. M., Pugazhendhi, A., Bhaisare, M., & 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**(11), 10164-10183.
- Sathiyavimal, S., Vasantharaj, S., Bharathi, D., Saravanan, M., Manikandan, E., Kumar, S. S., & Pugazhendhi, A. (2018). Biogenesis of copper oxide nanoparticles (CuONPs) using *Sida acuta* and their incorporation over cotton fabrics to prevent the pathogenicity of Gram negative and Gram positive bacteria. *Journal of Photochemistry and Photobiology B: Biology*, **188**, 126-134.
- Seerangaraj, V., Sathiyavimal, S., Shankar, S. N., Nandagopal, J. G. T., Balashanmugam, P., Al-Misned, F. A., ... & Pugazhendhi, A. (2021). Cytotoxic effects of silver nanoparticles on *Ruellia tuberosa*: Photocatalytic degradation properties against crystal violet and coomassie brilliant blue. *Journal of Environmental Chemical Engineering*, **9**(2), 105088.
- Shahzadi, S., Fatima, S., Shafiq, Z., & Janjua, M. R. S. A. (2025). A review on green synthesis of silver nanoparticles (SNPs) using plant extracts: a multifaceted approach in photocatalysis, environmental remediation, and biomedicine. *RSC advances*, **15**(5), 3858-3903. <https://doi.org/10.1039/d4ra07519f>
- Shaikh, W. A., Chakraborty, S., & Islam, R. U. (2020). Photocatalytic degradation of rhodamine B under UV irradiation using *Shorea robusta* leaf extract-mediated bio-synthesized silver nanoparticles. *International Journal of Environmental Science and Technology*, **17**(4), 2059-2072. <https://doi.org/10.1007/s13762-019-02473-6>
- Sharma, P., Vishvakarma, R., Gautam, K., Vimal, A., Gaur, V. K., Farooqui, A., . & Younis, K. (2022). Valorization of citrus peel waste for the sustainable production of value-added products. *Bioresource technology*, **351**, 127064. <https://doi.org/10.1016/j.biortech.2022.127064>
- Sharma, R., Lata, S., & Garg, R. (2024). Valorisation of agricultural waste and their role in green synthesis of value-added nanoparticles. *Environmental Technology Reviews*, **13**(1), 40-59.
- Shrinath, V., Gaur, S., Kaur, K., Thakur, P., Mahajan, A., & Makkar, J. S. (2023). Antioxidant properties of orange peel and their implications for health: a comprehensive review. *J Food Chem Nanotechnol*, **9**(S1), S546-S553.
- Siddiqui, S. A., Singh, S., & Nayik, G. A. (2024). Bioactive compounds from pomegranate peels-Biological properties, structure-function relationships, health benefits and food applications—A comprehensive review. *Journal of Functional Foods*, **116**, 106132.
- Slavin, Y.N., Asnis, J., Hafei, U.O., & Bach, H. (2017). Metal nanoparticles: Understanding the mechanisms behind antibacterial activity. *Journal of Nanobiotechnology*, **15**, 65.
- Srividhyaa, K., Ranjani, S., & Hemalatha, S. (2023). Citrus limon phytochemicals decorated nanoparticles control poultry pathogens. *Archives of microbiology*, **205**(4), 124.
- Toppo, S. R. (2024). Nanomaterials' synthesis from the fruit wastes. In *Green and Sustainable Approaches Using Wastes for the Production of Multifunctional Nanomaterials* (pp. 345-364). Elsevier.
- Vanaamudan, A., Soni, H., & Sudhakar, P. P. (2016). Palm shell extract capped silver nanoparticles—as efficient catalysts for degradation of dyes and as SERS substrates. *Journal of Molecular Liquids*, **215**, 787-794.
- Veer, B., Prajapati, S., Singh, A. P., & Yadav, S. (2025). Green Synthesis of Nanoparticles: Sustainable Solutions for Multisectoral Applications. *Recent Advances in Food, Nutrition & Agriculture*.
- Weng, X., Yang, K., Owens, G., & Chen, Z. (2022). Biosynthesis of silver nanoparticles using three different fruit extracts: Characterization, formation mechanism and estrogen removal. *Journal of environmental management*, **316**, 115224.
- Yaqoob, A.A., Umar, K., & Ibrahim, M.N.M. (2020). Silver nanoparticles: Various methods of synthesis, size affecting factors and their potential applications A review. *Applied Nanoscience*, **10**, 1369-1378.
- Zhafira, S., & Sajidah, E. S. (2025). Advances in the Green Synthesis of Plant-Based Nanoparticles and Their Diverse Applications. *Plant Nanomaterial Journal*, **1**(1).

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