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Comparative Analysis of the Optical Properties of Silver Nanoparticles Synthesized Using Tomato and Cabbage Extracts

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ABSTRACT

This study presents the use of tomato (*Solanum lycopersicum*) and cabbage (*Brassica oleracea*) extracts as reducing and capping agents in the synthesis of silver nanoparticles. During synthesis, key parameters including reaction time, extract-to-precursor volume ratio, initial silver nitrate (AgNO_3) concentration, and type of extract were varied. The resulting AgNPs were characterized using UV–Visible (UV–Vis) spectroscopy, Fourier Transform Infrared (FTIR) spectroscopy, and antibacterial assays. The experimental UV–Vis data were correlated with Mie theory simulations to estimate nanoparticle diameter, extinction efficiency, and number of particles per unit volume. In addition, a mathematical relation between surface plasmon resonance (SPR) and the size of the nanoparticle was derived from previous experimental works to estimate the size of the nanoparticle. The results demonstrate that tomato extract is a more effective agent for producing smaller, more monodisperse nanoparticles, producing AgNPs with an average diameter of approximately 48 nm and a sharp SPR peak at 419 nm. In contrast, cabbage extract produced larger, more polydisperse nanoparticles with an average diameter of 62 nm and a broader SPR peak around 434 nm. FTIR analysis confirmed the role of functional groups from the plant extracts in the reduction and stabilization of the nanoparticles. Furthermore, the synthesized AgNPs exhibited significant antibacterial activity against *Escherichia coli*, *Staphylococcus aureus*, and *Pseudomonas aeruginosa*. This work underscores that the choice of plant extract and the precise control of synthesis conditions are critical for tailoring the size, stability, and functional properties of AgNPs for targeted applications in areas such as biomedicine and water purification.

1 | Introduction

Silver nanoparticles (AgNPs) exhibit size- and shape-dependent optical, chemical, and biological properties that are critical for applications in biomedicine, environmental remediation, and optoelectronics [1, 2]. For AgNPs, precise control over particle size and dispersity is essential, as small variations strongly influence plasmonic response and antibacterial efficacy [3]. Such control is commonly achieved by tuning synthesis conditions,

including precursor concentration, reaction time, and the nature of reducing and capping agents [4].

Green synthesis using plant extracts offers a sustainable and cost-effective route for AgNP production, making it attractive for large-scale and industrial implementation. Plant extracts act simultaneously as reducing and stabilizing agents; however, their phytochemical compositions vary widely, leading to substantial differences in nanoparticle yield, size uniformity, and stability.

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Despite numerous reports on plant-mediated synthesis, systematic comparisons of different plant extracts with respect to nanoparticle yield and quality remain limited. Moreover, most studies rely heavily on electron microscopy for characterization, which restricts scalability due to its high cost and limited accessibility [5–7].

Nanoparticle size plays a decisive role in functional performance [8, 9]. Smaller AgNPs exhibit enhanced antibacterial activity due to increased surface area and improved cellular penetration, while the extract-derived surface chemistry further modulates biological response applications [10–12]. These observations highlight the need for synthesis strategies that simultaneously optimize extract selection, particle uniformity, and yield, using characterization methods compatible with routine process monitoring.

In this study, we systematically compare different plant extracts to identify those that produce high-yield, uniform AgNPs while avoiding electron microscopy-based characterization. Instead, UV–Vis spectroscopy combined with Mie theory is employed to analyze localized surface plasmon resonance (LSPR) behavior and infer nanoparticle size, concentration, and morphology. The LSPR peak position, bandwidth, and absorbance are extracted via spectral fitting and used in Mie theory-based extinction simulations to solve the inverse size-estimation problem.

By integrating plant-extract comparison with cost-effective optical characterization, this work establishes a scalable framework for optimizing green AgNP synthesis, advancing its feasibility for industrial and applied applications.

2 | Materials and Methods

2.1 | Synthesis of Nanoparticles

All chemicals were of analytical grade. Silver nitrate (AgNO_3) and ethanol were obtained from Sigma-Aldrich, India. Plant extracts were prepared by adding 20 g of finely chopped fresh tomato or cabbage to 100 mL of deionized water. The mixtures were heated at 60°C for 15 min, allowed to cool to room temperature, and filtered first through a muslin cloth and then through Whatman No. 1 filter paper. Figure s1 illustrates the preparation steps of the tomato and cabbage extracts, while Table s1 presents the phytochemical analysis of these extracts, confirming the presence of key phytochemicals responsible for the reduction and stabilization of the synthesized nanoparticles.

The synthesis of the AgNPs began by creating a precursor solution of 0.509 g of AgNO_3 in 500 mL of deionized water. The plant extract was then introduced to the AgNO_3 solution with continuous magnetic stirring. To determine the optimal synthesis conditions, key parameters were varied, including reaction time, the volume ratio of the plant extract to the AgNO_3 solution, and the initial AgNO_3 concentration. In addition, the two types of extracts were directly compared. The detailed parameters employed during AgNP synthesis are presented in the Supporting Information (Table s2 for cabbage extract and Table s3 for tomato extract).

2.2 | Characterization of the Nanoparticles

2.2.1 | UV–Vis Spectroscopy

A double-beam Lambda 35 UV–visible spectrophotometer (PerkinElmer, photograph shown in Figure s3) was employed to

characterize the AgNPs. The UV–Vis spectra were then analyzed by fitting with a combined Lorentzian–Gaussian model commonly referred to as a Voigt profile (equation (1)). Data analysis and visualization were performed using Python-based packages, including Matplotlib for plotting and SciPy Optimize for curve fitting and parameter optimization.

The Lorentzian–Gaussian curve was preferred for fitting the surface plasmon resonance (SPR) band because it accounts for the two primary broadening mechanisms: homogeneous broadening, caused by damping processes such as electron–electron and electron–phonon scattering and best described by the Lorentzian component; and inhomogeneous broadening, arising from statistical disorder—primarily nanoparticle size polydispersity—which is effectively captured by the Gaussian component. Fitting the extinction spectra with this model allows accurate extraction of three key parameters: SPR peak wavelength (λ_{max}), which reflects average nanoparticle size; FWHM, which provides a measure of size distribution; and peak absorbance, which correlates with nanoparticle concentration. Furthermore, the overall spectral profile offers additional insights into nanoparticle morphology [13, 14].

$$A(\lambda) = A_0 \left[(1 - \mu) \exp\left(-\frac{(\lambda - \lambda_0)^2}{2\sigma^2}\right) + \mu \left(\frac{(\eta/2)^2}{(\lambda - \lambda_0)^2 + (\eta/2)^2} \right) \right], \quad (1)$$

where $A(\lambda)$ is the absorbance at wavelength λ , A_0 is the absorbance at λ_0 , λ_0 is SPR, σ is the standard deviation of the Gaussian component (related to FWHM), Γ is the FWHM of the Lorentzian component, and η is the mixing parameter ($0 \leq \eta \leq 1$), where $\eta = 0$ is pure Gaussian and $\eta = 1$ is pure Lorentzian.

After determining the SPR peak and FWHM values, nanoparticle size was estimated from the Mie theory-based extinction simulations (σ_{ext} , equation (2) [15], which constitutes the material's dielectric function and the refractive index of the surrounding medium. The simulation was implemented in Python, an open-source software.

$$\sigma_{\text{ext}} = \frac{3\pi N V \epsilon_m^{3/2}}{\lambda a^3} \sum_{l=1}^{\infty} (2n+1) \text{Re}(A_n + B_n), \quad (2)$$

where V is the volume of each nanoparticle, ϵ_m is the dielectric constant of the surrounding medium, N is the electron density, λ is the wavelength of light in vacuum, d is the diameter of the nanoparticle, $a = \pi d \epsilon_m^{1/2} / \lambda$, n is an integer, A_n and B_n are the coefficients describing the contribution of the n th electric and magnetic partial oscillations of the electromagnetic field within the particle, respectively. These are given by Equations (3) and (4).

$$A_n = \frac{\epsilon j_n(b) [a j_n'(a)]' - \epsilon_a j_n(a) [b j_n'(b)]'}{\epsilon j_n(b) [a h_n^1(a)]' - \epsilon_a h_n^1(a) [b j_n(b)]'}, \quad (3)$$

$$B_n = \frac{j_n(b) [a j_n'(a)]' - j_n(a) [b j_n'(b)]'}{j_n(b) [a h_n^1(a)]' - h_n^1(a) [b j_n(b)]'}, \quad (4)$$

where $b = (2\pi R \epsilon^{1/2}) / \lambda$, ϵ is the complex dielectric constant of the metal ($\epsilon^{1/2} = n + ik$), $j_L(z)$ is the spherical Bessel function of the first kind, $h_L^1(a) = j_L(z) + iy_L(z)$, and $iy_L(z)$ is the spherical Bessel function of the second kind.

In the process of Mie extinction simulation, using Equation (2), the dielectric function of silver was modeled using the Drude approach, as it was validated by Campos et al. and Scholl et al. to provide reliable accuracy for particle diameters exceeding 10 nm [16, 17], and the refractive index of the surrounding medium was set to 1.4 to account for capping agents [18].

The relationship between extinction efficiency (Q_{ext}) and extinction cross section (σ_{ext}) was then used to determine the number of nanoparticles in solution following Haiss et al. (5) and (6) [15].

$$Q_{\text{ext}} = \frac{\sigma_{\text{ext}}}{\pi(d/2)^2}, \quad (5)$$

$$Q_{\text{ext}} = \frac{2.303A}{\pi(d/2)^2 L},$$

$$N = \frac{2.303A}{\pi(d/2)^2 Q_{\text{ext}} L}, \quad (6)$$

$$N = \frac{2.303A}{\sigma_{\text{ext}} L}.$$

Similarly, Hlaing et al. established the relation between measured absorbance and the extinction cross section, providing an alternative calculation for nanoparticle number (equations (7) and (8) [19]).

$$\sigma_{\text{ext}} = \frac{A \ln(10)}{NL}, \quad (7)$$

$$N = \frac{2.303A}{\sigma_{\text{ext}} L}. \quad (8)$$

In green-synthesized AgNPs, a broad particle-size distribution results in an extinction spectrum that is effectively a superposition of multiple plasmon resonance peaks corresponding to different particle sizes [20]. This overlap causes spectral broadening and peak shifts, making it challenging to accurately fit the data using a single theoretical Mie curve, as Mie theory assumes a population of monodisperse, perfectly spherical nanoparticles with uniform optical properties. Deviations from these assumptions can therefore lead to discrepancies between theoretical predictions and experimental observations. To enhance accuracy, particle sizes estimated from Mie theory were cross-validated using empirical relationships between nanoparticle size and UV-Vis resonance wavelength derived from TEM-based measurements reported in the literature (Equations (9)–(13) [21–25]). A detailed explanation of Equations (9)–(13) is provided in the Supporting Information, Section 2.2.

$$\lambda = 391.8 + 0.1737(d) + 0.008175(d)^2, \quad (9)$$

$$d = 0.78\lambda - 266, \quad (10)$$

$$\lambda = a + b(d)^2 \left(a = 397; b = 9.58 \times 10^{-3} \right), \quad (11)$$

$$\lambda = 0.11(d)^2 - 89.88(d) + 17.775, \quad (12)$$

$$d = 0.0048 \frac{\lambda^2}{\Delta\lambda}. \quad (13)$$

Here, d denotes the diameter of the AgNPs, L is the path length (1 cm), and λ and $\Delta\lambda$ represent the SPR peak position and the FWHM obtained from the UV-Vis spectrum, respectively.

2.3 | Fourier Transform Infrared (FTIR) Spectrophotometer Analysis of AgNPs

The surface functional groups of the synthesized AgNPs were identified using a Perkin Elmer FTIR spectrophotometer. The AgNP solutions were freeze-dried to obtain a powder [26]. FTIR spectra of both the raw plant extract and the AgNP powder were recorded in the range of 4000–500 cm^{-1} to identify the biomolecules involved in the reduction and stabilization processes.

2.4 | Antibacterial Test of the AgNPs

2.4.1 | Determination of Inhibition Zone Diameter

The antimicrobial activity of the AgNPs was assessed against pathogenic bacterial strains (*Escherichia coli*, *Staphylococcus aureus*, *Pseudomonas aeruginosa*, and *Proteus vulgaris*) using the Kirby–Bauer disc diffusion method. In the Supporting Information, Section 1.4 details the materials and bacterial strains used for testing the AgNPs. Bacterial cultures were grown in nutrient broth for 24 h and standardized to a turbidity equivalent to the 0.5 McFarland standard. Figure s2 shows (a) the four bacterial suspensions in 0.85% saline solution and (b) the McFarland standard solution. Sterile paper discs were impregnated with the AgNP solution, placed on inoculated Mueller–Hinton agar plates, and incubated at 37°C for 24 h. Deionized water and ciprofloxacin were used as negative and positive controls, respectively. The diameter of the inhibition zones was measured in millimeters.

2.4.2 | Determination of Minimum Inhibitory Concentration (MIC)

The MIC of AgNPs was determined using a broth microdilution method combined with UV-Vis transmission spectroscopy. Twofold serial dilutions of AgNPs (2–256 $\mu\text{g/mL}$) were prepared in Mueller–Hinton broth and inoculated with 5×10^5 CFU/mL of test bacteria. After incubation at 37°C for 24 h, bacterial growth was assessed by measuring optical transmission at 600 nm. Background absorbance from AgNPs was corrected using nanoparticle-containing sterility controls. The MIC was defined as the lowest AgNP concentration showing no increase in absorbance relative to the sterility control. All experiments were performed in triplicate.

3 | Results and Discussion

3.1 | Effect of Reaction Time on the Properties of AgNPs

Figure 1 presents the UV-Vis absorption spectra of AgNPs synthesized with cabbage extract at different reaction times, while Figure s5 shows a representative scanning electron microscope (SEM) image of AgNPs produced using the same extract. Nanoparticle size was determined using a combination of ImageJ and a custom Python script, yielding an average diameter of 67 nm. Full details of the size analysis procedure are provided in Supporting Information Section s6 (Scanning Electron Microscopy Analysis of AgNPs). The SEM images reveal that the synthesized AgNPs exhibit slight shape irregularities and are predominantly quasi-spherical rather than perfectly spherical. Additionally, partial nanoparticle aggregation is observed. These features may affect some properties of AgNPs, particularly in

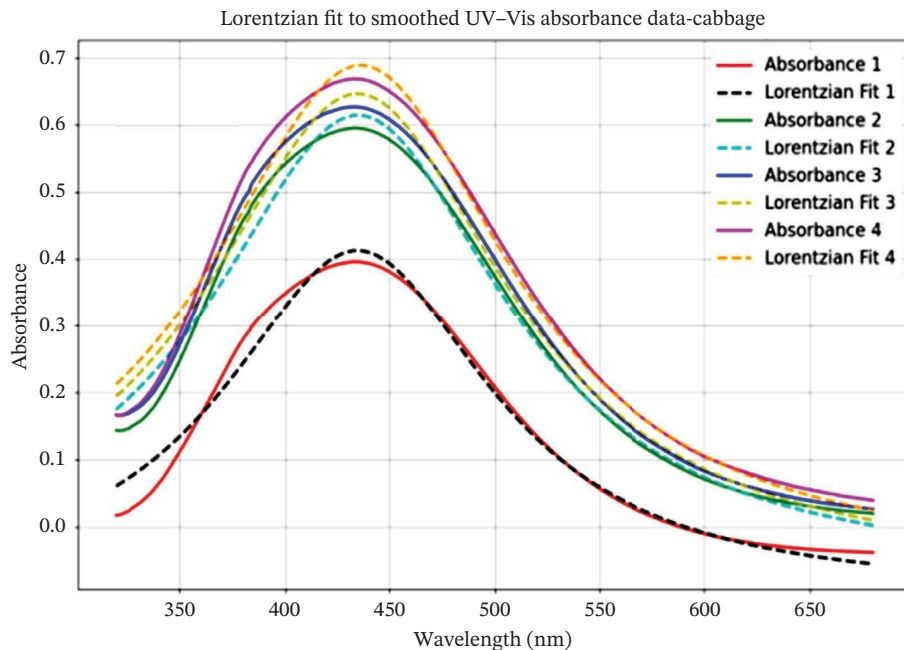


FIGURE 1 | UV-Vis spectra of AgNPs synthesized at different reaction times using cabbage extract at a concentration of 0.2%, fitted with a Gaussian-Lorentzian function.

relation to size estimation and concentration calculations using Mie theory, which assumes ideal spherical particles. The spectra (Figure 1) were fitted with a Lorentzian-Gaussian function to extract the LSPR peak position, FWHM, and absorbance, with the results summarized in Table 1. A gradual increase in absorbance accompanied by an almost constant SPR peak ($\lambda_{\text{max}} \approx 433\text{--}434\text{ nm}$) over time indicates continuous nucleation with limited particle growth or aggregation. Furthermore, the observed broadening of the FWHM from 137 to 165 nm reflects an increase in particle size dispersion as the reaction progressed, consistent with sustained nucleation activity.

Mie extinction simulations (equation (2)) were carried out by varying the particle size until the simulated SPR peak aligned with the experimental UV-Vis spectrum (Figure 1). Figure s4 is a screenshot of the Mie extinction simulation interface showing the input parameters entered in the designated fields. Figure 2 presents the corresponding Mie scattering simulations for AgNPs, showing SPR peaks that align closely with the experimental spectra displayed in Figure 1. While the simulated spectrum shows a secondary peak at shorter wavelengths, this feature is absent in the experimental data. The discrepancy can be explained by two main factors. First, organic biomolecules from the plant extracts introduce additional UV absorption, which damps spectral features [27]. Second, Mie theory assumes

an ideal, monodisperse nanoparticle solution, whereas the experimental samples exhibit size polydispersity, as reflected by the FWHM values. This polydispersity broadens and smooths sharp spectral features, causing minor peaks such as the secondary maximum to become indistinguishable in the experimental spectrum [28].

The particle size that produced an SPR peak matching the experimentally determined value was taken as the average size of the AgNPs. This value was then compared with particle sizes calculated using Equations (9)–(13), which relate the SPR peak wavelength from the UV-Vis spectra to nanoparticle diameter. Among these, (equations (9) and (11)) showed the closest agreement with the Mie extinction-derived sizes. The nanoparticle number density in solution was subsequently calculated using (6), and the results are summarized in Table 2.

As shown in the table, the average nanoparticle diameter remained nearly constant at 61–62 nm, while the nanoparticle number density increased from 2.1×10^{15} to 3.6×10^{15} particles/cm³ with increasing reaction time. This trend indicates the progressive formation of additional nanoparticles without significant coarsening, consistent with observations by Ahmad et al., who reported stable SPR features for gold nanoparticles with increasing reaction time [29].

The increase in particle population, rather than growth of existing particles, can be attributed to the dual role of plant extracts as reducing and capping agents. Bioactive compounds such as flavonoids, polyphenols, terpenoids, and saponins continuously reduce Ag^+ ions to Ag^0 , sustaining nucleation throughout the reaction. Simultaneously, these molecules adsorb onto nanoparticle surfaces, preventing aggregation and suppressing Ostwald ripening. Consequently, the system favors the formation of new nanoparticles, leading to an increased population while maintaining a nearly constant average size [30, 31].

TABLE 1 | Parameters derived from the fitting of the UV-Vis spectra of AgNPs (Figure 1).

Reaction hrs	Resonance, λ (nm)	FWHM (nm)	Absorbance
2	433.0	136.9	0.3962
18	434.0	159.0	0.5956
24	434.0	161.8	0.6270
48	433.0	165.0	0.6687

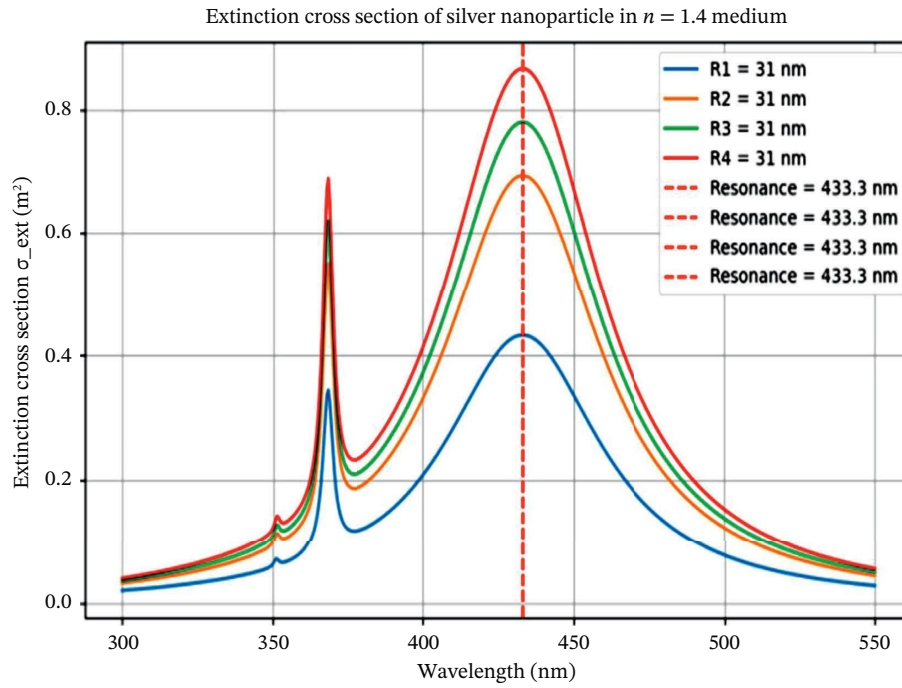


FIGURE 2 | Mie scattering simulation of AgNPs, showing SPR peaks corresponding to the experimental spectra presented in Figure 1.

TABLE 2 | Summary of the estimated particle diameters and nanoparticle number densities at each reaction time, calculated using the parameters in Table 1 and equation (6), for AgNPs synthesized with 0.2% cabbage extract.

Cabbage extract 5 mL/25 mL (analyzed range, λ : 330–530 nm), $n_{\text{medium}} = 1.4$				
Reaction hrs	Resonance, λ (nm)	Size (equations 9 and 11) (nm)	Size (simulation) (nm)	N (equation (2)) particles (m^3)
2	433.0	61.16 ± 2.5	62 ± 2	$(2.105 \pm 0.003)e + 15$
18	434.0	62 ± 2.3	62 ± 3	$(3.164 \pm 0.005)e + 15$
24	434.0	62 ± 2.2	62 ± 2.8	$(3.331 \pm 0.004)e + 15$
48	433.0	61.16 ± 2	62 ± 2.3	$(3.553 \pm 0.008)e + 15$

For comparison, AgNPs synthesized with tomato extract at various reaction times were analyzed under the same conditions, and the UV–Vis spectra are shown in Figure 3. Fitting the spectra

with the line-shape model provided the SPR peak positions and FWHM values (Table 3), which were subsequently used in Mie simulations (equation (2)) to generate the spectra in Figure 4 and

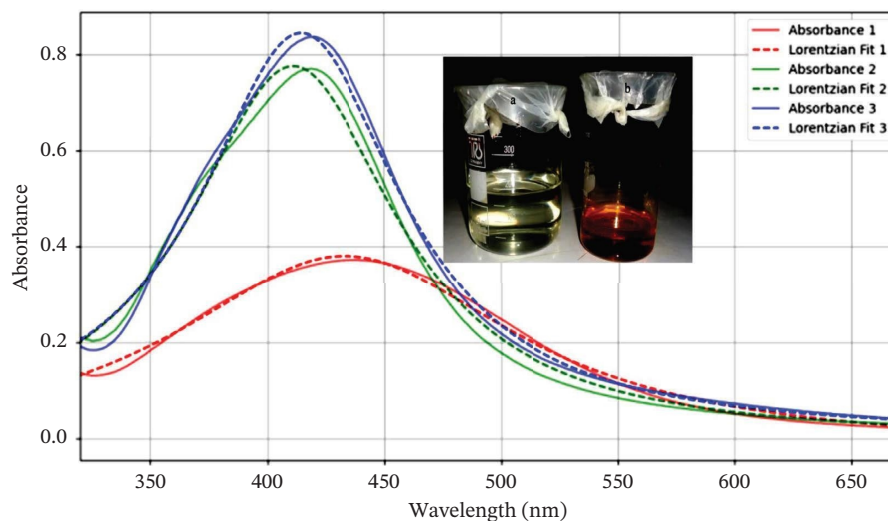


FIGURE 3 | UV–Vis spectra of AgNPs synthesized at varying reaction times using tomato extract. The inset shows the corresponding color changes associated with AgNP formation.

TABLE 3 | Parameters obtained from the Gaussian–Lorentzian fit of the UV–Vis spectra in Figure 3.

Tomato extract, 4 mL/24 mL, (analyzed range of λ : 330–530 nm), $n_{\text{medium}} = 1.4$			
Reaction time (hr)	SPR peak (nm)	FWHM (nm)	Absorbance
4	436.1	169.7	0.3713
12	419.98	110.3	0.7702
24	419.36	108.4	0.8361

to estimate nanoparticle sizes and number densities (Table 4). Unlike the relatively stable spectral features observed with cabbage extract, the tomato-mediated system exhibited pronounced dynamic changes. Within the first 12 h, λ_{max} shifted from 436 nm to 419 nm, indicating preferential formation of smaller nanoparticles. This observation is consistent with Darroudi et al., who reported a modest blue shift in the SPR peak of gold nanoparticles due to continued nucleation with limited particle growth [32]. Concurrently, the FWHM decreased from 170 to 108 nm, reflecting rapid nucleation followed by particle size refinement. As a result, the average nanoparticle diameter decreased from 64 to 49 nm, and by 24 h, the nanoparticle number density exceeded 4.8×10^{15} particles/cm³, demonstrating the higher efficiency of tomato extract in producing smaller, more monodisperse AgNPs compared to cabbage extract.

The pronounced blue shift of the SPR peak reflects the preferential formation of small nanoparticles at early stages. Tomato extract is rich in reducing phytochemicals such as flavonoids, polyphenols, terpenoids, and ascorbic acid [33], which accelerate the reduction of Ag⁺ ions, promoting a burst of nucleation events and generating a larger fraction of small nanoparticles. At the same time, the capping efficiency of tomato-derived biomolecules is comparatively weaker and less selective [34], resulting in more dynamic particle distributions and spectral shifts. Consequently, tomato extract favors rapid, ongoing nucleation and formation of smaller nanoparticles, in contrast to the controlled and stable growth observed in the cabbage-mediated system.

3.2 | Effect of Extract/AgNO₃ Volume Ratio on the Properties of AgNPs

The effect of the extract-to-AgNO₃ ratio on AgNP synthesis was investigated by varying the cabbage extract/AgNO₃ ratio from 0.05 to 0.2 while keeping the AgNO₃ concentration constant at 1 mM and the reaction time fixed at 24 h. The corresponding UV–Vis spectra are shown in Figure 5, with fitted SPR peak positions and FWHM values summarized in Table 5. As in the reaction time study, Mie extinction simulations were conducted using the LSPR peak values from the UV–Vis spectra to estimate particle diameter and number density for each ratio. Table 6 presents the particle diameters and nanoparticle number densities derived from the Mie extinction simulations for each extract-to-AgNO₃

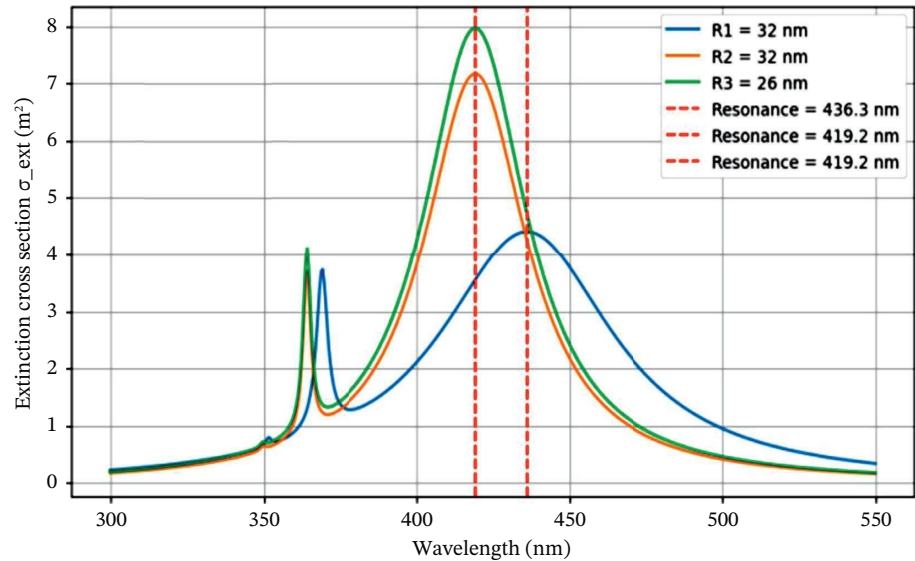


FIGURE 4 | Simulated absorption spectra of AgNPs calculated from the Mie equation (Equation (2)), in correspondence with the experimental results shown in Figure 3.

TABLE 4 | Summary of the estimated particle diameter and concentration of AgNPs from Figure 4 for each reaction time.

Tomato extract, 4 mL/24 mL, (analyzed range of λ : 330–530 nm), $n_{\text{medium}} = 1.4$				
Reaction time (hrs)	SPR peak	Size (equations 9 and 11) (nm)		N (equation (2)) particles (m ³)
		Size (simulation) (nm)		
4	436.1	63.7 ± 1.2	64 ± 3	(1.94 ± 0.006)E + 15
12	419.98	49 ± 1	52.4 ± 2.8	(4.45 ± 0.003)E + 15
24	419.36	49 ± 1	52.4 ± 2.8	(4.83 ± 0.002)E + 15

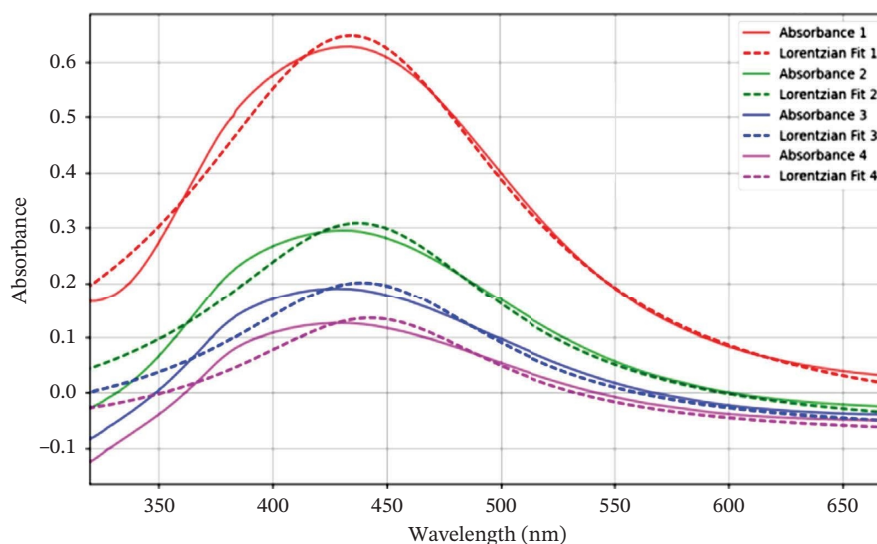


FIGURE 5 | UV-Vis spectra of AgNPs, along with the Gaussian-Lorentzian fits, synthesized at different cabbage extract-to-AgNO₃ volume ratios after a reaction time of 24 h.

TABLE 5 | Parameters obtained from the Gaussian-Lorentzian fit of the UV-Vis spectra (Figure 5) for AgNPs synthesized using different cabbage extract-to-silver nitrate ratios.

Cabbage extract, reaction time 24 h (analyzed range, λ : 330–530 nm), $n_{\text{medium}} = 1.4$			
Extract/ AgNO ₃	SPR, λ (nm)	FWHM (nm)	Absorbance
0.05	427	115.3	0.1262
0.067	427	128.9	0.1891
0.1	432	140.9	0.2945
0.2	434	161.8	0.627

volume ratio. The sizes derived from these simulations were further validated using empirical relationships (equations (9) and (11)) showing good agreement with the Mie-derived values. Increasing the cabbage extract/AgNO₃ ratio from 0.05 to 0.2 caused a red shift in the SPR peak from 427 nm to 434 nm primarily due to an increase in the average nanoparticle size. At higher extract concentrations, the abundance of reducing phytochemicals—such as flavonoids, polyphenols, and terpenoids—accelerates the reduction of Ag⁺ ions, resulting in rapid nucleation and a higher nanoparticle number density (N). However, excessive biomolecules can decrease the selectivity of surface

capping, allowing some nuclei to undergo further growth or aggregation, which increases the mean particle size and shifts the SPR peak to longer wavelengths.

This red shift was accompanied by FWHM broadening (from 115 nm to 162 nm) and a significant increase in absorbance (from 0.126 to 0.627) with a rising extract/AgNO₃ ratio, reflecting greater size polydispersity and higher nanoparticle concentration. The FWHM broadening indicates a wider particle-size distribution arising from the coexistence of small and large nanoparticles when capping efficiency is reduced at high extract concentrations. The marked increase in absorbance confirms a higher nanoparticle number density, as more Ag⁺ ions are efficiently reduced to Ag⁰. Consistently, the calculated number density (N) increased from 8.17×10^{14} particles/cm³ to 3.30×10^{15} particles/cm³ [35, 36].

To enable direct comparison, a parallel experiment was performed using tomato extract as the reducing agent. Figure 6 shows the UV-Vis spectra of AgNPs synthesized at different tomato extract-to-AgNO₃ ratios while keeping the AgNO₃ concentration constant at 1 mM and the reaction time fixed at 24 h. Spectral fitting yielded the SPR peak positions, FWHM values, and absorbance for each ratio, summarized in Table 7. These parameters were used in Mie scattering simulations to estimate nanoparticle diameters, which were further validated using empirical relations (equations (9) and (11)). The derived

TABLE 6 | Influence of the cabbage extract-to-AgNO₃ volume ratio on the particle diameter and nanoparticle number density of AgNPs, as obtained from Mie extinction simulations.

Cabbage extract, reaction time 24 h (analyzed range, λ : 330–530 nm), $n_{\text{medium}} = 1.4$			
Extract/AgNO ₃	Size (equations 9 and 11) (nm)	Size (simulation) (nm)	Particles (m ³)
0.167	59.43308 ± 2	60.6 ± 3.2	$(8.17 \pm 0.006)E + 14$
0.2	63.67012 ± 3	64 ± 3.6	$(8.17 \pm 0.006)E + 14$
0.33	48.02837 ± 2.1	52 ± 2.5	$(3.30 \pm 0.005)E + 15$
0.5	48.02837	52	1.84E + 15

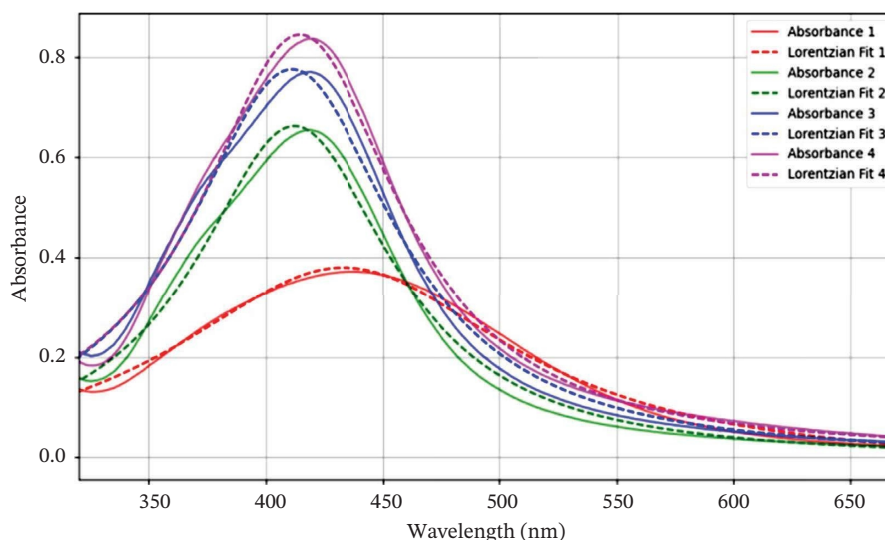


FIGURE 6 | UV-Vis spectra of AgNPs synthesized at different tomato extract-to-AgNO₃ volume ratios, with a fixed reaction time of 24 h.

TABLE 7 | Summary of the effect of the tomato extract-to-AgNO₃ volume ratio on the SPR peak position, FWHM, and absorbance of AgNPs synthesized after a 24-h reaction period.

Tomato extract, reaction time 24 h (analyzed range, λ : 330–530 nm), $n_{\text{medium}} = 1.4$			
Tomato extract/AgNO ₃	SPR, λ (nm)	FWHM (nm)	Absorbance
0.167	431	156.4	0.1072
0.2	436	169.7	0.3713
0.33	419	106.2	0.6544
0.5	419	108.4	0.8361

diameters and absorbance were then used to calculate N , as presented in Table 8. The spectral evolution of tomato-extract-mediated AgNPs followed a trend similar to that observed with cabbage extract.

Increasing the tomato extract/AgNO₃ ratio from 0.167 to 0.5 induced a red shift in the SPR from 419 nm to 431–436 nm, along with FWHM broadening—indicating the formation of larger and more polydisperse nanoparticles. This observation aligns with the findings of Wondmnew et al., who reported that increasing orange peel extract concentration led to larger zinc oxide nanoparticles [37]. The underlying mechanism involves the greater availability of electron-donating biomolecules at higher extract concentrations, which enhances the reduction rate of metal ions and accelerates nucleation and growth,

ultimately yielding larger nanoparticles and a red-shifted SPR band.

However, when the extract ratio increased further, from 0.33 to 0.50, the SPR peak stabilized around 419 nm, corresponding to a narrower size distribution (FWHM $\approx$ 107 nm) and an average particle diameter of approximately 51 nm. This behavior—where lower extract-to-metal ratios produce a red shift and higher ratios lead to stabilization or even a slight blue shift—agrees well with the findings of Chou et al. and Anandalakshmi et al., who reported a slight blue shift in SPR with increasing extract concentration [38, 39]. This phenomenon, where the SPR peak remains unchanged or shifts slightly blue beyond a certain extract concentration, can be attributed to the interplay between metal ion availability and reducing agent concentration.

TABLE 8 | Summary of the effect of the tomato extract-to-AgNO₃ volume ratio on the size and concentration of AgNPs synthesized after a 24-h reaction period.

Tomato extract, reaction time 24 h (analyzed range, λ : 330–530 nm), $n_{\text{medium}} = 1.4$			
Extract/AgNO ₃	Size (equations 9 and 11) (nm)	Size (simulation) (nm)	Particles (m ³)
0.167	59.4 $\pm$ 1.1	60.6 $\pm$ 3	(8.17 $\pm$ 0.002)E + 14
0.2	63.67 $\pm$ 2.1	64 $\pm$ 3.2	(8.17 $\pm$ 0.002)E + 14
0.33	48.02 $\pm$ 1.2	52 $\pm$ 2.6	(3.30 $\pm$ 0.0025)E + 15
0.5	48.02 $\pm$ 1.2	52 $\pm$ 2.5	(1.84 $\pm$ 0.0012)E + 15

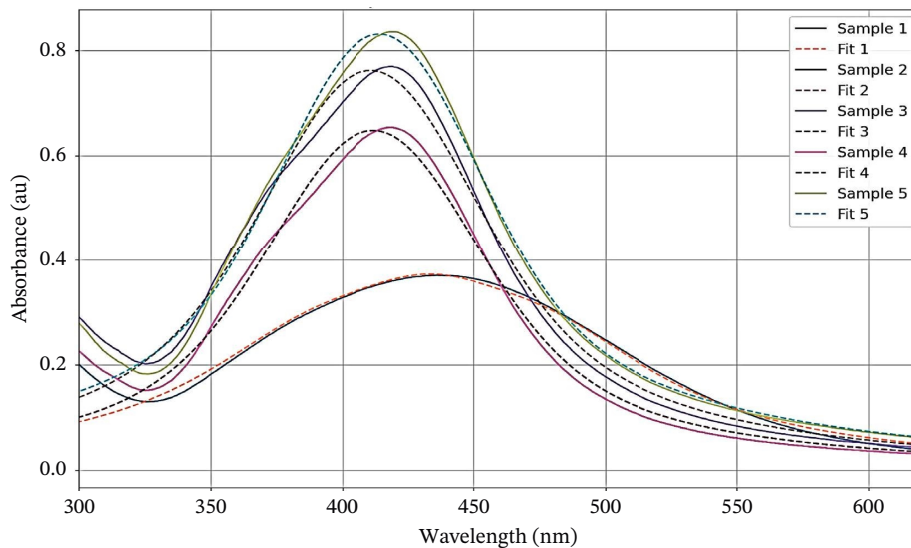


FIGURE 7 | UV-Vis spectra of AgNPs synthesized using varying AgNO_3 concentrations ranging from 1 to 6 mM, while maintaining a fixed tomato extract concentration.

Specifically, increasing the reducing agent affects the nanoparticle formation rate only if sufficient metal ions are present; if metal ions are limited, further increases in extract concentration do not significantly alter particle growth or SPR characteristics.

Collectively, these findings emphasize the critical role of phytochemical concentration in governing nucleation, growth, and colloidal stability during the green synthesis of AgNPs.

3.3 | Effect of AgNO_3 Concentration on the Properties of the AgNPs

The influence of silver precursor concentration on the optical properties of AgNPs was examined by varying the AgNO_3 concentration from 1 to 4 mM while keeping the amount of tomato extract constant. The corresponding UV-Vis absorption spectra are presented in Figure 7. Spectral analysis provided the SPR peak positions and FWHM values, summarized in Table 9, while the calculated particle sizes and number densities are listed in

Table 10. Increasing the AgNO_3 concentration resulted in a distinct blue shift of the SPR maximum (λ_{max}) from 436 to 419 nm, accompanied by a reduction in both FWHM and average particle diameter from 64 nm to 48 nm. Simultaneously, the nanoparticle number density increased markedly, suggesting enhanced nucleation efficiency at higher silver-ion concentrations, provided that sufficient phytochemical capping agents were available. The observed narrowing of the FWHM further indicates improved monodispersity, likely resulting from rapid nucleation kinetics that outpaced subsequent growth or aggregation. Interestingly, this behavior contrasts with the findings of Bamsaoud et al. and Sobczak-Kupiec et al., who observed no significant SPR shift with increasing metal precursor concentration [40, 41]. The discrepancy likely arises from the considerably lower extract concentrations used in their studies compared to the present work. Indeed, previous research has shown that the influence of metal salt concentration on nanoparticle size and optical properties is strongly modulated by

TABLE 9 | Effect of AgNO_3 concentration on the SPR, FWHM, and area of the absorption band of the AgNPs synthesized using a fixed concentration of tomato extract.

Tomato extract, 4 mL/8 mL, reaction time 24 h, $n_{\text{medium}} = 1.4$			
AgNO_3 con (mM)	Resonance, λ (nm)	FWHM (nm)	Absorbance
1	436.0	169.7	0.3713
2	419.0	106.2	0.6544
4	419.0	110.3	0.7702

TABLE 10 | Effect of AgNO_3 concentration on the size and concentration of AgNPs synthesized using a fixed concentration of tomato extract.

Tomato extract, 4 mL/8 mL, reaction time 24 h (analyzed range, λ : 330–530 nm), $n_{\text{medium}} = 1.4$			
Size (equations 9 and 11)			
AgNO_3 con. (mM)	(nm)	Size (simulation) (nm)	N (equation (2)) particles (m^3)
1	63.67 ± 4	64 ± 4.2	$(1.940 \pm 0.002)\text{e} + 15$
2	48.03 ± 3	52.6 ± 3.2	$(3.776 \pm 0.003)\text{e} + 15$
4	48.03 ± 3	52.6 ± 3.1	$(4.444 \pm 0.005)\text{e} + 15$

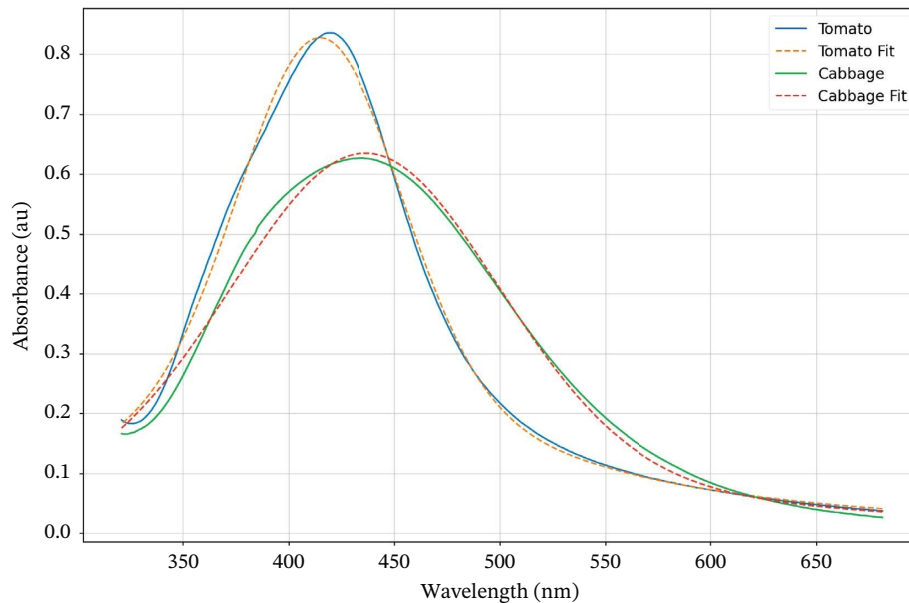


FIGURE 8 | UV-Vis spectra of AgNPs synthesized using 0.1 concentration of cabbage and tomato extracts after 24 h of reaction time.

extract concentration—higher phytochemical content promotes rapid nucleation while limiting particle growth, thus shifting the resonance peak toward shorter wavelengths [37]. Overall, these results highlight the critical interplay between precursor concentrations and extract availability in governing nanoparticle nucleation, growth dynamics, and optical behavior.

3.4 | Effect of Extract Type on the Properties of AgNPs

A direct comparison of cabbage and tomato extracts under identical reaction conditions (24 h reaction time and extract ratio of 0.10) revealed notable differences in the optical and physical characteristics of the synthesized nanoparticles. The corresponding UV-Vis absorption spectra are shown in Figure 8, and the extracted parameters—including SPR peak position, FWHM, particle diameter, and particle number density (N)—are summarized in Tables 11 and 12. AgNPs produced using tomato extract displayed a sharper and more intense SPR band centered at 419 nm, with a substantially narrower FWHM of 108 nm, compared to 435 nm and 162 nm for nanoparticles synthesized

with cabbage extract. The corresponding particle diameters were 48 nm and 63 nm, respectively, while the particle number densities were 4.8×10^{15} and 3.3×10^{15} . These results indicate that tomato extract facilitates the formation of smaller, more monodisperse nanoparticles with higher particle concentrations.

The enhanced reducing and capping performance of tomato extract can be attributed to its higher levels of polyphenols, organic acids, and other phytochemicals, which accelerate nucleation and stabilize nanoparticles against secondary growth and aggregation. In contrast, cabbage extract, with its comparatively lower phytochemical concentration, yields larger and less uniform particles [36, 42, 43].

Overall, these findings highlight the decisive influence of extract composition on the nucleation-growth balance and, consequently, on the optical behavior of AgNPs. While both extracts contain compounds capable of reducing Ag^+ ions, the molecular structure and abundance of stabilizing agents in tomato extract make it more effective at preventing aggregation, leading to a more uniform colloidal dispersion. On a fresh-weight basis, a tomato contains approximately 26 mg flavonoids/100 g,

TABLE 11 | Summary of the effect of extract type on the SPR, FWHM, and absorbance of the spectra of AgNPs.

Tomato extract, 4 mL/24 mL, cabbage 5 mL/25 mL, reaction time 24 h, $n_{\text{medium}} = 1.4$			
Plat type	Resonance, λ (nm)	FWHM (nm)	Absorbance
Tomato	419.0	108.4	0.8361
Cabbage	435.0	161.9	0.6270

TABLE 12 | Summary of the effect of extract type on the size and concentration of AgNPs.

Tomato extract, 4 mL/24 mL, cabbage 5 mL/25 mL, reaction time 24 h, $n_{\text{medium}} = 1.4$			
Plant type	Size (equations 9 and 11) (nm)	Size (simulation) (nm)	N , particles (m^3)
Tomato	62.84 ± 4.5	52.6 ± 3.6	$(4.823846 \pm 0.003)\text{e} + 15$
Cabbage	48.03 ± 3	63 ± 5	$(3.303901 \pm 0.002)\text{e} + 15$

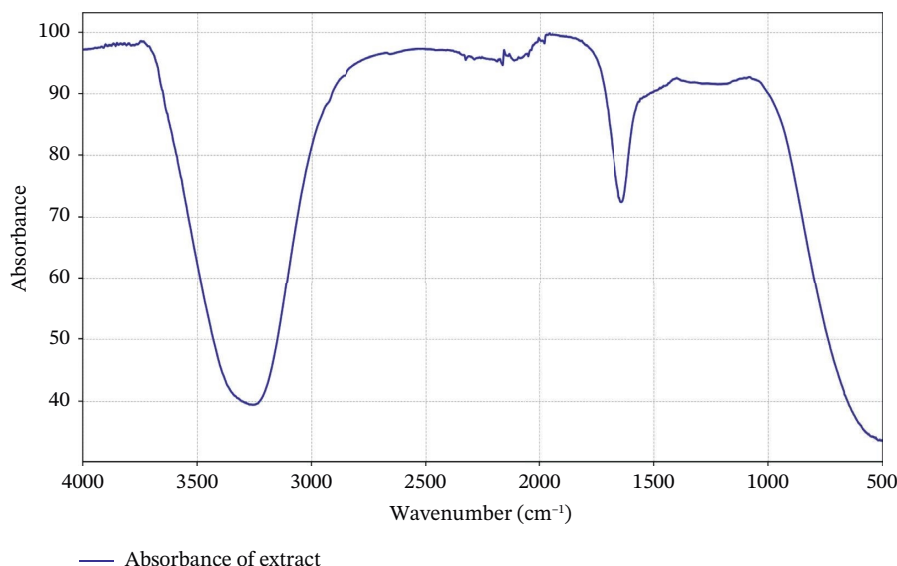


FIGURE 9 | FTIR spectra of the cabbage extract.

13.1 mg GAE/100 g (increasing to ~46 mg/100 g after boiling), and ~3 mg saponins/100 g, along with abundant terpenoid carotenoids. In comparison, white cabbage contains roughly 6.9 mg quercetin equivalents/100 g and ~30 mg GAE/100 g, with limited data on terpenoids or saponins. Thus, thermally treated tomato extract offers a richer pool of natural reducing and stabilizing agents, enabling the synthesis of smaller, more uniform, and highly stable AgNPs [44–49].

3.5 | FTIR Analysis of the AgNPs

In the green synthesis of AgNPs using plant extracts, the major phytochemical groups involved are polyphenols, flavonoids, terpenoids, and saponins. These compounds contain electron-donating functional groups—particularly hydroxyl groups in polyphenols and flavonoids—that enable the reduction of Ag^+ from their salt precursors to their zero-valent state Ag^0 , forming

the nanoparticle core [50]. After reduction, these same molecules or other components of the plant extract adsorb onto the surface of the AgNPs. This action, known as capping or stabilization, is crucial for preventing the nanoparticles from aggregating and maintaining their small size and colloidal stability in the solution.

To confirm the presence and involvement of these phytochemical groups, FTIR spectroscopy was used to characterize the AgNPs synthesized with cabbage extract. Figures 9 and 10 show the FTIR spectra recorded in the range of 500–4000 cm^{-1} for the cabbage extract and the synthesized AgNPs, respectively. In both spectra, prominent absorption bands are observed mainly in the regions of 3800–2600 cm^{-1} and 1750–1450 cm^{-1} , signifying the presence of functional groups responsible for nanoparticle reduction and stabilization [51]. Table 13 summarizes the specific bonds contributing to these absorption bands.

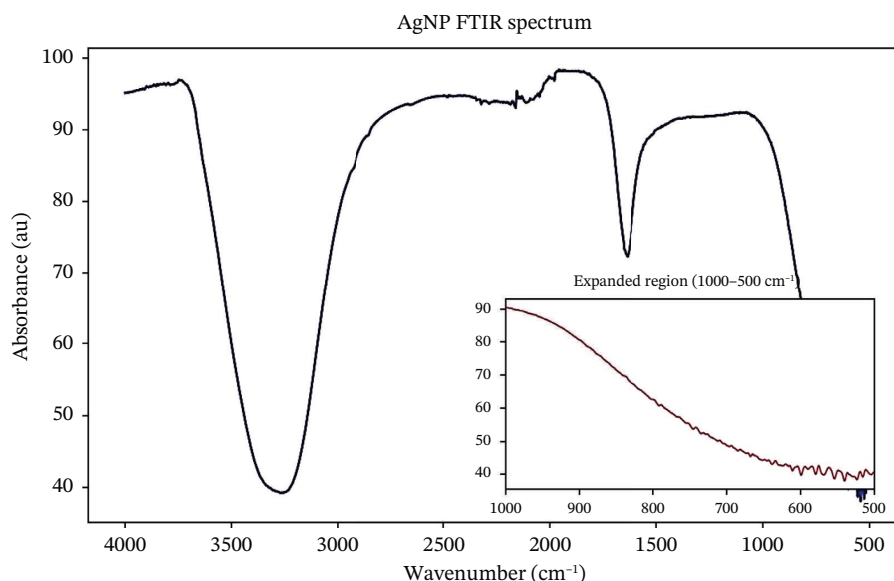


FIGURE 10 | FTIR spectra of the AgNPs synthesized using cabbage extract as a reducing and capping agent.

TABLE 13 | Summary of the bonds that contribute to the absorption bands.

No.	Absorption bands	Peaks	Bonds	Groups
1	3800–2600 cm ⁻¹	3700–3500	O–H stretch	Phenols, flavonoids
		3400–3300	N–H stretching	Proteins, amino acids, alkaloids
		3100–2850	C–H stretching	Lipids, fatty acids, terpenoids, phenolic compounds
		2700–2600	O–H stretch	Organic acids, polyphenolic acids
2	1750–1450 cm ⁻¹	1750–1700 cm ⁻¹	C=O stretching	Flavonoids, terpenoids, and fatty acids
		1690–1650	C=O/C=C stretching	Phenolic acids
		1650–1600	C=C/C=O stretching	Flavonoids, polyphenols, lignin
		1600–1550	N–H bending/C–N stretching	Proteins, enzymes
		1550–1500	C=C stretching/N–H deformation	Phenolics, tannins, alkaloids
		1490–1450	CH ₂ and CH ₃ bending	Lipids, terpenoids, fatty acids

The FTIR spectrum of the cabbage extract exhibits prominent absorption bands attributed to O–H stretching in polyphenols (~3271 cm⁻¹), C=O stretching in amides and carbonyl compounds (~1642 cm⁻¹), and C–O stretching in polyols (~1226 cm⁻¹) [42]. In the FTIR spectrum of the synthesized AgNPs (Figure 10), the intensity of these characteristic peaks—particularly the C–O stretching band—was significantly diminished. This reduction indicates that biomolecules containing hydroxyl, carbonyl, and amide functional groups actively participated in the reduction of Ag⁺ ions and subsequently acted as capping and stabilizing agents for the nanoparticles [43]. In the inset, which presents the magnified FTIR region of the AgNPs between 1000 and 500 cm⁻¹, small noise-like peaks are visible around 600–500 cm⁻¹. These low-wavenumber bands are often associated with Ag–O bonds or more generally metal–ligand (Ag–L) stretching vibrations, confirming the attachment of organic or biological molecules to the nanoparticle surface [52]. In the context of green synthesis, such features further verify the role of biomolecules—such as proteins, amino acids, and phenolic compounds—as capping agents forming the organic layer around the nanoparticle core [53].

3.6 | Antimicrobial Test

The antibacterial efficacy of the AgNPs was initially evaluated using the disc diffusion method, with inhibition zone diameters (mm) as the readout. Ciprofloxacin and deionized water served as positive and negative controls, respectively. Four pathogenic

strains—*E. coli*, *S. aureus*, *P. aeruginosa*, and *P. vulgaris*—were tested. After 24 h incubation at 37°C, inhibition zones ranged from 8.5 to 12 mm (Figure 11, Table 14), demonstrating that plant-mediated AgNPs exhibit substantial antibacterial activity. The enhanced performance against *P. vulgaris* at higher concentrations highlights the potential of these nanoparticles for practical antimicrobial applications.

MICs were determined using twofold serial dilutions of AgNPs (2–256 µg/mL) in Mueller–Hinton broth with bacterial inocula. Complete inhibition was observed at 16 µg/mL for *S. aureus*, 32 µg/mL for *E. coli*, and 32 µg/mL for *P. aeruginosa*, reflecting size- and species-dependent activity. The higher MIC for Gram-negative *P. aeruginosa* is consistent with its reduced membrane permeability, illustrating that inhibition zone size in agar does not directly correlate with MIC in broth.

Overall, the study demonstrates that plant-mediated AgNPs possess significant antibacterial potential, with activity governed by nanoparticle size, surface chemistry, and bacterial species, and highlights the complementary roles of disc diffusion and MIC assays in evaluating nanoparticle efficacy.

Table 15 presents a literature-based comparison of inhibition zone diameters for AgNPs evaluated using the disc diffusion method, enabling direct comparison between the results obtained in this study (Table 14) and previously reported data. The tested pathogens include *Erwinia pyrifoliae* (bac1), *Staphylococcus warneri* (bac2), *Xanthomonas citri* (bac3), *E. coli* (bac4),

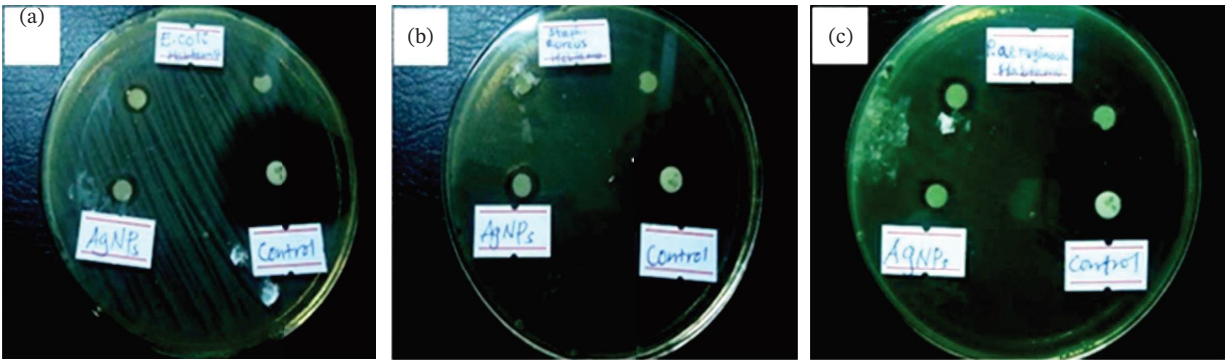


FIGURE 11 | Antimicrobial activity of AgNPs against different human pathogenic bacterial strains: (a) *Escherichia coli*, (b) *Staphylococcus aureus*, and (c) *Pseudomonas aeruginosa*.

TABLE 14 | Inhibition zone diameters (mm) and minimum inhibitory concentrations (MIC, $\mu\text{g/mL}$) of AgNPs against different bacterial strains.

Inhibition zone diameter (mm) of AgNPs against different bacterial strains				
Reagent	<i>E. coli</i> inhibition zone diameters (mm)	<i>S. aureus</i> inhibition zone diameters (mm)	<i>P. aeruginosa</i> inhibition zone diameters (mm)	<i>P. vulgaris</i> inhibition zone diameters (mm)
Di. water	0	0	0	0
Ciprofloxacin	35 ± 2	34 ± 2	33 ± 1.8	29 ± 1.8
AgNPs	8.5 ± 0.1 , 35	10.5 ± 0.13 , 34	12 ± 0.15	0
<i>Minimum inhibitory concentrations ($\mu\text{g/mL}$)</i>				
AgNPs	32	16	32	16

TABLE 15 | Literature-based comparison of inhibition zone diameters for AgNPs evaluated using the disc diffusion method.

No.	Bacteria name	Extract type	Resonance of AgNPs	Size of AgNPs	Shape of AgNPs	Gram stain	Inhibition zone diameter in mm
1 [54]	Bac1	Gr1	450	67	sph	Gram-negative	9
2 [54]	Bac2	Gr1	450	92.5	sph	Gram-negative	10.5
3 [54]	Bac3	Gr1	450	92.5	sph	Gram-negative	9.5
4 [55]	Bac4	Gr2	424	53.8	sph	Gram-negative	8.8
5 [56]	Bac5	Gr4	410	24	mix	Gram-positive	10

and *S. aureus* (bac5). The AgNPs were synthesized using cyanobacterial extract (Gr1), plant extract (Gr2), and green tea leaf extract (Gr3). Variations in inhibition zone sizes between this work and the literature can be attributed to differences in the structure–activity relationships governing the antimicrobial performance of AgNPs. In particular, nanoparticle size, shape, concentration, surface characteristics, and dispersion state play critical roles in determining antibacterial efficacy.

4 | Conclusion

This work establishes a sustainable and quantitatively rigorous framework for the green synthesis and optical characterization of AgNPs using tomato and cabbage extracts. By integrating UV–Vis spectroscopy with Lorentzian–Gaussian spectral analysis and Mie theory, nanoparticle size and number density were reliably extracted without electron microscopy, demonstrating a scalable and cost-effective alternative for nanoparticle characterization. The results show that tomato extract, owing to its richer phytochemical composition, consistently produces smaller and more monodisperse AgNPs with sharper SPR features and higher particle concentrations than cabbage extract. FTIR analysis confirms the dual role of plant biomolecules in Ag^+ reduction and nanoparticle stabilization.

Antibacterial evaluation further demonstrates effective activity against both Gram-positive and Gram-negative bacteria. Disc diffusion assays revealed clear inhibition zones, while MIC measurements provided a quantitative assessment of antibacterial potency. For AgNPs in the 55–62 nm size range, MIC values were found to be lowest for *S. aureus*, intermediate for *E. coli* and *P. vulgaris*, and highest for *P. aeruginosa*, reflecting size- and species-dependent antibacterial behavior. These results highlight

the importance of combining diffusion-based and broth-based assays for a complete evaluation of AgNP efficacy.

Beyond AgNPs, the combined UV–Vis–Mie approach presented here offers a broadly applicable strategy for correlating synthesis conditions with structure–property–function relationships in green-synthesized nanomaterials. By enabling predictive control of nanoparticle size, optical response, and antibacterial performance using simple, environmentally benign methods, this study provides a practical roadmap for the scalable design of plasmonic and antimicrobial nanomaterials for biomedical, environmental, and sensing applications.

Author Contributions

Habtamu Mengesha conducted the experimental work, while Getachew Tizazu performed the process of model fitting to the experimental data. The manuscript was written by Getachew Tizazu.

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Disclosure

All authors read and approved the final manuscript.

Ethics Statement

The authors have nothing to report.

Consent

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data will be made available on request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. (*Supporting Information*)

In the Supporting information, Section 1 presents supporting figures and tables related to the synthesis and antibacterial testing of the AgNPs, while Section 2 provides additional details on the characterization techniques employed during their synthesis.