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UV–Visible Spectroscopic Analysis Of Citrate-Capped Silver Nanoparticles

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Silver nanoparticles (AgNPs) have been widely studied due to their unique optical, physicochemical and plasmonic properties that are valuable for sensing, environmental monitoring, biomedicine and nanotechnology. In this work citrate-capped silver nanoparticles were synthesized by utilizing a citrate-mediated chemical reduction method and characterized using UV-Visible spectroscopy, which confirmed the optical properties and colloidal stability. The formation of silver nanoparticles was confirmed by the presence of a characteristic Surface Plasmon Resonance (SPR) absorption band in the visible region that was identified in the UV-Visible spectrum. The absorption spectrum was recorded in the range of 200 to 800 nm with a sharp and symmetrical SPR peak at 395 nm with a maximum absorbance of 0.685. The absence of significant peak broadening or secondary absorption bands further confirmed the strong stabilization by citrate ions and good colloidal stability of the synthesized nanoparticles.
Trisodium citrate serves as both a reducing and a stabilizing (capping) agent to both form and maintain a stable suspension. The results of this study indicate that UV-Visible spectroscopy is a fast, reliable, non-destructive and inexpensive method to monitor nanoparticle synthesis and evaluate the optical properties of the nanoparticles. Citrate-mediated synthesis is a promising method for forming stable silver nanoparticles with desirable plasmonic properties which can be used in biosensing, environmental monitoring, analytical detection and other nanotechnology-based applications.

KEYWORDS: Silver nanoparticles (AgNPs); Citrate capping; UV visible spectroscopy; Surface Plasmon Resonance (SPR); Optical stability; Nanotechnology; Biosensing; Environmental monitoring.

1. Introduction

Nanotechnology is one of the most rapidly advancing areas in science and technology today and provides new solutions in many fields including medicine, environmental science, electronics, agriculture and materials engineering. The unique properties of materials at the nanoscale have enabled the design of advanced systems with better physical, chemical, optical, electrical and biological properties. Among the nanomaterials studied to date, metallic nanoparticles have received great attention due to their exceptional physicochemical properties and broad range of applications.[1–5]

Silver nanoparticles (AgNPs) are one of the most studied noble metal nanomaterials due to their optical, antimicrobial, catalytic, and sensing properties. The properties of the AgNPs are strongly influenced by particle size, shape, surface chemistry and dispersion stability. These properties determine their effectiveness in biosensing, environmental monitoring, drug delivery, medical diagnostics, antimicrobial coatings, food packaging, and plasmonic devices. Therefore, the controlled synthesis and reliable characterization of silver nanoparticles remain important areas of nanotechnology.[1–3]

Various physical, chemical and biological techniques have been developed for the synthesis of silver nanoparticles. Physical methods of the production of nanoparticles often require sophisticated instrumentation and high energy consumption. Biological methods can involve complex purification processes and longer reaction times. This has led to chemical reduction techniques being increasingly popular because they are easy to apply, reproducible, cost effective and produce nanoparticles of a controlled size and shape. Among the chemical reduction methods, citrate-mediated synthesis is particularly attractive as trisodium citrate is used as both a reducing agent and a stabilizing (capping) agent.[11]

In citrate-induced synthesis, silver ions (Ag^+) are reduced to metallic silver atoms (Ag^0), which in turn are nucleated and grown into nanoparticles. At the same time, citrate ions are adsorbed to the nanoparticle surface to create electrostatic repulsive forces to avoid particle aggregation. This promotes the formation of stable colloidal suspensions with better dispersion and long-term stability. As a result, citrate-capped silver nanoparticles are widely used as model systems for studying the optical properties and surface plasmon resonance.[6,11]

Silver nanoparticles have a unique property of localized surface plasmon resonance (LSPR). LSPR is created by the collective oscillation of conduction electrons on the surface of the nanoparticle while exposed to electromagnetic radiation, and this creates a characteristic absorption band in the visible part of the electromagnetic spectrum. The position, intensity, and shape of the LSPR band are highly sensitive to the particle size, particle shape, concentration, aggregation state, and the surrounding dielectric environment. As such, LSPR can be an effective indicator for the formation of nanoparticles and colloidal stability.[6,8]

UV-Visible spectroscopy is currently an efficient, cheap, fast and more convenient method for characterization of metallic nanoparticles. The spectroscopy technique provides the opportunity to directly study the characteristic surface plasmon resonance band of a nanoparticle and provides information on its formation, optical properties, aggregation behavior and stability in suspension. Compared with more sophisticated characterization techniques such as Transmission Electron Microscopy (TEM), Dynamic Light Scattering (DLS), Scanning Electron Microscopy (SEM), and X-ray Diffraction (XRD), UV-Visible spectroscopy is a simple and accessible way for nanoparticle characterization.[7,16]

Although synthesis and characterization of silver nanoparticles have been reported, the role of citrate capping in controlling their optical and colloidal behavior remains insufficiently studied. In addition, the interaction of citrate stabilization with plasmonic properties is vital to optimize the performance of the nanoparticles in sensing and analytical applications.

Therefore, detailed UV-Visible spectroscopic analysis can be useful for the formation and optical properties of nanoparticles.
In this work, we synthesized and studied citrate-capped silver nanoparticles under UV-Visible spectroscopy. The nanoparticles were synthesized using a citrate-mediated chemical reduction method and analyzed on the wavelength range 200-800 nm. We focused on examining the surface plasmon resonance properties and optical properties of the synthesized nanoparticles. Our results may find utility in biosensing, environmental monitoring, analytical detection, and other nanotechnology applications to discover the properties of citrate-stabilized silver nanoparticles. [6,9,14]

2. Review of Literature

Nanotechnology has revolutionized many scientific fields by allowing for the manipulation of matter at the nanoscale. Metallic nanoparticles, particularly silver nanoparticles (AgNPs), have attracted a lot of attention for their optical, antimicrobial, catalytic, and plasmonic properties. AgNPs are widely used in medicine, environmental monitoring, catalysis, sensing, and advanced materials research. Silver nanoparticles are 1-100 nm in size and have a high surface area-to-volume ratio. Their physicochemical and biological properties are strongly influenced by particle size, morphology, and surface chemistry. That is, a controlled synthesis is necessary to obtain desired functional properties.[2,5,9,11]
There are numerous synthesis approaches reported in the literature such as physical, chemical and biological ones. Chemical reduction is the most widely used because of its simplicity, reproducibility and scalability. Green synthesis methods are the most ecologically friendly. Citrate-mediated synthesis is a well-studied and well-established method for producing stable AgNPs. Trisodium citrate acts as a reducing and capping agent and can reduce Ag^{+} ions to metallic silver and stabilize them with electrostatic repulsion.[17]
Localized Surface Plasmon Resonance (LSPR) is one of the most important optical properties of silver nanoparticles. The SPR band is highly sensitive to nanoparticle size, shape, aggregation state, concentration, and surrounding medium, and thus is a valuable indicator of the formation and stability of nanoparticles. UV-Visible spectroscopy is a promising and fast, reliable, non-destructive, and inexpensive method of nanoparticle characterization. Silver nanoparticles contain SPR peaks in the range of 390-450 nm depending on synthesis conditions and particle shape and morphology. UV-Visible spectroscopy informs the formation, aggregation behavior, and colloidal stability of the nanoparticles.[13,14,16]
Aggregation plays an important role in the physicochemical and biological behavior of AgNPs. Citrate capping helps in stabilizing colloidal components and the particles are repulsed by current and cannot agglomerate into a clumpy state. The position of the SPR peak is influenced by the size of the particles, concentration, aggregation state, and the dielectric properties of the medium around them. Small variations in these parameters can produce measurable shifts in the SPR wavelength. Citrate-capped AgNPs are used in biosensing, environmental monitoring, antimicrobial coatings, catalysis, analytical detection systems, and biomedical applications. Their very good plasmonic response enables very sensitive sensing platforms.[9,12,16]
While there has been a lot of research on silver nanoparticles, different synthesis conditions and stabilizing agents are still affecting the optical behavior and colloidal stability. The more detailed UV–Visible spectroscopic studies on citrate-capped silver nanoparticles are necessary

in order to understand the relationship between citrate stabilization and plasmonic performance.[7,17]

Table 2.1: Summary of Selected Literature Studies

Author	Year	Focus	Technique	Key Finding
Ahmad et al.	2019	Green synthesis	UV–Vis	Demonstrated eco-friendly synthesis of AgNPs using biological reducing agents, producing stable nanoparticles with promising antimicrobial properties.
Nguyen et al.	2023	Synthesis methods	Multiple methods	Provided a comprehensive comparison of conventional and modern AgNP synthesis methods, highlighting the advantages and limitations of each approach.
Loiseau et al.	2019	Biosensing	Plasmonic sensing	Reported the application of silver-based plasmonic nanoparticles in highly sensitive biosensing and analytical detection platforms.
Bélteky et al.	2019	Aggregation	Spectroscopic analysis	Showed that nanoparticle aggregation significantly influences colloidal stability, physicochemical behavior, and biological activity.
Husain et al.	2023	Applications	Biomedical studies	Reviewed emerging biomedical and translational applications of AgNPs, including diagnostics, therapeutics, and antimicrobial technologies.

The reviewed studies demonstrate that silver nanoparticles possess significant potential in synthesis, sensing, biomedical, and environmental applications. However, the relationship between citrate-mediated stabilization and the optical behavior of AgNPs remains an area requiring further investigation. Therefore, the present study focuses on the UV–Visible spectroscopic characterization and stability assessment of citrate-capped silver nanoparticles.

3. Experimental Details

All chemicals used in this study were of analytical grade and were used without further purification. Silver nitrate ($AgNO_3$) was employed as the silver precursor, trisodium citrate dihydrate as the reducing and stabilizing agent, and double-distilled water as the solvent.

Table 3.1: Chemicals and Reagents Used for the Synthesis of Citrate-Capped Silver Nanoparticles (AgNPs)

Chemical	Formula	Purity	Function
Silver Nitrate	$AgNO_3$	Analytical Grade	Silver precursor for nanoparticle formation
Trisodium Citrate	$Na_3C_6H_5O_7 \cdot 2H_2O$	Analytical Grade	Reducing agent and stabilizing (capping) agent
Double-distilled Water	H_2O	Laboratory Grade	Solvent and reaction medium

Table 3.2: UV–Visible Spectroscopy Instrument Parameters

Parameter	Value
Spectral range	200–800 nm
Scan rate	24,000 nm/min
Data interval	5 nm
Spectral bandwidth	1 nm
Beam mode	Dual beam

3.2 Synthesis of Citrate-Capped Silver Nanoparticles

Silver nanoparticles were synthesized by citrate reduction. Silver nitrate solution was heated under continuous stirring and trisodium citrate solution was added dropwise. Citrate ions reduced Ag^+ to Ag^0 and simultaneously stabilized the nanoparticles through surface capping.

Figure 3.1. Schematic representation of citrate-mediated synthesis of silver nanoparticles.

3.3 Visual Observation

The reaction mixture changed from colorless to pale yellow and finally brownish-yellow, confirming nanoparticle formation and development of localized surface plasmon resonance (LSPR).
UV–Visible spectra were recorded in the wavelength range of 200–800 nm using distilled water as the blank. The characteristic SPR peak was used to evaluate nanoparticle formation, dispersion, and colloidal stability.

Table 3.3: Experimental Conditions for UV–Visible Spectroscopy Analysis

Experimental Parameter	Condition
Wavelength range	200–800 nm
Blank	Distilled water
Mode	Absorbance
Measurement	UV–Visible spectroscopy

3.4 Experimental Workflow

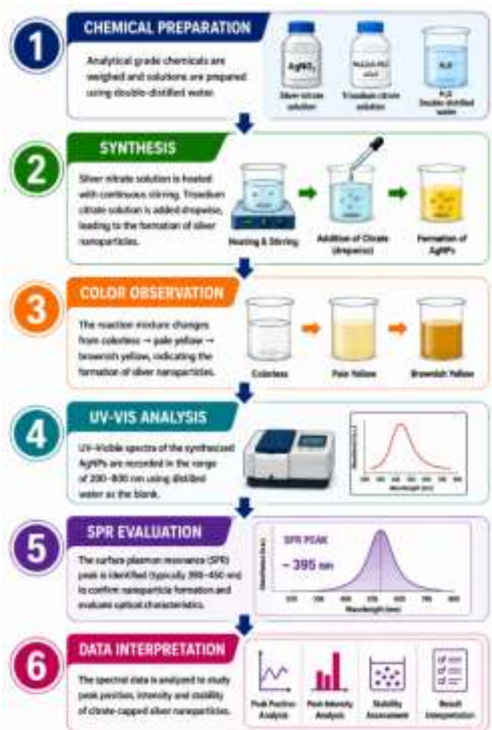

Figure 3.2. Overall experimental workflow in the study.

The adopted method provides a simple, reproducible, and cost-effective way to synthesize citrate-capped silver nanoparticles and study optical properties using UV–Visible spectroscopy.

4. Methodology

Analytical-grade chemicals were used for the experiments without further purification. Silver nitrate ($AgNO_3$) was used as a precursor to the silver ions and trisodium citrate dihydrate was used as a reducing and capping agent. Distilled water was used for the reaction process as it contains very low levels of impurities and is compatible with nanoparticle synthesis.

a. Silver Nitrate ($AgNO_3$) - Silver precursor.
b. Trisodium Citrate – Reducing and capping agent.
c. Distilled Water – Solvent.

4.1 Synthesis of Citrate-Capped Silver Nanoparticles

Citrate-capped silver nanoparticles were synthesized through the chemical reduction method. An aqueous 1 mM silver nitrate ($AgNO_3$) solution was used as the metal precursor. The measured volume of silver nitrate solution was heated to 90–95°C under continuous magnetic stirring. A 1% (w/v) trisodium citrate solution was then slowly introduced into the reaction medium, and the reaction was allowed to proceed for approximately 30 minutes.

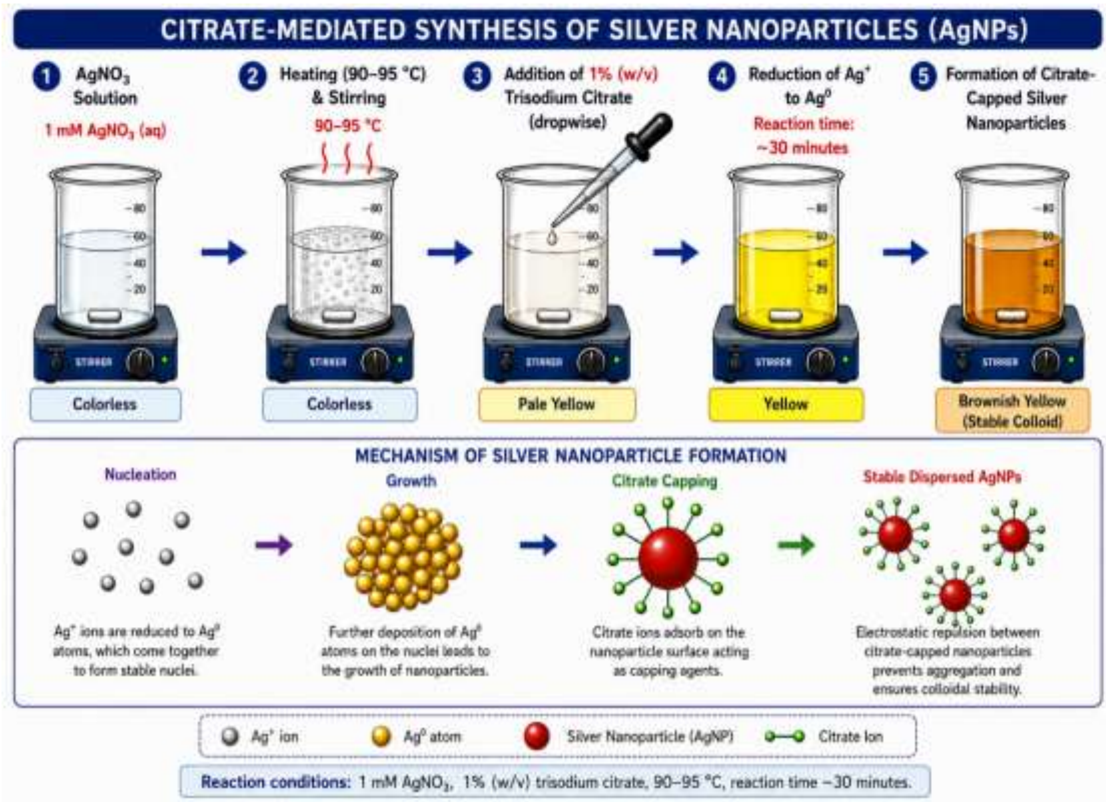

Figure 4.1: Schematic representation of the citrate-mediated synthesis of silver nanoparticles, illustrating nucleation, growth, citrate capping, stabilization mechanisms, and the characteristic color changes observed during nanoparticle formation

4.2. Mechanism of Nanoparticle Formation

The formation process involves reduction, nucleation, growth, and stabilization. Citrate ions reduce silver ions to metallic silver atoms, which form nuclei and subsequently grow into nanoparticles. Citrate molecules adsorb on the surface of the nanoparticle, preventing aggregation.

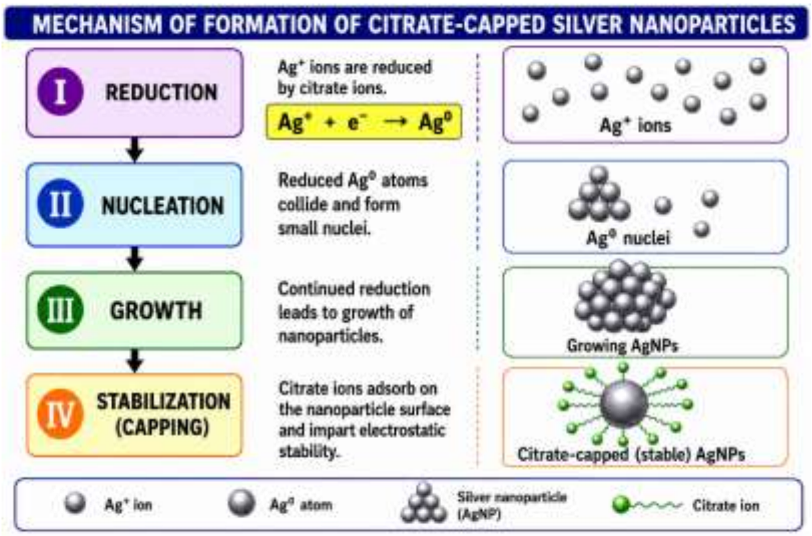

Figure 4.2: The mechanism of citrate-capped silver nanoparticle formation with Ag^{+} ions reduced and nucleated, Ag^{0} atoms formed, nanoparticle growth and citrate-mediated stabilization of colloidal nanoparticles

4.3. UV–Visible Spectroscopic Characterization

The synthesized nanoparticles were characterized with UV-Visible spectroscopy over the wavelength range 200–800 nm. The spectral bandwidth, scan rate and the data interval were chosen to obtain accurate absorption spectra. The characteristic SPR peak at 395 nm confirmed nanoparticle synthesis. SPR is the most important optical feature of silver nanoparticles. The position, intensity and shape of the peak can provide information regarding aggregation state, concentration and colloidal stability of the nanoparticles. The sharp and symmetric SPR peak suggests good colloidal stability and limited aggregation. However, particle size and size distribution cannot be directly determined using UV–Visible spectroscopy alone and would require complementary characterization techniques such as Transmission Electron Microscopy (TEM) or Dynamic Light Scattering (DLS). According to the Beer–Lambert Law, absorbance is directly proportional to the concentration of the absorbing species when the optical path length and molar absorptivity remain constant. Therefore, changes in absorbance intensity can provide useful information regarding nanoparticle concentration and colloidal stability. In the present study, the relatively stable absorbance values observed during storage suggest that the concentration and dispersion state of the citrate-capped silver nanoparticles remained largely unchanged over time.

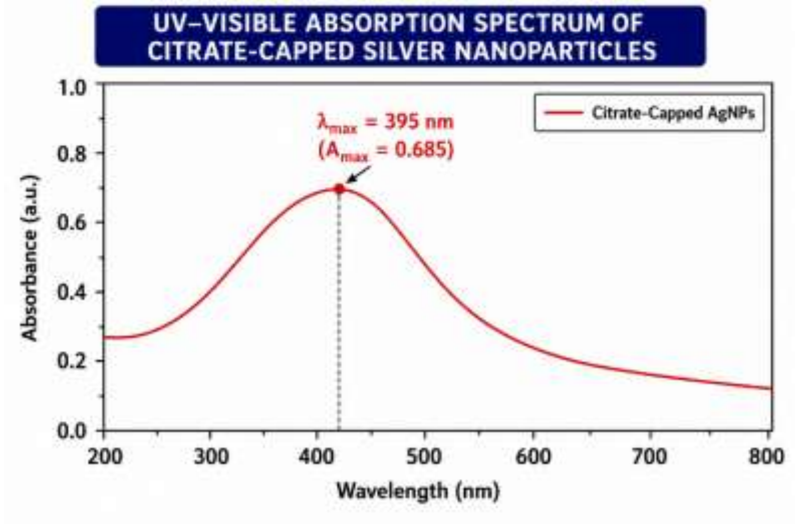

Figure 4.3: UV-Visible absorption spectrum of citrate-capped silver nanoparticles showing the characteristic surface plasmon resonance (SPR) peak at 395 nm

The colloidal stability of the synthesized citrate-capped silver nanoparticles was evaluated by monitoring the SPR peak position (λmax) and absorbance intensity over a storage period of 28 days. The absence of significant spectral shifts or absorbance variations indicates good colloidal stability and minimal nanoparticle aggregation during storage.

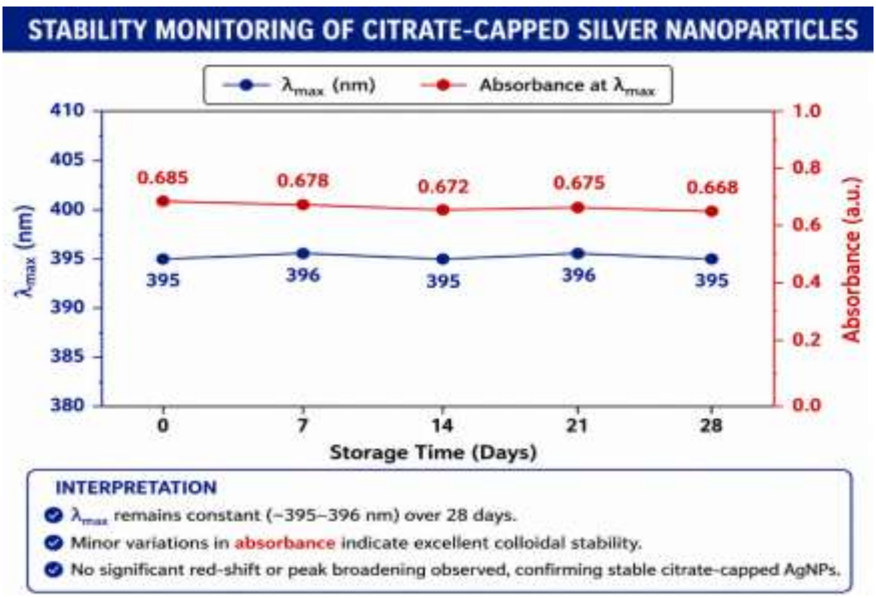

Figure 4.4: UV–Visible spectroscopic stability assessment of citrate-capped silver nanoparticles based on monitoring λmax and absorbance values over a 28-day storage period

4.4 Data Processing and Spectral Analysis

The recorded UV–Visible spectra were analyzed to determine the maximum absorbance (Amax), surface plasmon resonance (SPR) peak wavelength (λmax), and overall peak characteristics, including peak symmetry and broadening. These spectral parameters were used to assess nanoparticle formation, optical behavior, and colloidal stability. The experimental observations were compared with previously reported literature values to verify the successful synthesis and stabilization of citrate-capped silver nanoparticles. Since the study was primarily focused on qualitative spectroscopic evaluation, no advanced statistical analysis was performed.

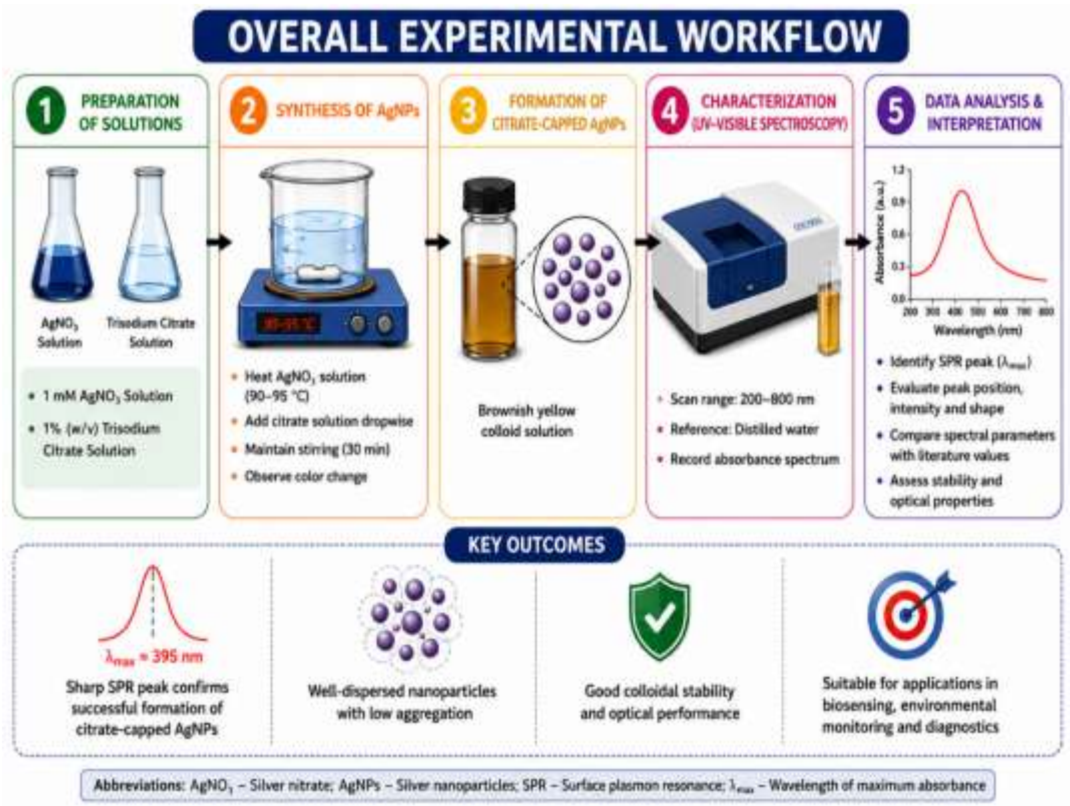

Figure 4.5: Schematic representation of the experimental methodology adopted for the preparation, synthesis, characterization, and analytical evaluation of citrate-capped silver nanoparticles using UV-Visible spectroscopy.

5. Results and Discussion

The successful synthesis of citrate-capped silver nanoparticles (AgNPs) was confirmed by UV-Visible spectroscopic analysis. The absorption spectrum in the 200–800 nm wavelength range exhibited a clear SPR absorption band with an SPR peak in the region near 395 nm. A maximum absorbance of 0.685 at the SPR peak was observed, and the sharp and symmetrical SPR peak was indicative of well-dispersed nanoparticles with little aggregation. However, particle size and size distribution cannot be directly determined using UV–Visible spectroscopy alone and would require complementary characterization techniques such as Transmission Electron Microscopy (TEM) or Dynamic Light Scattering (DLS).

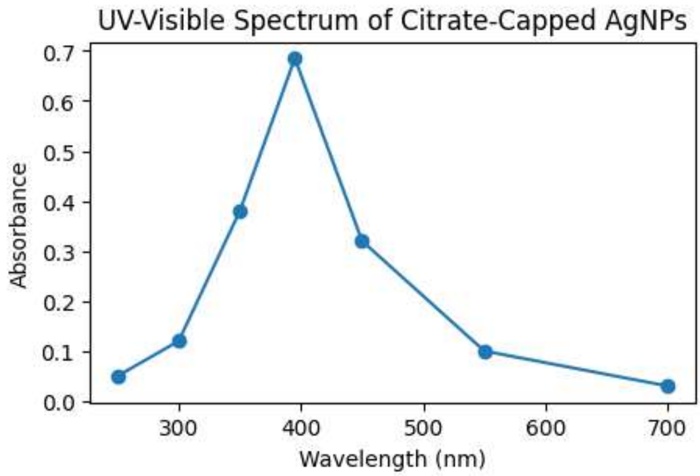

Figure 5.1. UV–Visible absorption spectrum of citrate-capped silver nanoparticles showing the characteristic SPR peak at 395 nm.

Table 5.1: UV–Visible Spectroscopic Observations of Citrate-Capped Silver Nanoparticles

Parameter	Observation
Nanoparticle Type	Citrate-Capped AgNPs
Spectral Range	200–800 nm
SPR Peak Position	395 nm
Maximum Absorbance	0.685
Peak Shape	Sharp and Symmetric
Aggregation Evidence	Not Significant
Stability Status	Good

5.1 Effect of Citrate Functionalization on Optical Stability

Trisodium citrate acted as both a reducing and stabilizing agent. Citrate molecules were adsorbed on the nanoparticle surface and resulted in electrostatic repulsion between the neighboring particles, preventing aggregation and maintaining colloidal stability.

Table 5.2: Interpretation of SPR Characteristics

Spectral Observation	Interpretation
Sharp Peak	Well-dispersed nanoparticles with limited aggregation
Broad Peak	Possible particle aggregation or polydispersity
Red Shift	Increase in particle size or aggregation tendency
Blue Shift	Smaller particle size or changes in local dielectric environment
Stable Peak Position	Good colloidal stability

The SPR peak at 395 nm is within the expected wavelength range for citrate-mediated silver nanoparticles. Although some studies have reported SPR peaks in the range of 400–430 nm for citrate-stabilized silver nanoparticles, the slightly blue-shifted peak observed at 395 nm may be attributed to differences in synthesis conditions, citrate concentration, particle characteristics, and the dielectric environment surrounding the nanoparticles. The wavelength position suggests limited aggregation and favorable optical properties of the synthesized nanoparticles. The stability of the nanoparticles was further evaluated by monitoring the SPR peak position over a 28-day storage period. Only minor variations in λmax were observed, indicating good colloidal stability and effective citrate-mediated stabilization.

Table 5.3: Comparison of SPR Peak Position with Reported Literature

Study	SPR Peak (nm)	Observation
Literature Report A	400–420	Citrate-Stabilized AgNPs
Literature Report B	390–430	Chemically Synthesized AgNPs
Present Study	395	Citrate-Capped AgNPs

We examined the colloidal stability of citrate-capped silver nanoparticles by measuring the surface plasmon resonance (SPR) peak wavelength (λmax) and absorbance intensity over a storage period of 28 days. UV-Visible spectra showed only slight variations in both parameters during this time. The peak position of the SPR was almost constant between 395 and 396 nm, which indicates that the nanoparticles did not accumulate or change in size during storage. The absorbance intensity only showed fluctuations from 0.668 to 0.685. The lack of peak broadening, peak splitting, or significant red-shift indicates that the citrate molecules stabilize the nanoparticle surface through electrostatic repulsion. As a result, the synthesized citrate-capped silver nanoparticles had excellent colloidal stability over the storage period.

Table 5.4 Stability Monitoring Data of Citrate-Capped AgNPs

Storage Time (Days)	λmax (nm)	Absorbance at λmax

0	395	0.685
7	396	0.678
14	395	0.672
21	396	0.675
28	395	0.668

The almost constant λmax and small absorbance levels mean that the optical properties of the nanoparticles remained stable during the storage, confirming citrate-mediated stabilization.

5.2 Data Processing and Spectral Evaluation

The UV-Visible spectra were analyzed to determine the maximum absorbance (Amax), the peak wavelength (λmax), and the overall spectra. The characteristic peak of SPR was observed at 395 nm and had a maximum absorbance of 0.685. The sharp and symmetrical structure of the peak indicates the formation of well-dispersed silver nanoparticles with very low aggregation. The spectra show no secondary absorption bands or high peak broadening, indicating a homogeneous colloidal system. The comparison of the experimental data with the previously reported values further confirmed the synthesis of citrate-capped silver nanoparticles.

Table 5.5 Summary of Spectral Evaluation Parameters

Parameter	Experimental Value
λmax	395 nm
Maximum Absorbance	0.685
Spectral Range	200–800 nm
Peak Shape	Sharp and Symmetric
Peak Broadening	Not Observed
Secondary Peaks	Not Observed
Stability Assessment	Excellent

The spectral properties reported in this work are consistent with the optical behavior of citrate-capped silver nanoparticles and show the utility of UV-Visible spectroscopy for rapid and reliable characterization.

6. Conclusion

This work was successful in synthesizing and UV-Visible spectroscopic characterization of citrate-capped silver nanoparticles (AgNPs). The formation of silver nanoparticles was confirmed by the characteristic band of Surface Plasmon Resonance (SPR) at 395 nm, which is a well-known indicator of nanoparticle formation. The maximum absorbance of 0.685 and the sharp, symmetrical shape of the SPR peak indicated that well-dispersed silver nanoparticles were formed with little aggregation. Trisodium citrate served as a reducing agent and a stabilizing (capping) agent for nanoparticle formation. The adsorption of citrate molecules to the nanoparticle surface generated electrostatic repulsive forces which prevents particles from aggregating and strengthens the stability of the nanoparticle. The absence of large peak broadening or secondary plasmon resonance bands also proved that citrate stabilization is effective and the nanoparticle suspension is stable.

Stability monitoring with a 28-day storage period revealed only small changes in SPR peak position and absorbance intensity, indicating the excellent colloidal stability of synthesized citrate-capped silver nanoparticles. These results show the effect of citrate functionalization on nanoparticle stability over time. UV-Visible spectroscopy proved to be fast, reliable, non-destructive, and cost-effective for monitoring nanoparticle formation, evaluating optical behavior, and assessing stability. The spectral characteristics indicated that citrate-mediated synthesis is an effective technique for creating silver nanoparticles with desirable optical properties and good reproducibility.

The findings of this study will help us to better understand the relationship between nanoparticle synthesis, surface functionalization, and optical behavior. The plasmonic response of the synthesized nanoparticles might be useful in biosensing, environmental monitoring, chemical sensing, analytical detection systems, antimicrobial technologies, and other nanotechnology-related applications. In future work, we may use complementary characterization techniques such as Dynamic Light Scattering (DLS), Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), X-ray Diffraction (XRD), and Zeta Potential analysis to get an idea of the distribution of particle size, shape, crystallinity, and surface charge. These studies would enhance our understanding of citrate-capped silver nanoparticles and develop them for practical science and industry applications. Finally, citrate-mediated synthesis combined with UV–Visible spectroscopic analysis is an effective and reliable method to prepare and characterize stable silver nanoparticles with great promise in technological, biomedical, and environmental applications.

Table 6.1: Summary of Major Findings

Parameter	Result
Nanoparticle Type	Citrate-Capped AgNPs
Characterization Technique	UV–Visible Spectroscopy
Spectral Range	200–800 nm
SPR Peak Position (λmax)	395 nm
Maximum Absorbance	0.685
Peak Shape	Sharp and Symmetric
Colloidal Stability	Excellent
Aggregation Evidence	Negligible to Not Observed

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