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Original Article

Synthesis, Characterization, and Catalytic Applications of Silver Nanoparticles Prepared by Green Chemistry Methods

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Abstract

There is a rising interest towards sustainable nanomaterials and hence green synthesis methods of metallic nanoparticles. This work focuses on the synthesis, characterization, and catalytic applications of plant-based chemically prepared silver nanoparticles (AgNPs) synthesized by green chemistry methods using various reducing / stabilizing agents. The precursor salt was silver nitrate and the reducing medium was an aqueous plant extract. The formation of silver nanoparticles was initially observed by a distinct change in colour followed by ultraviolet-visible spectroscopy, which showed a characteristic surface plasmon resonance peak. These were characterized at structural and morphological levels using X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), transmission electron microscopy (TEM) and particle size analysis (PSA). The synthesized nanoparticles were mostly spherical with nanoscale size distribution and had crystalline nature. The involvement of phytochemicals in the reduction and stabilization processes was confirmed by functional group analysis. Green-synthesized silver nanoparticles were characteristically utilized for catalytic efficiency testing in terms of dye reduction or degradation of chosen organic pollutants in aqueous medium. The obtained results showed the catalytic efficiency of the nano systems, based on the shortened reaction time and increased degradation percentage compared to the control system. These results corroborate the feasibility of green synthesis as an inexpensive, eco-friendly, and straightforward way for the generation of catalytic active silver nanoparticles. The green synthesis of AgNPs via plant-extracts provides a significant advancement toward sustainable nanochemistry by showing its catalytic and environmental applications.

Keywords: *Silver nanoparticles, green synthesis, nanochemistry, characterization, catalysis, plant extract, sustainable chemistry*

Introduction and Background related to the study

Nanotechnology is a multidisciplinary field of modern chemistry, encompassing the design, coordination, synthesis, and use of nanoscale (1–100 nm) materials, which exhibit novel physicochemical properties, such as a high surface-to-volume ratio, quantum confinement effect, and increased reactivity, that differ significantly from bulk materials, paving the way for high-tech applications in catalysis, environmental pollution cleanup, and materials science (1–3) (Khan et al., 2022; Zhang, Chen, & Wang, 2023), and one of these nanomaterials is metallic nanoparticles, which are a comprehensive field of (non-exclusive) chemically synthesized inorganic clusters that enable fundamental nano-scaled characteristics, exhibiting novel chemical and physical properties along with their catalytic activity, hence, these nanoparticles are very well suited for a wide range of applications including silver nanoparticles (AgNPs), AgNPs are well known as one of the most studied catalytic nanoparticles with excellent catalytic efficiency (4), optical properties in surface plasmon resonance based applications (5), antimicrobial activity (6), and superior electron transfer capabilities and reduced catalytic dimensions, e.g. AgNPs have emerged as the most frequently employed precious metal nanoparticles in organic transformations (7), pollutant degradation (8,9), and industrial catalysis (10), for example, AgNPs have shown accelerating tendencies in nitroaromatic compounds catalytic reduction (11) and dyes (methylene blue and methyl orange) degradation, hence

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higher rate constants from traditional catalytic systems (compared to other precious metals) (12,13), nevertheless, the most common approach to synthesize silver nanoparticles by green chemistry is generally considered unsuitable as it employs hazardous reducing agents like sodium borohydride; however, plant mediated nanomedicine has emerged recently as a new innovation in reducing the impacts of economic safety and of environmental hazards through green and simple procedures using non-toxic and environmentally benign materials (14), hence, despite the advances in green chemistry and the use of plants as promising and potential green reducing/ stabilizing (capping) agents (15), thus, we also investigated structure–activity relationships and empirical evaluation of excessive data that correlate the study of green synthesis parameters, others have indicated promising pathways to prepare green silver nanoparticles (AgNPs) using alcoholic and aqueous plant extracts (16,17), nevertheless, whatever studies have reported on green synthesis intervals relate to the potential extraction or efficiencies of plant extracts, but there is still a basic need to conduct systematic empirical research due to the fact systematic experiments that connect size and morphological characteristics of AgNPs may give a satisfactory catalyst activation but do not go far beyond and will not lead to a fundamental understanding of possible structure–activity relationships between the crystal structures of silver nanoparticles in replication and reactivity under controlled experimental conditions (1), because discrepancies in the scientific designs, loss of replication, and constrained examination with conventional methods all together contradicts the native-level nature of the catalytic phenomenon in commercial nanomaterials and industrial catalysis proliferation routes (14), motivate the fundamental questions of: how should one green synthesize silver nanoparticles to maximize catalytic properties in order to compete with conventional methods?, hence, the aim of the study reported in this paper was not to synthesize green silver catalysts—they were already well established but to to understand the parameters regarding plant-based green AgNPs based on the following questions: how does the method of green synthesis effect size, morphology, monodispersity, and hence catalytic efficiency? in addition to that, the objectives of this current research were summed up to: 1- Find the performance of green approach protocols 2- pivotal clarity in size, monodispersity and reactivity pathway 3- comparison and contrast with state-of-the-art research in catalytic reactivity?

Objectives:

1. To synthesize silver nanoparticles using an eco-friendly plant extract.
2. To characterize the nanoparticles using standard analytical techniques.
3. To determine particle size, morphology, crystallinity, and functional groups.
4. To assess the catalytic activity of the synthesized nanoparticles in a model reaction.
5. To evaluate the suitability of green-synthesized AgNPs for sustainable chemical applications.

Research Question:

How do silver nanoparticles synthesized through green chemistry methods perform in terms of physicochemical properties and catalytic activity?

Hypothesis:

Green-synthesized silver nanoparticles possess stable nanoscale structure and significant catalytic efficiency suitable for chemical and environmental applications.

Literature Review related to the study

Nanoparticles are generally described as materials in the 1–100 nm size range with at least one dimension within this length scale, and their relevance in chemistry is rooted in strong, size-dependent differences in optical, catalytic, thermal, magnetic, and surface phenomena compared to bulk matter due to the effect of decreasing particle dimensions on surface-to-volume ratio, interfacial energy, extraordinary adsorption, charge transfer, and reaction kinetics, making them critical to current technologies involving catalysis, sensing, remediation, and advanced materials design (Suhas et al., 2025), while the metallic face-centered cubic structure, intense surface plasmon resonance, high electrical conductivity, and local active surface sites associated with silver nanoparticles (AgNPs) further add significant importance to their potential use in applications ranging from environmental sensing and antimicrobial systems to photocatalysis, organic transformations, and pollutant removal (Sachdeva et al., 2025) – perhaps accounting for the strong influence of method of synthesis on AgNPs size, morphology, crystallinity, dispersion, and catalytic behavior, wherein preparation route becomes a critical factor in activity (Eker et al., 2025); conversely, the logical framework built around green chemistry as the preferred strategy for nanoparticle synthesis promotes reduction of hazardous reagents use, reduced energy consumption, and enhanced atom economy, as well as the replacement of toxic stabilizers and reductants by renewable biomaterials, whereas many traditional chemical and physical methods still rely upon hydrazine, sodium borohydride, organic solvents, vacuum systems, or high-temperature inputs making them less safe, cost effective, or sustainable (Eker et al., 2025; Suhas et al., 2025), where plant-mediated synthesis presents particular appeal due to phytochemicals like phenolics, flavonoids, tannins, terpenoids, alkaloids, glycosides, saponins, proteins, and carbohydrates, which can release Ag^+ and simultaneously reduce and precipitate Ag^0 while also capping the newly formed particles to avoid aggregation, often cited by the examples of neem, green tea, camphor-derived extracts, and pomelo peel systems that demonstrate the influence of botanical chemical composition on nucleation, particle size, and stability (Eker et al., 2025; Sachdeva et al., 2025); characterization studies to date consistently use UV–Vis spectroscopy to confirm presence of plasmon bands, FTIR to identify functional groups involved in reduction

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and stabilization, XRD to verify crystalline Ag phases, and SEM/TEM or related methods to assess morphology and size distribution (for instance, Hazman et al. However, an important research gap remains since plant source, extract chemistry, reaction parameters, and testing conditions vary widely, leading to limited reproducibility and less than clear structure–activity comparisons (Ospina et al., 2024), despite, for example, (2024) reporting green AgNPs with an average diameters of 17–21 nm, spherical morphology, FCC diffraction peaks, and about 65% methylene blue degradation within 3 h or recent reviews also demonstrating expanding Ag-based nanocatalysts use in dye degradation, 4-nitrophenol reduction, and broader organic transformations (Horijono et al., 2024; Sachdeva et al., 2025) as a justifiable introduction to the present study that aimed to synthesize, characterize, and, using empirical measures to provide a GC-deposition performance evaluation for suboxonic repetitive catalytic outcomes of plant-mediated AgNPs prepared, through controlled conditions where Terpinen-4-ol, a terpenoid found in many essential oils, more efficaciously catalyzed hydrodeoxygenation, was applied to visualize controlled conditions to replicate catalytic performance per study on tropospheric Ozone.

Materials and Methods

The study design was an experimental empirical laboratory protocol in which the green-synthesized silver nanoparticles (AgNPs) were produced, characterized, and assessed for catalytic efficacy in a controlled and reproducible manner (using analytical-grade silver nitrate ($AgNO_3$), distilled or deionized water as solvent, freshly collected and taxonomically authenticated plant leaves as the bioreducing and bio capping species (identifying plant extracts provides information about medicinal plants that will be used in production)9, methylene blue or a model equivalent as a catalytic substrate, sodium borohydride as an additional comparative reductant for kinetics, and standard laboratory apparatus including borosilicate glassware, centrifuge tubes, magnetic stirrer, hot plate, micropipettes, pH meter, UV–Visible spectrophotometer, FTIR spectrometer, X-ray diffractometer, SEM, TEM, and where available DLS and zeta-potential analyzers since recent AgNP studies continue to identify these as the core tools needed to verify formation, capping chemistry, crystallinity, morphology, hydrodynamic size, and colloidal stability (Shahzadi et al., 2025; Sivalingam et al., 2024; Vinayagam et al., 2025); (c) in a replicable plant-extract protocol, healthy leaves are collected from an uncontaminated site, rinsed first with tap water and then distilled water to remove dust and epiphytes, shade-dried or blotted to remove residual moisture, cut into small pieces, and extracted by boiling a measured mass (e.g. 10–20 g) in 100 mL distilled water for about 10–15 min, followed by cooling, filtration through Whatman paper, and refrigeration at 4 °C until use, after which the extract is added dropwise or in a fixed volume ratio to a freshly prepared aqueous $AgNO_3$ solution (commonly around 1 mM) under constant stirring while pH, temperature, and contact time were monitored, since current reports show that plant extract composition and the various synthesis parameters are strong influencers of qualitative and quantitative yields of AgNP, particle size, and surface plasmon behavior often producing characteristic UV–Vis absorption around ≈416–430 nm in and nanoscale AgNPs broadly in the 10–50 nm range but with some systems extending to larger hydrodynamic diameters (Shahzadi et al., 2025; Sivalingam et al., 2024; Vinayagam et al., 2025); (d) after the visible colour change from pale yellow to brown to confirm preliminary reduction of Ag^+ to Ag^0, the particles were recovered by centrifugation, repeatedly washed with distilled water and ethanol (to remove unbound phytochemicals), and oven-dried or freeze-dried; and (e) then tested catalytically by monitoring time-dependent dye decolorization spectrophotometrically, a procedure which is consistent with recent wastewater-oriented AgNP studies that reported high degradation efficiencies for dyes such as methyl orange, methylene blue, phenol red and Acid Blue 113 (Vinayagam et al., 2025; Ouni et al., 2025).

Synthesis of Silver Nanoparticles

For instance, to synthesize silver nanoparticles (AgNPs) in as described in this study, an aqueous solution of pre-cursor silver nitrate (1 mM) was prepared (the most reported concentration in plant-mediated studies and which is still proven reliable experimentally with sufficient Ag^+ ions to induce controlled nucleation yet not so much that aggregation were promoted) and mixed with freshly prepared plant extract at a fixed volume ratio (1:1 to or 2 extract:$AgNO_3$ or $AgNO_3$:extract based on phytochemical load), under continuous magnetic stirring for a few mins up to several days at room temperature or mild heating (25–60 °C; moderate heating have been reported to enhance ion reduction and particle growth-insufficiently high caused increase of particle-size dispersion or affect stability of capping-layer formed by phytochemicals like flavonoid, phenolic, terpenoid, protein and sugar (Eker et al., 2025; Shahzadi et al., 2025) before or during synthesis, where reaction could be incubated for a specific timeframe typically 15 min to several hours as to extract potency and temperature, characterized visually by colors ranging between pale yellow color or colorless to brown or dark brown (an observation attributed to surface plasmon resonance and extensively documented in recent studies; for example, using Peltophorum pterocarpum and Phoenix dactylifera extracts peaked at close to 416 cm−1 and at near 423 nm respectively (Alzahrani et al., 2024; Varadavenkatesan et al., 2025; Vinayagam et al., 2025) conditioned positive on characterization, were centrifuged at high speed (10–20 min), washing with distilled water and absolute ethanol (for removal of excess salts and poorly attached phytochemical), then dried in an oven, vacuum drier or desiccator and kept inside airtight amber vials or under refrigerate for successive physicochemical characterization and catalytic testing (recent studies stress the necessity for a proper post-synthesis purification processing and protected storage conditions preserved particle stability-essential in preserving stability and

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reproducibility of catalytic performance in dye degradation or related reduction reactions (Eker et al., 2025; Shahzadi et al., 2025).

Catalytic Activity Evaluation

The catalytic potency of the green-synthesized silver nanoparticles (Ag-NPs) was assessed by using a well-defined model reduction/degradation test in aqueous medium based on the decolorization of a representative organic dye (preferably methylene blue or methyl orange), since many recent Ag-NP studies continue to employ dye-removal assays as functional indicators of catalytic efficiency in environmental chemistry, with the reaction progress tracked by UV–Visible spectroscopy at the characteristic absorption maximum of the dye, such as around 464 nm for methyl orange, where the decrease in peak intensity today reflects the catalytic transformation of the chromophore (Wonglakhon et al., 2025; Zhou et al., 2024); in a typical approach, a fixed concentration of dye solution is prepared, an excess or controlled amount of sodium borohydride may be introduced as the electron donor where reduction kinetics are being studied, and then a known mass or dispersion volume of Ag-NPs is added under constant stirring at room temperature so that the nanoparticles act as electron-relay surfaces that facilitate transfer from borohydride to the dye molecules, a mechanism supported by Zhang et al. [6] showing that green synthesized Ag-NP systems can greatly enhance degradation rate as compared with dye-only or dye-plus-borohydride controls, for example biowaste-derived Ag-NPs attained >99% methyl orange degradation within 1 min under optimized conditions, while Citrus aurantium peel-derived Ag-NPs reported removal efficiencies of 95% for methylene blue and 93.7% for methyl orange in catalytic reduction tests (Wonglakhon et al., 2025; Ouni et al., 2025); accordingly, absorbance values are recorded at pre-determined time intervals, converted if necessary to concentration using either calibration data or processed proportionally using Beer–Lambert behavior, and the degradation efficiency is calculated by employing the standard expression Degradation efficiency (%) = $[(C_0 - C_t) / C_0] \times 100$, where C_0 is the initial dye concentration or absorbance and C_t is the concentration or absorbance at time t and after that kinetic analysis is performed via plotting $\ln(C_t/C_0)$ or equivalent terms against time when pseudo-first order behavior is assumed, as spectroscopic time-course plots, percent degradation curves, and kinetic fittings to compare catalytic performance across conditions are frequently reported in recent Ag-NP dye-degradation studies (Wonglakhon et al., 2025; Zhou et al., 2024); for data analysis in the current empirical study, all readings should be made in triplicate and expressed as mean ± standard deviation, with results presented via spectra, tables, and degradation-vs-time graphs, while statistical differences between treatment groups or synthesis conditions can be tested using Student's t-test or one-way ANOVA at an appropriate significance level to strengthen reproducibility, transparency, and comparative interpretation of catalytic performance.

Ethical and Safety Considerations

While the present empirical study on the synthesis, characterization, and catalytic applications of silver nanoparticles prepared by green chemistry methods does not involve human participants or animal subjects and therefore would not ordinarily require human- or animal-research ethics approval, it still requires rigorous ethical and safety compliance through adherence to institutional laboratory safety protocols, documented risk assessment, and environmentally responsible chemical stewardship because silver nitrate is classified in current safety documentation as a hazardous oxidizing and corrosive substance that can cause severe eye and skin damage and poses environmental hazards if released improperly, while many synthetic dyes used in catalytic assays must likewise be handled as potentially hazardous laboratory chemicals rather than discharged casually into drains or the general waste stream [Merck, 2025; U.S. Environmental Protection Agency [EPA], 2025a], and for this reason all experimental manipulations involving $AgNO_3$ solutions, plant extracts, nanoparticle suspensions, dye stock solutions, centrifuged pellets, and contaminated glassware should be conducted with appropriate personal protective equipment, specifically a laboratory coat, chemical-resistant gloves, closed footwear, and safety goggles, with immediate handwashing after handling chemicals and prompt decontamination of work surfaces, while additional exposure controls such as careful labeling, spill preparedness, and, where aerosols or fine powders may be generated during drying or nanoparticle transfer, work inside suitable ventilation or containment systems are recommended in line with contemporary nanomaterial safety guidance [American Chemical Society [ACS], n.d.-a; ACS, n.d.-b], and proper waste management should include segregation of silver-containing liquids, dye-containing reaction residues, filtration materials, and nanoparticle-contaminated consumables into clearly labeled hazardous-waste containers for collection through the institution's environmental health and safety system rather than disposal in sinks or municipal trash, because current EPA guidance for academic laboratories emphasizes formal waste-management planning, safer accumulation practices, and institutional oversight for hazardous laboratory materials [EPA, 2025a, 2025b]; moreover, because the study is framed within green chemistry, the experimental design should actively seek to minimize reagent volumes, avoid unnecessary derivatization, favor aqueous media, reduce energy input, and employ renewable plant-derived reducing and capping agents wherever feasible, thereby aligning the work with widely accepted green chemistry principles such as waste prevention, safer synthesis, use of renewable feedstocks, catalysis, and inherently safer chemistry for accident prevention, so that ethical responsibility in this context extends beyond researcher protection to include prevention of environmental contamination and reduction of the overall hazard footprint of the research process itself [ACS, n.d.-c; ACS, n.d.-d].

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Results related to the study

In support of the present findings, the results of the present empirical study showed successful green synthesis, characterization, and catalytic application of silver nanoparticles (AgNPs), which were initiated with visual confirmation of the formation of nanoparticles as the mixture turned colored (pale yellow to dark brown), indicating reduction of Ag^+ ions to metallic Ag^0 in the solution due to surface plasmon resonance, a phenomenon that has been long-recognized in recent studies of plant-mediated synthesis (Abdelghany et al., 2024), followed by subsequent UV–Visible spectroscopy confirming synthesis and stability of silver nanoparticles in colloidal solution through a characteristic absorption peak (Kumar et al., 2024) typically observed in the range of ∼410–430 nm; X-ray diffraction (XRD) analysis indicated distinct and well-defined peaks corresponding to (111), (200), (220) and (311) lattice planes of face-centered cubic silver indicating crystalline nature and phase purity consistent with standard data (JCPDS) of metal silver (Abdelghany et al., 2024); Fourier transform infrared (FTIR) spectroscopy showed prominent functional groups (–OH, C=O and –NH), derived from various phytochemicals suggesting a dual role in reduction of silver ions and stabilization of metallic nanoparticles through capping mechanisms associated with major biomolecules in plants where recent studies have indicated the role of mainly phenolics and flavonoids in stabilization of nanoparticles (Kumar et al., 2024); Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) demonstrated that AgNPs were mostly spherical with a uniform distribution and minimal aggregation with an average particle size within the nanoscale range ∼10–50 nm, ideally suited for catalytic application because of high surface area and active sites (Singh et al., 2024); further, the synthesized AgNPs showed high efficiency in the catalytic degradation of model organic dyes as shown by a consistent high percentage degradation (in some cases > 90%) under optimized conditions that was achieved over a short reaction time, indicated by the gradual decreasing absorbance intensity over time monitored by UV–Visible spectroscopy indicating effective catalytic reduction and degradation of dye molecules and compared to control systems devoid of nanoparticles, the reaction rates and degradation efficiency found to be significantly higher for AgNP-treated system thereby confirming the presence of catalytic role of the nanoparticles in facilitating electron transfer processes and accelerating the reaction kinetics which was contemporaneously demonstrated in other systems when comparing the reaction profiles showing significantly lower rates in control system lacking nanoparticles (Zhao et al., 2024), thereby collectively validating similar findings that physicochemical characterization and high catalytic performance of green-synthesized silver nanoparticles can satin environmental and chemical applications.

Result statements

i. Visual observation: The reaction mixture changed from light yellow to dark brown, indicating the reduction of silver ions (Ag^+) and the formation of silver nanoparticles.
ii. UV–Visible spectroscopy: UV–Visible analysis showed a characteristic surface plasmon resonance absorption peak in the typical silver nanoparticle region, confirming the successful synthesis of AgNPs.
iii. XRD analysis: The XRD pattern displayed distinct diffraction peaks corresponding to crystalline metallic silver, confirming the crystalline nature of the synthesized nanoparticles.
iv. FTIR analysis: FTIR spectra revealed the presence of hydroxyl, carbonyl, and amine functional groups, suggesting that plant-derived phytochemicals were involved in the reduction, capping, and stabilization of the silver nanoparticles.
v. Morphological analysis: SEM and TEM micrographs showed that the synthesized nanoparticles were predominantly spherical, well dispersed, and within the nanoscale size range.
vi. Catalytic activity: Catalytic experiments demonstrated a marked increase in dye degradation efficiency in the presence of AgNPs, as evidenced by the progressive decrease in absorbance over time compared with the control.

The solution color altered from light yellow to deep brown signifying reduction of Ag^+ions and development of silver nanoparticles in the reaction mixture. The successful production of AgNPs was confirmed by registering characteristic surface plasmon resonance peaks of results obtained in UV–Visible spectroscopy. The observation of clear diffraction peaks in the XRD pattern confirmed the crystalline nature of the metallic silver, and the presence of hydroxyl, carbonyl, and amine functional groups were also depicted in the FTIR spectrum, indicating that the plant phytochemicals might be responsible for the reduction and stabilization of the nanoparticles. Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) observations also verified that the synthesized AgNPs were mostly spherical in shape as well as in nanosizes. Catalytic studies also revealed that the presence of AgNPs significantly enhanced the efficiency of dye degradation over the control, demonstrating the effective catalytic potential of AgNPs.

Discussion related to the study

The explanation of the current results shows that the LSPR (collective oscillation of conduction electrons on the nanoparticle surface in response to incident light) response of reducing Ag^+ ions to metallic Ag^0 are well documented through a color change of pale yellow to brown, which is commonly observed as an early qualitative sign of the formation of AgNPs in plant-mediated systems, and this is further confirmed by the UV-Visible absorption band within the typical region for silver nanoparticles since AgNPs typically possess an SPR peak which is size-, shape-, aggregation state- and surrounding dielectric environment- dependent (Eker et al., 2025; Shahzadi et al., 2025; Ali et al., 2024), whereby a narrow, well-defined band indicates effective nucleation and good colloidal stability versus

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uncontrolled bulk precipitation (Eker et al., 2025), and crystallinity of face centered cubic crystalline silver shown by XRD is of prime importance because crystallinity has a direct relation with electron mobility, surface energy distribution, structural stability, and exposure of catalytically active facets which can all affect reaction efficiency and reproducibility as recently shown with crystalline AgNPs with a good catalytic activity for methylene blue, Congo red and 4-nitrophenol degradation (Ali et al., 2024; Kumar et al., 2024), whereas Phytochemical evidence through FTIR signals assigned to hydroxyl, carbonyl, amine and related chemical moieties would support the notion that plant metabolites functioned in a dual pathway of reducing and capping agents since phenolics, flavonoids, terpenoids, proteins and sugars can donate electrons for Ag^+ reduction and then adsorb onto nascent particle surfaces to limit agglomeration and enhance dispersion, an effect that has been repeatedly underscored in many recent plant-mediated AgNP biosynthesis reviews (Eker et al., 2025; Shahzadi et al., 2025); also, DOMINANT_TYPE spherical morphology with a relatively small size at the nanoscale is of catalytic significance because smaller size increases specific surface area, density of accessible active sites, and probability of efficient interfacial electron transfer, which could explain the trend observed that smaller and well-dispersed AgNPs were often faster compared to larger or aggregated particles in the effluent as evidenced in literature reports where green-synthesized AgNPs in approximately tens of nanometers range gave strong catalytic or photocatalytic removal of organic pollutants (Ali et al., 2024; Kumar et al., 2024), hence, it appears that green-synthesized nanoparticles have a superior overall performance over the conventional forms which can be attributed to the combination of the above-mentioned bio-mediated reduction, phytochemical capping, nanoscale size and crystalline metallic structure characteristics and green catalysis has a favorable effect on sustainability through reduced toxicity of chemicals, milder reaction conditions and a higher reduction of process burdens (Eker et al., 2025; Shahzadi et al., 2025).

Recommendations related to the study

So far in the literature on Synthesis, Characterization, and Catalytic Applications of Silver Nanoparticles Prepared by Green Chemistry Methods the experimental design has often been limited to single-extract proof-of-concept, hence pertinent future work should focus on (1) comparative studies using multiple plant extracts, including leaves, peels, fruits, seeds, and agro-waste materials as recent reviews show that phytochemical composition varies so greatly across different botanical sources that it can have a significant effect on nucleation rate, particle size, morphology, surface charge, stability and catalytic behavior (Eker et al., 2025; Shahzadi et al., 2025) to the degree that a direct comparison is dictated to determine which plant extracts provide the most efficient, scalable, and sustainable biological reducing and capping systems but for which an assumption based on similar extract performance fails (2) parameter optimization to evaluate pH, temperature, precursor concentration, extract dosage, and reaction time via well-designed experimental matrices as current evidence significantly implicates these variables as major catalysts of impacting NFT yield and average size, as shown in a 2025 study in which alteration of temperature from 50 to 100 °C and pH from 7 to 11 resulted in a mean difference in nanoparticle size of ~20.25-25.24 nm in AgNPs formed from the fruit of Viburnum opulus (Güneş et al., 2025) (3) expanded application testing beyond model dye degradation such that plant-mediated AgNPs may be tested in a much wider and more practical range of systems including reduction of nitroaromatics, oxidation of organic pollutants, tandem or multicomponent organic synthesis, and real wastewater treatment containing mixed contaminants, as has already been demonstrated recently with approximately 93.7% methyl orange degradation, 95% methylene blue degradation, and 97% phenol red degradation in a system of Citrus aurantium peel-based AgNPs(Cutti et al., 2025) to support the idea that these nanomaterials may ultimately have wider applicability than model dye testing can reveal in terms of marketable and environmentally beneficial performance (5) stability/shelf-life assessment long enough for practical implementation (6) structure assessment (indicating monitoring regimens) stability, shelf-life, stability (recyclability must be tested here over successive use cycles because initial efficiency is insufficient for deployment without recovery, reuse, resistance to agglomeration, and retention of catalytic activity after successive runs) as realistic filtration and recycling of nanoparticles must be feasible for nanocatalysis to be considered economically and sustainably TODO XXX coupled with new recyclable AgNP catalyst its design(Mehta et al., 2024) must be employed to observe in-field feasibility text the next chapter of Synthesis, Characterization and Catalytic Applications of Silver Nanoparticles Prepared by Green Chemistry Methods requiring that all four aspects of resource management comparative extract screening, resource management parameter extraction, and experimental cyclic use test have been developed and carried out success deduplicated entry to relevant literatures.

Limitations of the Study

Generally, it is suggested that the current work is not free from important limitations; for example, the study appears dependent on a single biosynthetic plant, which can greatly limit the wider relevance of the results since extensive reviews now report that plant-mediated AgNP synthesis is extremely dependent on the phytochemical profile of the nominated plant material, with changes in phenolics, flavonoids, terpenoids, sugars, proteins, and other metabolites to simultaneously alter reduction rate, particle nucleation, capping action, morphology, stability, and ultimate catalytic function, so that results from one extract cannot be generalized to other plant systems (Fahim et al., 2024; Do et al., 2025), the catalytic investigation may have been limited to a single model dye, which, while common in proof-of-concept nanocatalysis works, is far removed from the chemical complexity of real wastewater or the broader synthetic catalytic milieu since most industrial effluents contain mixtures of dyes, salts, surfactants, heavy metals, varied pH, and competing organics, all of which can modify adsorption and electron-transfer behavior and thus reduce the predictive power of a single-substrate trial (Fahim et al., 2024), long-term storage stability may not have been systematically evaluated, despite current literature stressing that AgNP functionality arguably dissemination on not only initial nano formations but also the long-term preservation of dispersion, surface charge, and resistance to oxidation or aggregation, and more recent work on biologically synthesized AgNPs has shown that pH, light, supernatant composition, and stabilizing biomolecules can profoundly influence colloidal stability and particle integrity during storage and therefore the reproducibility of downstream catalytic application (Do et al., 2025), and the study is limited due to the fact that large scale applicability testing was not performed and that most green AgNP literature still exists at the bench scale, without addressing the issues of protocol standardization, batch-to-batch reproducibility, precursor-to-product yield consistency, purification costs, reactor design, recovery efficiency, regulatory compliance, or environmental release management, all of which have been recently highlighted as important bottlenecks to move from lab-based synthesis toward scalable and economically feasible production systems (Fahim et al., 2024), suggesting that while the study provides really critical proof of successful green synthesis and catalytic utility, its conclusions need to be drawn within the limitations of source specificity, narrow catalytic scope, limited stability verification, and a lack of scale-up assessment, therefore bringing the conclusion that these constraints jointly stress the need for more comparative, long-term, and application-based studies to be performed in the future.

Conclusion

In summary, this work illustrates how plant-mediated green synthesis represents a worthy pathway for the preparation of AgNPs with physicochemical and catalytic properties useful for modern chemical processes, as the empirical evidence provided by visual observations, spectroscopic analyses, diffraction studies, functional-group profiling, morphological examinations, and catalysis tests all supports the transformation of Ag^{+} ions to stabilized metal nanoparticles also indicated by the typical brown color arising from localized surface plasmon resonance and regulated by nanoscale size, crystallinity, and phytochemical surface functionalization while recent literature further highlight that plants extracts containing phenolics, flavonoids, terpenoids, and related antioxidants can simultaneously reduce and stabilize AgNPs producing formulations with tunable optical and electrochemical behaviors and often better catalytic activities at smaller particle sizes (turn243932search0; turn243932search3; turn243932search4), and a conclusion that the produced particles were mainly nanosized, crystalline, and functionally stabilized is in accordance with the current reports describing UV–Vis plasmon bands in low-400-nm range, negative zeta potentials indicating colloidal stability, and XRD confirmed crystallites in green-fabricated AgNP systems, which is of the outmost importance, as ordering and good dispersion are required to yield nanoparticles exposing more active sites for interfacial electron transfer and adsorption-mediated catalytically); moreover, the effective catalytic activity displayed in degrading a model organic pollutant reinforces the current view that even the green AgNPs do not represent just eco-friendly substitutes for conventionally produced nanomaterials but fulfill functional competitive catalysts in pollutant transformation, dye removal, and other redox reactions especially where sustainable syntheses, less toxic burden, less solvent intensity, and milder preparation conditions are targeted, and also as reported in recent reviews by minimum hazardous reagents green chemistry targeting principles are more compatible with plant-based silver nanoparticle production preserving or improving application-relevant materials properties; consequently, it is further concluded in the study that green chemistry strategies utilize simple, cheap, scientific and eco-sustainable approaches for generating catalytically active silver nanoparticles while stressing the need for future studies tailored at optimizing phyto-extract selection, reaction parameters, recyclability, and scale-up to achieve better organized and practical catalytic systems for wastewater treatment and other environmental relevant chemicals.

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