

REVIEW

Green Synthesis of Silver Nanoparticles Using Plant Extracts and Their Applications in Photocatalytic Degradation of Dyes: A Review

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ABSTRACT

The relatively low toxicity of silver nanoparticles (AgNPs) with their unique physical and chemical properties and their wide range of applications in medicine, electronics and environmental treatment has yielded an increased interest in their synthesis in recent years. However, traditional methods of synthesizing these particles are often associated with the use of toxic chemicals, high-energy consumption, high synthesis costs, and negative environmental impacts. Green synthesis has therefore emerged as a sustainable and environmentally friendly alternative to the synthesis of nanoparticles. Plants are one of the promising biological sources in the green synthesis of silver nanoparticles because they contain effective secondary compounds such as phenols, flavonoids, and terpenes, capable of reducing silver ions and converting them into nanoparticles through multiple biological mechanisms. This review summarizes the green synthesis of AgNPs using plant extracts as reducing and capping agents, characterization of the nanoparticle, factors affecting the synthesis, and their potential in photocatalytic applications.

Keywords: Silver Nanoparticles (AgNPs); Biosynthesis; Environmental Remediation; Organic Dyes; Plant Extracts.

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INTRODUCTION

Silver nanoparticles (AgNPs) are very small particles of silver that have an average diameter of between 1-100nm and unique physical and chemical properties that are distinct from bulk silver. These properties such as high surface area, improved reactivity and special optical features make them very attractive for a range of applications in various fields (Marathe *et al.*, 2023).

AgNPs have emerged as versatile agents with a variety of applications in different areas, because of their peculiar physicochemical properties. These NPs are especially important for the biomedical field where they applied as antimicrobial, anticancer and diagnostic agents. In other applications than health care, AgNPs have been applied to the protection of the environment, electronics, and agriculture. These sections provide details about specific uses of silver nanoparticles, based on recent research findings. AgNPs can also help combat a broad spectrum of bacteriological species, including multidrug-resistant strains, because of their high antimicrobial properties. They cause damage to microbial cell membranes and oxidative stress which finally result in cell death (Eker *et al.*, 2024).

In cancer therapy, the AgNPs have been employed because they can induce apoptosis (programmed cell death) of cancer cells. They have the potential to be used as a single agent or in combination with other drugs to enhance therapeutic efficacy (Jangra *et al.*, 2025). The anti-inflammatory and antimicrobial related properties of AgNPs contribute to shortening the time of wound closure through inhibition of inflammation, to foster tissue regeneration (Gao, 2025). AgNPs function as carriers for targeted drug delivery systems, which increase the bioavailability and controlled release of drugs. Because of their attractive surface plasmon resonance, AgNPs have been employed in bioimaging for diagnosis and early detection of diseases (Eker *et al.*, 2024).

The administration of AgNPs in wastewater effluents has been widely reported to enhance the removal of both pollutants and pathogens thus adding up to the clean water supply. AgNPs display catalytic behavior in diverse chemical reactions, therefore elevating the reaction rates and efficacy (Amruta Magar *et al.*, 2024). In agriculture, AgNPs are employed for catalytic and protection role against microbial infections and used as plant growth promoting agent (Ck *et al.*, 2026).

Likewise, AgNPs are also added to dental products (nanocomposites and implant coatings) in order to prevent bacteria from colonizing the surface and other types of tooth decay. They are also used in the therapy for oral cancers as they are antitumor agents (Bolenwar *et al.*, 2023).

There are many ways for the preparation of silver nanoparticles, and each has its advantages and disadvantages. These methods can be widely classified into chemical, physical, and biological means, which accord varying routes to control size and shape of the nascent particle (Table 1).

Table 1. Methods of Silver nanoparticles synthesis

Methods	Description and mechanism		References
Chemical methods	Chemical Reduction	This is one of the most common methods, involving the reduction of silver ions in solution using reducing agents. The process is often enhanced with stabilizing agents to prevent agglomeration and control particle size	(Sabaghian, 2024)
	Microemulsification and Microwave-Assisted Synthesis	These methods involve using surfactants to establish microenvironments for the reduction of the silver ions, with the aim of achieving good control over the particle size and distribution.	(Marathe <i>et al.</i> , 2023)
	Electrochemical Methods	Silver ions have been reduced to silver nanoparticles by electrolysis. It is a simple method with quick synthesis.	(Rahmah & Kurniawan, 2017)
Physical Methods	Evaporation and Condensation	This technique is based on the physical evaporation of silver and subsequent condensation to create silver nanoparticles. It is a process that does not use chemical reagent and is clean.	(Marathe <i>et al.</i> , 2023)
	Plasma Method	Silver raw materials are introduced into a plasma reactor, where the vacuum level and plasma power are controlled to form nanoparticles. This method allows for rapid synthesis and precise control of particle size and composition	(Kim <i>et al.</i> , 2018)
Biological Methods	Green Synthesis	This environmentally friendly approach uses living organisms such as bacteria, fungi, and plant extracts as reducing agents. The proteins and enzymes present in these organisms facilitate the reduction of silver ions into nanoparticles	(Sabaghian, 2024)

Generally, two approaches related to the formation of silver nanoparticles, either a (top-down) approach or a (bottom-up) approach (Figure 1). As the name implies, in a (bottom-up) approach, smaller atoms or molecules assemble themselves for the formation of nanoparticles. On the other hand, the (top-to-bottom approach) is the opposite. Synthesis Nanoparticles occur in this process by breaking down bulk materials into small-sized particles using many Lithography techniques such as milling and grinding, sputtering, thermal / laser ablation.

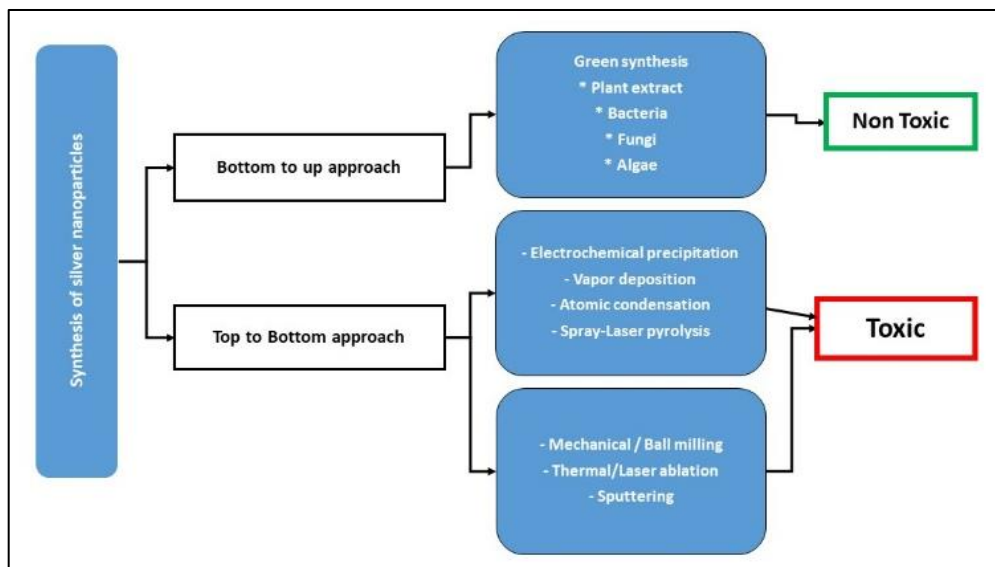


Figure (1) Different approaches used for the synthesis of silver nanoparticles

Green synthesis is of particular interest in research, since it minimizes the release of toxic wastage and yields nanoparticles with distinctive physical and chemical properties that are suitable for medical as well as environmental utilization. This method uses plant extracts as reducing agents and stabilizing agents (Başoğlu & İSkefiYeli, 2023). This allows a highly efficient formation of nanoparticles and at the same time an increase in stability, a reduction in tendency to agglomeration and elevated biological activity through bio-molecular functionalization of such particles on their surface (Mohammed & Hawar, 2022).

The plant extracts are electrostatically attractive to the metal ions. Silver ions were effectively reduced by many plant extracts like *Mentha spicata*, *Rhizophora stylosa*, and *Moringa oleifera* extract as studies showed. These plants have bioactive compounds with the ability to act as capping agent providing its long-term stability of bio-generated nanoparticles. Moreover, optimization approaches have recently been discussed to achieve a particular geometric description of the particles. Key factors affecting particle size and shape include the silver nitrate concentration, reaction time, temperature and pH.

Rizwana *et al.*, (2023) have investigated green synthesis of AgNPs using extracts of *Vaccinium oxycoccos* (cranberry). They observed that the reduction of AgNPs was made easier and also these nanoparticles were stabilized, spherical particles with diameter in the range 5–30 nm. The AgNPs were characterized with UV-Vis, XRD and TEM to indicate the NP size and properties of these NPs that showed strong antioxidant and antifungal activities.

Singh *et al.*, (2021) obtained the green synthesis of AgNPs from *Carissa carandas* L. leaf extract, which act as a reducing and stabilizing agent. The method consisted the mixing of 1 mM silver nitrate with leaf extract after which AgNPs were formed in one hour at room temperature, indicated by the yellowish-brown color. The successful synthesis was verified using UV-Vis, FTIR and XRD studies. The biofabricated AgNPs showed powerful antioxidant and antibacterial characteristics against human pathogenic bacteria, suggesting that this method could be a low-cost and energy-saving technology.

On the other hand, Mohamed, (2022) focused on green synthesis of AgNPs with biosynthesis routes from the natural sources by using organic waste products such as orange peel (*Citrus sinensis*) as eco-friendly reducing agents.

It is a cheap and sustainable method based on reducing action of food industry by products. UV-Vis and SEM were utilized for characterizing the synthesized AgNPs, which indicated their spherical shape with different sizes. This

methodology fabricates the NPs and tests their antimicrobial and cytotoxic activity against various pathogens and cell lines as well.

This review is aimed to give a focused overview of the green synthesis of AgNPs using the plant extracts with special emphasis on the physicochemical properties, characterization techniques, and application of AgNPs in the photocatalytic degradation of organic dyes. The review highlights the applications of plant-derived metabolites in Ag^+ reduction and stabilization of nanoparticles, and the effect of synthesis parameters on the size, shape, stability and photocatalytic efficiency of the produced nanoparticles. It has also provided comparison of the recent studies with respect to degradation efficiency, catalyst dose, irradiation source, reaction time and other process parameters which have effect on the dye removal. The literature used in this review was chosen based on its relevance to plant-mediated AgNPs synthesis, characterization of nanoparticles, dye degradation with photocatalysis and other related applications in the environment and prioritized by the recent publications and studies directly related to the topics.

1. Literature Search and Selection Criteria

The literature included in this review was selected from published studies focusing on the green synthesis of silver nanoparticles (AgNPs) using plant extracts, their characterization, and their applications, with particular emphasis on photocatalytic dye degradation. Relevant studies were identified through searches of scientific databases, including Scopus, ScienceDirect, SpringerLink, PubMed, Web of Science, and Google Scholar. The main search terms included “green synthesis of silver nanoparticles”, “plant-mediated AgNPs”, “plant extract silver nanoparticles”, “phytochemical reduction of silver ions”, “AgNPs characterization”, “photocatalytic degradation of dyes”, and related combinations of these terms.

Priority was given to studies that described plant-mediated AgNP synthesis and provided information on nanoparticle characterization using techniques such as UV–Visible spectroscopy, FTIR, XRD, SEM, TEM, DLS, or zeta potential analysis. Studies addressing the role of plant metabolites in Ag^+ reduction and nanoparticle stabilization were also considered, together with reports evaluating the photocatalytic degradation of organic dyes. Additional studies describing antimicrobial, biomedical, or other environmental applications were included when they provided relevant information on the properties or functional behavior of plant-mediated AgNPs. Recent publications were prioritized, while older studies were retained when they provided fundamental information or were frequently cited in the field.

Studies were considered less relevant when the plant source was not clearly identified, the synthesis procedure was insufficiently described, or the work was unrelated to plant-mediated AgNPs synthesis and its applications. The selected literature was subsequently compared according to plant source, plant part, phytochemical composition, synthesis conditions, nanoparticle characteristics, characterization methods, and photocatalytic performance where such information was available.

2. Mechanisms of silver ion reduction by plant extract

Plant-mediated synthesis of silver nanoparticles is a series of related processes that includes silver ion reduction, nucleation, particle growth, stabilization and surface capping. Upon mixing of a plant extract with AgNO_3 solution, there is a reaction between Ag^+ ions and reducing biomolecules present in the extract. Phenolic compounds and flavonoids are of special importance as they have hydroxyl groups which are able to donate electrons or hydrogen atoms that enable the reduction of Ag^+ to metallic silver (Ag^0). Other phytochemicals such as terpenes, tannins, proteins, amino acids, sugars, organic acids and vitamins can also be involved in this process; however, the relative contribution of these phytochemicals can vary based on the phytochemical composition of the plant extract and not a single dominant phytochemical class (Devi & Barooah, 2025; Hussein Ali Hussein Al-Sa’idi *et al.*, 2022).

After the reduction, the fresh Ag^0 atoms start to combine and the small nuclei are created. As the reduction continues, more silver atoms are added to these nuclei, and the silver particles grow in size. Nucleation and growth rate will affect the

final particle size and size distribution and thus have a significant dependence on reducing strength of the extract and reaction conditions. Concurrently, the molecules present in plants can be absorbed by the growing AgNPs by functional groups like –OH, –COOH, C=O and –NH on the surface. By limiting further growth and the aggregation of particles, this surface association can act as a natural capping layer and help stabilize the nanoparticles. So, the same plant extract also acts as a reducing and stabilizing system, but to the extent of the metabolites present in the extract (Bhat *et al.*, 2025).

The overall mechanism is therefore as follows: Electron-donating plant metabolites first reduce the Ag⁺ ions to Ag⁰, which nucleate and grow, followed by biomolecules in the extract attaching to the surface of the nanoparticles to stabilize and cap. Crude plant extracts may be composed of many phytochemicals, making it challenging to assign the Ag⁺ reduction solely to one chemical compound. The variation in particle size, morphology, stability and surface properties mentioned in the various plant mediated AgNPs synthesis studies could be partly attributed to the differences in the amounts of phenolics, flavonoids, terpenes, protein and various metabolites present.

In most of the experiments, the biosynthesis of AgNPs by plants follows these simple steps:

- 1- Preparation of Plant Extract by one of the methods commonly used for plant extraction.
- 2- Preparation of ionic metallic compound molar solutions (silver nitrate solution).
- 3- Both plant extract and ionic metallic compound solutions are incubated together for a specified period (at specific experimental conditions, either stirred or non-stirred) (Figure 2).

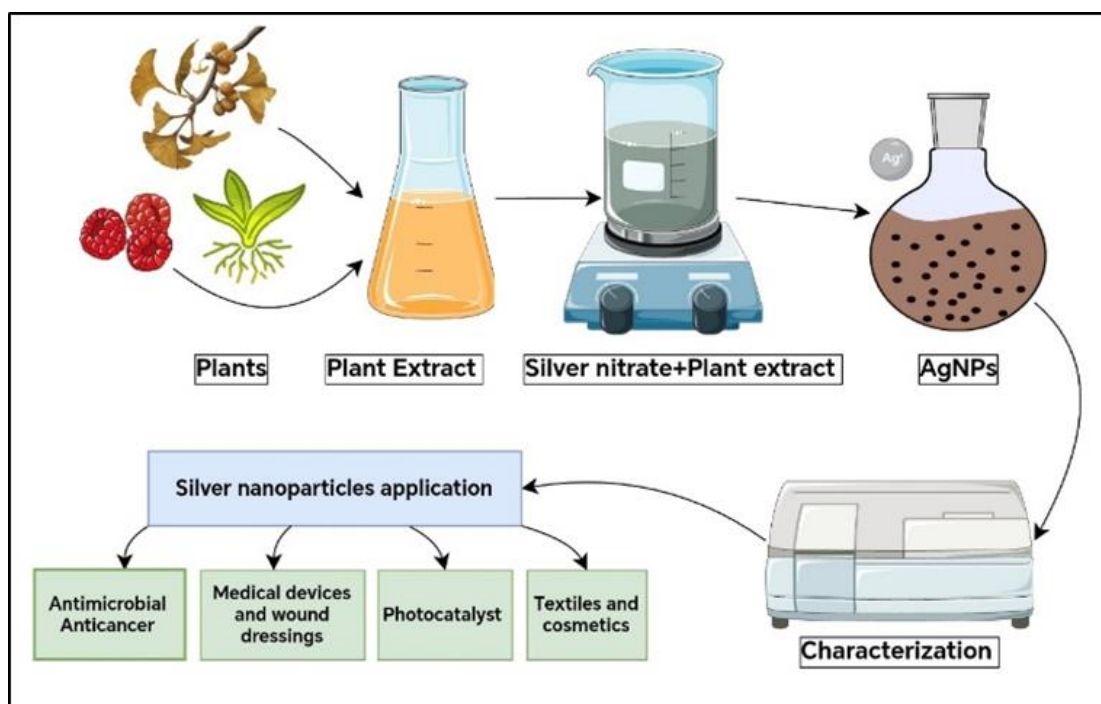


Figure (2) Biosynthesis of Silver Nanoparticles from plants extracts

3. Factors Influencing AgNPs Synthesis

The quality of the nanoparticle's product is highly dependent on the reaction conditions, with plant extract, pH, temperature and silver nitrate concentration having key roles in determining reduction response of both particle size and distribution (Figure 3). As a result, regulation of these factors is technically required in order to maintain the product's physical and chemical stability (Wickramarachchi & Paragodaarachchi, 2021).

3.1. The type and concentration of plant extract

This factor is crucial in affecting the reaction efficiency. Lemon peel extract, for example, is a high phenolic and flavonoid primary source, which are not present in other reducing agents (such as ascorbic acid), and which can be used as a reducing, double coating agent to generate very stable particles. This procedure was found to be effective with the antioxidant activity of the extract; extracts with high antioxidant activity are reported to produce small and effective NPs in the various applications (Mustapha *et al.*, 2023). This technology has been successfully applied in practice. Silver nanoparticles prepared with ginger root extract exhibited promising activity against Gram+ve and Gram-ve bacteria (Thi Phuong *et al.*, 2019), and polyphenol rich green tea extract was one of the most effective extracts regarding this activity (Hasan *et al.*, 2024). Nanoparticles of 2-26 nm size were also found to be active against *Staphylococcus aureus* after preparation from *Rosella* petals (Purwati *et al.*, 2023). Despite the many advantages of green synthesis including its eco-friendly nature and low toxicity, the field is also limited by the differences in the chemical composition of plant extracts that may adversely affect the size distribution and characteristics of the nanoparticles. One of the greatest challenges today in the science of the synthesis is to provide a standard protocol, and to understand the interaction of those particles with biological systems, allowing them to be safely used in advanced industrial and medical applications. The diverse range of plant sources used for AgNPs green synthesis, as summarized in Table 2, suggests that the studies are widely dispersed. The leaves are the part of plant that is mostly used as a source, which contain phenolics, flavonoids, proteins and reducing sugars that can effectively reduce Ag⁺ ions and stabilize the AgNPs. Other parts of the plant, however, such as peels, flowers, bark, fruits, rhizomes and callus cultures, have been successfully used. The diversity reflects the strong influence of the selected plant on the reduction rate, nucleation, and particle growth, capping efficiency, morphology and final stability of AgNPs.

In general, phenolic and flavonoid-rich extracts promote faster reduction because hydroxyl groups can donate electrons to Ag⁺ ions, leading to the formation of metallic Ag⁰. Terpenoids, alkaloids, proteins, and organic acids may further contribute to surface stabilization by binding to the nanoparticle surface through functional groups such as –OH, C=O, –COOH, and –NH. Therefore, plant-mediated synthesis is not a single uniform process; rather, it depends on the chemical composition of each extract and the optimized reaction conditions, including pH, temperature, reaction time, AgNO₃ concentration, and extract/precursor ratio. While a large number of plant-based AgNPs have been investigated for antimicrobial and biomedical applications, very few have been assessed for photocatalytic or catalytic degradation of dyes. This is a significant research gap. Future research will involve linking the phytochemical composition with the properties of nanoparticles (size, shape, charge and optical properties) to the photocatalytic efficiency in an experimental setup of standardized dye degradation conditions.

Table (2) Examples of plant extracts used in the green synthesis of AgNPs

No.	Plant source	Plant part	Main phytochemicals involved	Role in AgNPs synthesis	Application	Reference
1	<i>Moringa oleifera</i>	Leaves	Phenolics, proteins, flavonoids	Reducing and stabilizing agent	Antimicrobial and cytotoxic AgNPs	(Mohammed & Hawar, 2022)
2	<i>Camellia sinensis</i>	Tea leaves	Catechins, polyphenols	reducing agent	Photocatalytic degradation of methylene blue	(Trieu <i>et al.</i> , 2023)
3	<i>Morinda tinctoria</i>	Leaves	Phenolics, flavonoids	Reducing and capping agent	Dye degradation activity reported	(Vanaja <i>et al.</i> , 2014)
4	<i>Brassica oleracea</i> var. <i>botrytis</i>	Cauliflower waste	Phenolics, proteins, organic acids	Reducing and stabilizing agent	Photocatalytic degradation of methylene blue	(Kadam <i>et al.</i> , 2020)

5	<i>Solanum lycopersicum</i>	Leaves	Phenolics, flavonoids, alkaloids	Reducing and capping agent	Photocatalytic degradation of methylene blue	(Tooba <i>et al.</i> , 2026)
6	<i>Disporopsis longifolia</i>	Leaves and stems	Phenolics and other reducing metabolites	Reducing, capping, and stabilizing agent	Solar-light degradation of methylene blue	(Tam <i>et al.</i> , 2022)
7	<i>Cestrum nocturnum</i> L.	Leaves	Alkaloids, flavonoids, phenolics	Reducing and capping agent	Catalytic degradation of several dyes	(P. Kumar <i>et al.</i> , 2022)
8	<i>Acacia ehrenbergiana</i>	Cortex extract	Polyphenols, tannins, flavonoids	Reducing and stabilizing agent	Removal of Rhodamine B dye	(Alamier <i>et al.</i> , 2023)
9	<i>Thespesia populnea</i>	Bark/plant extract	Phenolics, flavonoids, tannins	Reducing and capping agent	Photocatalytic degradation of methylene blue	(Yahya Tahir <i>et al.</i> , 2022)
10	<i>Talipariti tiliaceum</i> L.	Flower extract	Flavonoids, phenolics	Reducing and capping agent	Sunlight degradation of azo dyes	(Gunasekaran <i>et al.</i> , 2025)
11	<i>Inula viscosa</i>	Aqueous extract	Phenolics, terpenoids	Reducing and stabilizing agent	Stable AgNPs with formation kinetics	(Okka <i>et al.</i> , 2023)
12	<i>Curcuma longa</i> L.	Flower extract	Curcuminoids, phenolics	Reducing and capping agent	Antibacterial AgNPs	(Rajak <i>et al.</i> , 2023)
13	<i>Alcea rosea</i>	Leaves	Flavonoids, phenolics, mucilage compounds	Reducing and stabilizing agent	Antioxidant, antibacterial, and anticancer AgNPs	(Ojha <i>et al.</i> , 2026)
14	<i>Ocimum tenuiflorum</i>	Leaves	Eugenol, phenolics, flavonoids	Reducing and capping agent	Bioactive AgNPs	(Alex <i>et al.</i> , 2024)
15	<i>Acalypha indica</i>	Leaves	Phenolics, flavonoids, alkaloids	Reducing and capping agent	Antibacterial AgNPs	(Sakaray <i>et al.</i> , 2024)
16	<i>Linum usitatissimum</i> L.	Callus culture	Phenolics, flavonoids	Reducing agent	Antimicrobial AgNPs	(Anjum & Abbasi, 2016)
17	<i>Melia azedarach</i> L.	Bark extract	polyphenolic compounds, flavonoids	Reducing and capping agent	Antibacterial AgNPs	(Pani <i>et al.</i> , 2016)
18	<i>Chrysanthemum indicum</i> L.	Flower extract	Flavonoids, phenolics	Reducing and stabilizing agent	Antibacterial and cytotoxic AgNPs	(Arokiyaraj <i>et al.</i> , 2014)
19	<i>Solanum xanthocarpum</i> L.	Berry extract	Alkaloids, phenolics, flavonoids	Reducing and stabilizing agent	Antimicrobial and enzyme inhibitory AgNPs	(Amin <i>et al.</i> , 2012)
20	<i>Mussaenda erythrophylla</i>	Leaves	Phenolics, flavonoids	Reducing and capping agent	Catalytic degradation of methyl orange	(Varadavenkatesan <i>et al.</i> , 2016)
21	<i>Zanthoxylum armatum</i>	Stem extract	Phenolics and alcohol functional groups	Reducing and stabilizing agent	Antimicrobial AgNPs	(Habib <i>et al.</i> , 2022)

3.2. Temperature

Temperature is another essential factor to accelerate the reaction rate and obtain the preferable size with different ranges depending on plant source. For instance, for 27 °C, an efficient result in the formation of nanocubes derived from citrus was achieved; however, moringa required a temperature of 60 °C to attain total reduction. It must be noted that, too high or low temperatures can lead to agglomerates and affect the colloid stability (Mela Yoro *et al.*, 2022; Trivedi *et al.*, 2014). However, very high temperatures may damage heat-sensitive phytochemicals or weaken the capping layer around the nanoparticles. For this reason, the optimum temperature depends on the type of plant extract and its active compounds. Haji and Barzinjy reported that temperature influenced the synthesis behavior of *Citrullus colocynthis*-mediated AgNPs together with pH and AgNO₃ concentration (Haji & Barzinjy, 2022).

3.3. pH

pH has a significant effect on uniformity of particle size and narrowness of surface plasmon resonance peak. The reduction of Ag⁺ ions may be slower and larger particles may form in acidic conditions. Many functional groups become more active under alkaline conditions, potentially increasing reduction and nucleation. To synthesize AgNPs using guarana seed skin extract, Nogueira *et al.* reported that the average particle size of AgNPs was reduced from 34.8 nm to 7.23 nm

when the pH level was raised from 5 to 11. From their statistical analysis, they revealed that pH contributed most to the particle-size variation; since the geometric form of the particle growth is controlled by the pH (Botinelly Nogueira *et al.*, 2025).

3.4. The concentration of silver nitrate

The proportion of the concentration of Silver nitrate to plant extract is an essential factor to keep chemical equilibrium for reduction and coating. The concentration of the silver nitrate will affect the concentration of Ag^+ ions in the reaction medium. The number of the formed AgNPs could possibly be restricted in case the concentration of the precursor is too low. However, if AgNO_3 is in high concentration, the phytochemicals present in the plant extract might not be enough to reduce and stabilize all silver ions. This can result in the non-completion of the reduction process, particle growth or aggregation. Nogueira optimized the synthesis of AgNPs (Ag^+ ions) with guarana seed skin extract and evaluated the pH, temperature and concentration of extract in the presence of Ag^+ ions (1 to 10 mM). They demonstrated that during the optimization process, the concentration of silver nitrate was one of the factors considered to control the size of AgNPs (Botinelly Nogueira *et al.*, 2025). Hence, the concentration of AgNO_3 should be adjusted based on reducing capacity of the plant extract to get stable particles of controlled size.

3.5. Reaction time

Reaction time determines whether Ag^+ reduction and nanoparticle growth have reached completion. During the early stage of synthesis, nucleation begins as Ag^0 atoms accumulate. Continued reaction allows these nuclei to grow and become stabilized by plant-derived compounds. An insufficient reaction period may lead to incomplete reduction, whereas unnecessarily prolonged incubation may promote aggregation, secondary growth, or changes in particle distribution. Monitoring the UV–Visible spectrum at different time intervals can help identify the point at which the SPR band becomes stable, indicating that nanoparticle formation has approached completion (Ratan *et al.*, 2025).

Overall, these variables interact with one another rather than acting independently. For example, increasing temperature may shorten the required reaction time, while changing pH may alter the reducing ability of the same extract. This interaction makes direct comparison between published studies difficult when synthesis conditions are reported inconsistently. Future studies should therefore provide complete experimental details and use systematic optimization methods to improve reproducibility and facilitate scale-up.

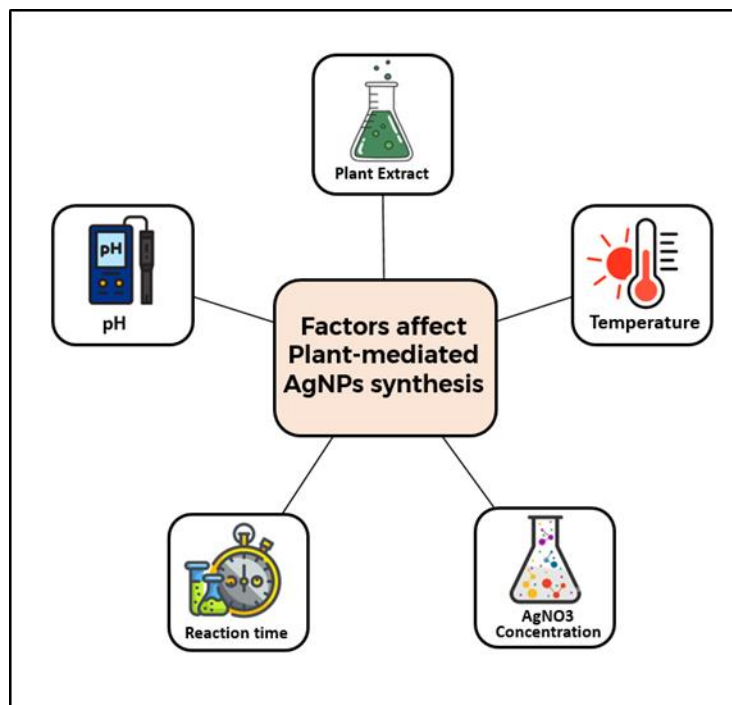


Figure (3) The critical factors in the green synthesis of AgNPs.

4. Characterization Techniques for AgNPs

Characterization and analyses of nanoparticles is crucial to confirm the results. The methods summarized in Table 3 convert biochemical reactions into explicit quantitative and qualitative information. Accordingly, the presence of plant matter in the reduction and fixation reactions is confirmed by UV-Vis and FTIR analyses (Joshi *et al.*, 2025), while TEM and XRD techniques provide physical evidence of the structural and crystal properties that qualify these molecules for medical applications (Gabi *et al.*, 2024). This combined spectroscopy and microscopic survey ensures the reliability of the green method used to synthesize nanoparticles. One of the simplest, fastest and broadly used methods for initial detection of silver nanoparticle (AgNPs) formation is UV-Vis spectroscopy. The technique was found to be very useful as the AgNPs have characteristic optical response (surface plasmon resonance) due to the oscillation of free electrons on the surface of the nanoparticles in the presence of light. The size, shape, concentration, aggregation and surrounding phytochemical environment have strong influences on the position and intensity of the SPR band (Bala & Rani, 2020).

In plant-mediated synthesis, a yellowish-brown to dark brown color is usually considered an initial visual sign of AgNP formation. However, UV–Visible spectroscopy provides stronger evidence by detecting the SPR absorption band. In the study reported by (Chand *et al.*, 2020), AgNPs were synthesized using onion, tomato, and Acacia catechu extracts, as well as a mixed extract system. The UV–Visible spectra confirmed the formation of AgNPs by the appearance of absorption bands in the visible region. The observed SPR peaks appeared around 432, 450, 440, and 430 nm for AgNPs synthesized using different plant extracts, confirming the reduction of Ag^+ ions into metallic AgNPs as shown in Figure (4).

FTIR analysis is commonly used to identify the functional groups that participate in the formation and stabilization of AgNPs. In plant-mediated synthesis, plant extracts contain many bioactive molecules, such as phenolic compounds, flavonoids, proteins, amino acids, and organic acids. These molecules include functional groups such as $-\text{OH}$, $-\text{NH}$, $\text{C}=\text{O}$, $-\text{COOH}$, and $\text{C}-\text{O}$, which may take part in the reduction of Ag^+ ions and the stabilization of the formed nanoparticles. Any shift in the position of these bands, or change in their intensity after nanoparticle formation, suggests that these biomolecules interact with the surface of AgNPs. Therefore, FTIR gives useful evidence that plant metabolites are involved not only in reducing silver ions, but also in coating the nanoparticles and limiting their aggregation (Agnihotri *et al.*, 2014); (Ghasemi *et*

al., 2024). In cases like hydroxyl, carbonyl, and amine, for example, band shifts and reductions in band intensity of extracts from different botanicals serve as empirical evidence of the specific metabolic pathways in which capping occurs, (I. Liaqat *et al.*, 2022; Mahakham *et al.*, 2017).

Another crucial technique employed for the confirmation of crystalline nature of synthesized AgNPs is XRD. Typical diffraction peaks of metallic silver with a face centered cubic structure are typically observed in silver nanoparticles. These peaks are commonly indexed to the (111), (200), (220), and (311) crystal planes. The presence of these reflections indicates the formation of crystalline AgNPs and the average crystallite size can be determined from the Scherrer equation. Weak additional peaks may also sometimes be seen, which could be due to organic residues or phytochemical compounds bound to the surface of the nanoparticle (Parvathalu *et al.*, 2023).

In microscopic techniques, direct information regarding the shape, size and distribution of the AgNPs is obtained. SEM can be used to see the surface morphology and overall distribution of the particles. It can reveal the shape of synthesized nanoparticles (spherical, irregular, aggregated or relatively well dispersed) (Ansari *et al.*, 2023). TEM gives more detailed information as the nanoparticles can be observed directly at the nanoscale. TEM images can be used to more accurately determine the actual particle size and shape, and estimate the particle-size distribution. Furthermore, SAED patterns acquired through TEM examination can complement XRD results with the presence of diffraction rings, which indicates the presence of a crystal structure in AgNPs (Githala *et al.*, 2022).

The hydrodynamic size of AgNPs in suspension is determined using DLS analysis. The volume produced by DLS is usually larger than that measured by TEM because DLS measures the entire molecular system in a solution, including the mineral core, the phytochemical encapsulation layer, and the surrounding fluid layer. The DLS provides information on the particle size distribution and the polydispersity index (polydispersity) is also available, which helps to assess the homogeneity and stability of the colloidal suspension. Accordingly, this technique is useful for understanding whether synthesized AgNPs are well dispersed or tend to clump in aquatic media (Dubey *et al.*, 2023). Taken together, these characterization techniques give a more complete understanding of green-synthesized AgNPs. Using these techniques together makes it possible to relate the composition of the plant extract and synthesis conditions to the stability, morphology, and photocatalytic performance of AgNPs.

Representative characterization of green-synthesized AgNPs

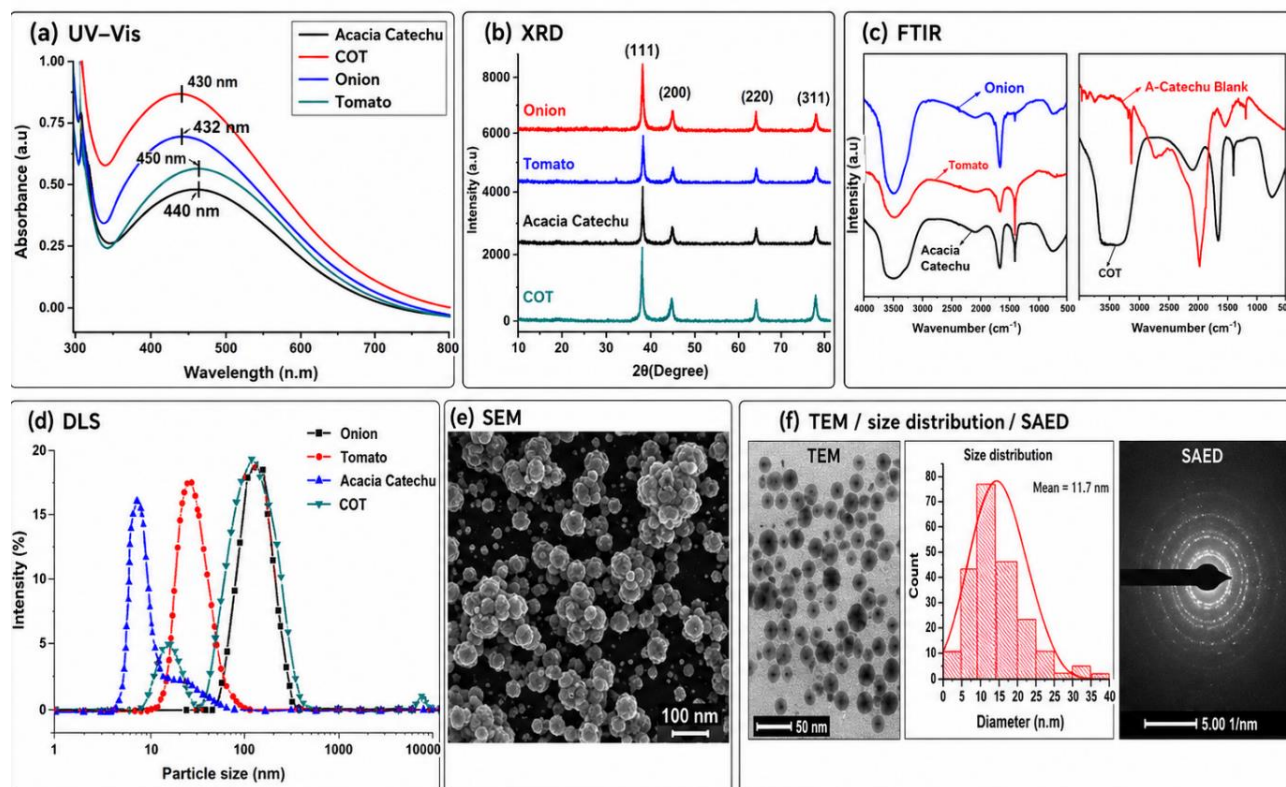


Figure (4) Representative characterization of green-synthesized AgNPs: (a) UV–Visible spectra showing the surface plasmon resonance (SPR) bands of AgNPs in the visible region, (b) XRD pattern confirming the crystalline face-centered cubic structure of metallic silver, (c) FTIR spectra showing the involvement of plant-derived functional groups in the reduction and capping of AgNPs, (d) DLS particle-size distribution indicating the hydrodynamic size of the synthesized nanoparticles, (e) SEM micrograph showing particle morphology and aggregation behavior, and (f) representative TEM image with particle-size histogram and SAED pattern confirming nanoscale particle size, morphology, and crystalline nature of plant-mediated AgNPs. Adapted and redrawn based on characterization features reported by (Chand *et al.*, 2020).

Table (3) Commonly used Characterization Techniques for AgNPs

Analytical Technique	Description	Expected Results and Observations	References
UV-Visible Spectroscopy (UV-Vis)	Confirms the formation of AgNPs and monitors their colloidal stability.	The presence of a Surface Plasmon Resonance (SPR) peak is usually found in the range 400 – 450 nm.	(Reddy <i>et al.</i> , 2019)
Transmission Electron Microscopy (TEM)	Determines the internal morphology, exact particle size, and shape at a high resolution.	Represents spherical, oval or triangular forms; determines grain size (15–40 nm).	(Githala <i>et al.</i> , 2022)
Scanning Electron Microscopy (SEM)	Analyzes surface morphology, topography, and the distribution of nanoparticles.	Demonstrates the surface texture (e.g., flower-like or smooth texture) and particle clustering.	(Koduru <i>et al.</i> , 2018)

X-Ray Diffraction (XRD)	Identifies the crystalline nature, phase purity, and face-centered cubic (FCC) structure.	Narrow diffraction peaks with the angles of theta (e.g., 38°, 44°, 64°, 77°) that are identical to silver standards.	(Bala & Rani, 2020)
Fourier Transform Infrared Spectroscopy (FTIR)	Recognizes the functional groups (biomolecules) that are involved in reduction and capping.	Presence of groups such as -OH, N-H, or C=O on the surface, which can be detected using bands.	(Titus <i>et al.</i> , 2019)
Dynamic Light Scattering (DLS)	Determines the hydrodynamic diameter and size distribution (Polydispersity Index - PDI).	Gives the average size of the particle (including the hydration layer) and homogeneity.	(Alshameri <i>et al.</i> , 2022)

5. Dye pollution

Dye pollution is a significant threat to the environment due to the widespread use of synthetic compounds in the textile, leather, and food industries. Besides their complex chemical structure (containing aromatic rings and chromophores), the molecules of these dyes are relatively stable due to their strong resistance to natural degradation, resulting in their continuous survival within aquatic systems (Maheshwari *et al.*, 2021). The textiles industry is the major polluter of fresh water on the planet. Among them, azo dyes are the most hazardous pollutants because they are believed to be carcinogenic because of the release of amine and benzene derivatives (Wang *et al.*, 2013). Water pollution by artificial dyes, such as methylene blue (MB) and rhodamine B (RhB), has become a severe global problem because of their high stability and kind of complicated chemical structure, which is not easy to degrade. This is the reason why they remain in water bodies for a longer period and are accumulated into food chain (Kolya & Kang, 2024). The harmfulness of these dyes is not only related to the visual effect they produce, but also entails serious consequences on the aquatic ecosystem due to blocking sunlight and hindering photosynthesis of water plants, on one hand, as well as by the risk for human health ranging from skin irritation to complex relationships with drugs (Kolya & Kang, 2024; Tkaczyk-Wliziło & Mitrowska, 2022). To address this difficult problem, several emerging therapies have also been developed: physical (adsorption and filtration), chemical (oxidation and photolysis), and even some interesting biological solutions — such as the ability of strains of microorganisms to break down complex compounds by reducing their toxicity (L. Kumar & Bharadvaja, 2020). There is now an emphasis towards sustainable and economic practices, such as the utilization of agricultural waste/natural biomaterials as economically viable adsorbent instead of commercial activated carbon (Ong *et al.*, 2012). However, complete removal of dyes and restoration of water quality is still a major challenge, which also encourages the development of more environmentally benign and effective decolorization techniques (Pereira & Alves, 2012). The future demands stronger legislation on industrial waste disposal and high-performance sustainable colorants that can minimize environmental impact of these industries (M. Liaquat *et al.*, 2025). Due to its chemical recalcitrance several advanced technologies have been developed to remove or convert such compounds into harmless products: Nanotechnology and photolysis: Nanoparticles produced using as green route (iron and palladium etc.) could effectively degrade dye molecules in a sustainable fashion (Pandey *et al.*, 2020).

Photocatalysts such as nanocomposites are also attractive for the efficient utilization of solar light to achieve higher degradation efficiency of methylene and rhodamine dyes, which is an economically viable and environmentally friendly method (Nikolic *et al.*, 2025).

5.1. Adsorption and Physical Technologies:

Advanced materials including MOFs and two-dimensional boron nitride nanosheets that exhibit high adsorption performance able to remove dyes from water without respect to molecular size or ionic properties have been designed (Tsukada & Konno, 2024). Dielectric barrier discharge plasma systems (DBD) provide an economically competitive method for replacing conventional oxidation technologies that produce reactive oxygen species. The real-time monitoring of dye

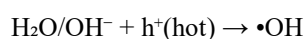
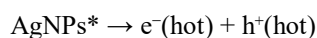
concentration leads to the development of carbon-nitride-sheet-based electrochemical sensor for the management of water quality along with its treatment (Bashir *et al.*, 2025). Although these technologies are proving the effective in the laboratory, a critical problem remains to be solved for their implementation in large industrial plants. Further research on eco-friendly dyes and stringent policies on wastewater discharge are the most desirable approach to reduce the ecological impact of these dyes. Improvement of this is urgent for the new kind of treatment with relatively high efficiency standards but strict requirements on environment. The photocatalysis technology is one of the most sustainable ones for water containing dyes pollution. In contrast to classic adsorption methods removing pollutants from one phase to another, and merely moving them around in the original forms, photocatalysts can decompose intricate dye structures into harmless substances (water and carbon dioxide) with light under conditions that allow complete mineralization. Competitive features of this technology are that it can be operated at mild environmental conditions and by the use of renewable energy sources such as sunlight, it can contribute to reducing carbon footprint and lower operational costs. Moreover, by integrating green synthesis of nanoparticles with photocatalytic technology a real eco-friendly system is developed to reduce toxic materials during synthesis and treatment. This provides a viable and affordable solution for the removal of synthetic dyes from aquatic ecosystems.

5.2. AgNPs as Photocatalysts

Silver nanoparticles have attracted considerable interest in water treatment because of their ability to promote the degradation of organic pollutants, including synthetic dyes. Their catalytic behavior is closely related to their nanoscale dimensions and surface properties. Particle size, morphology, surface area, surface charge, and the nature of the capping layer can all influence the interaction between AgNPs and pollutant molecules. In photocatalytic systems, the optical response of silver is particularly important because AgNPs exhibit localized surface plasmon resonance (LSPR), which allows them to interact efficiently with light and participate in light-driven surface reactions (R. Zhou, 2022).

When AgNPs are exposed to light of a suitable wavelength, the conduction electrons at their surface undergo collective oscillation, resulting in LSPR excitation. The decay of this excited plasmon can generate energetic, non-equilibrium electron-hole pairs, commonly described as hot carriers. These charge carriers may participate in reactions occurring at the nanoparticle surface. Hot electrons can be transferred to dissolved oxygen and promote the formation of superoxide radicals ($O_2^{\bullet-}$), whereas hot holes and other oxidative surface processes may contribute to the formation of hydroxyl radicals ($\bullet OH$) from water or hydroxide ions. These reactive oxygen species can attack chromophoric groups and aromatic structures within dye molecules, resulting first in decolorization and structural degradation and, under favorable reaction conditions, further oxidation toward mineralization products such as CO_2 , H_2O , and other inorganic species (L. Zhou *et al.*, 2024). A schematic representation of the proposed plasmon-assisted photocatalytic degradation mechanism of AgNPs is shown in Figure 5.

The main steps of this plasmon-assisted process can be represented in a simplified form as follows:



These equations provide a simplified representation of the proposed reaction pathway rather than a fixed stoichiometric mechanism. The relative contribution of $O_2^{\bullet-}$, $\bullet OH$, and other reactive species may vary according to the surface characteristics of the AgNPs and the conditions under which the photocatalytic reaction is carried out. Consequently, photocatalytic efficiency cannot be attributed to the optical properties of AgNPs alone. Catalyst loading, initial dye

concentration, solution pH, irradiation wavelength and intensity, exposure time, and nanoparticle size can all influence the observed degradation rate (Nayak *et al.*, 2025). An important point in evaluating dye removal is the distinction between adsorption and photocatalytic degradation. Adsorption involves the accumulation of dye molecules on the nanoparticle surface and does not necessarily result in chemical breakdown of the dye. Photocatalytic degradation, in contrast, involves light-induced chemical transformation of the adsorbed or dissolved dye molecules through reactions involving photo-generated reactive species. A reduction in dye concentration or UV–Visible absorbance should therefore not automatically be interpreted as evidence of photocatalytic degradation, since part of the observed decrease may arise from adsorption. For this reason, photocatalytic experiments commonly include a dark-equilibration period before irradiation. Changes occurring during this period can provide an estimate of adsorption, while the additional removal observed after illumination is used to assess the light-driven process. The efficiency of dye degradation is also strongly influenced by the operating conditions of the photocatalytic system. Increasing the amount of AgNPs can initially improve degradation by providing more available surface sites and greater interaction with incident light. Excessive catalyst loading, however, may increase aggregation or light scattering and reduce photon penetration through the reaction medium. High dye concentrations can similarly limit light transmission and occupy active surface sites, resulting in lower degradation efficiency. Solution pH is another important parameter because it can affect nanoparticle surface charge, dye speciation, and the generation of reactive oxygen species. Alkaline conditions have been reported to favor $\bullet\text{OH}$ formation in some systems, although the optimum pH varies with the AgNP–dye combination and should not be generalized to all photocatalytic systems (Hernández-De Los Santos *et al.*, 2025; Lellis & Oliveira, 2024).

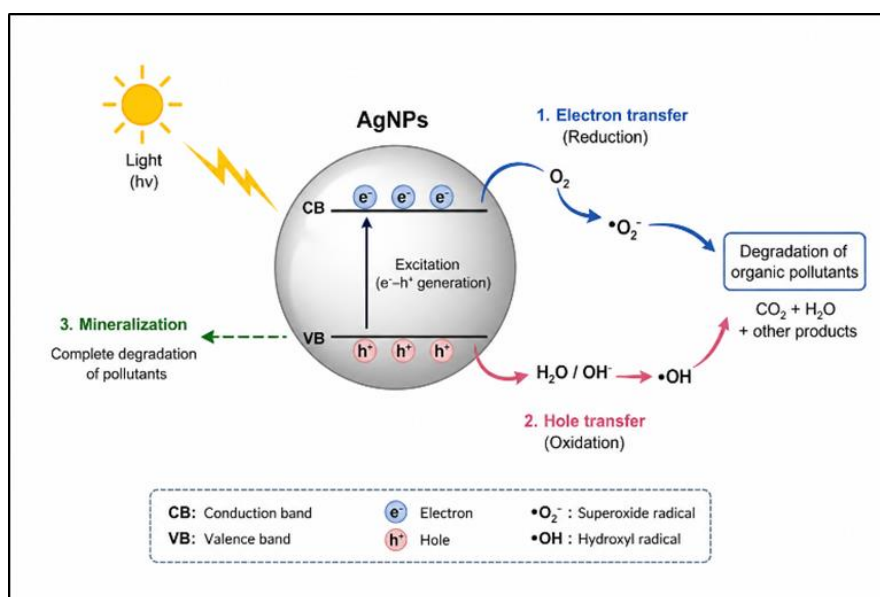


Figure (5) Schematic illustration of the photocatalytic mechanism of green-synthesized AgNPs under light irradiation, showing electron–hole generation, reactive oxygen species formation, and degradation of organic pollutants.

Photocatalytic activity of the plant-mediated AgNPs has been studied with a variety of organic dyes with widely varying efficiencies, depending on the size of the nanoparticles, the amount of catalyst used, the source of the irradiation, the pH, the concentration of the dye, and the reaction time. In one of the previous studies done by Vanaja *et al.* (2014), the degradation efficiency of methylene blue by AgNPs synthesized using *Morinda tinctoria* leaf extract was determined as 95.3% after 72 h of exposure to sunlight. The used dosage in this system was 10 mg of AgNPs and the decrease of the characteristic absorption band of methylene blue showed that the color of the dye was getting faded over time. In contrast, significantly shorter treatment times have been reported with other plant extracts type.

For instance, [Kadam et al. \(2020\)](#) reported 97.57% degradation of methylene blue dye in 150 min using AgNPs synthesized from cauliflower (*Brassica oleracea* var. *botrytis*) waste under the sunlight irradiation. In a similar manner, AgNPs synthesized using the bark extract of *Thespesia populnea* degraded 92% of the methylene blue after 120 min of exposure in sunlight, and the degradation process was attributed by the formation of hydroxyl radicals and the generation of superoxide reactive species ([Yahya Tahir et al., 2022](#)).

Further studies highlight the synthesis method adopted for the preparation of AgNPs and experimental conditions employed for the dye treatment, which significantly influence the photocatalytic response of AgNPs. [Dua et al. \(2023\)](#) used the leaf extract of *Eupatorium adenophorum* for synthesis of AgNPs and obtained 78.69% Rhodamine B degradation under sunlight irradiation for 90 min. In that experiment, 5 mg/L of AgNPs was allowed to stand in a 10 mg/L solution of Rhodamine B in the dark for 20 minutes before adding to the solution, this was done to evaluate the contributions of adsorption and photocatalysis separately. The activity was even higher with AgNPs prepared using *Disporopsis longifolia* leaf and stem extracts, where almost 100% of the methylene blue was removed in 240 min under sunlight conditions with negligible amount of silver leached ([Tam et al., 2022](#)). *Citrus aurantium* peel-mediated AgNPs were also demonstrated to have the ability to degrade a number of structurally distinct dyes by [Ringwal et al., \(2021\)](#), Methylene blue, acridine orange and rose bengal were degraded to 95.35%, 87.34% and 90.09%, respectively, after 98 h, and 4 h respectively of exposure to the ultraviolet radiation. However, less responsive was methyl orange, and methyl orange was degraded by ~51% after 10 h of solar irradiation, suggesting that photocatalytic efficiency cannot be generalized for different dye structures even with the same AgNPs catalyst.

The same irradiation dependency and property of nanoparticles has been also seen in the more recent investigations. [Alshehri and Malik \(2020\)](#) reported 93.37% degradation of Rhodamine B dye after 130 min as a result of the UV irradiation using AgNPs synthesized by *Matricaria chamomilla*. The efficiency of degradation was also enhanced as the reaction temperature was raised, to around 98.55% at 60 °C, showing that reaction conditions can have a significant influence on the apparent photocatalytic efficiency. [Bustos-Guadarrama et al. \(2023\)](#) directly compared ultra-small AgNPs prepared by using extracts of *Pelargonium hortorum* flower and *Allium fistulosum* stem. Both materials were spherical, but the AgNPs obtained from *A. fistulosum* were smaller in size, with a modal value of ~0.6 nm and achieved 100% photocatalytic efficiency, while the AgNPs obtained from *P. hortorum* were larger, with a modal value of ~2 nm, and reached an efficiency of 95%. The authors then proposed a correlation between response in the photocatalytic and particle size.

The wide photocatalytic potential of plant-based AgNPs is further supported by recent findings, while at the same time; it is challenging to directly compare different systems. The Rhodamine B degradation data were reported to be followed by pseudo-second-order kinetic model with R² value of 0.91, with 91.20% degradation after 80 min at pH 12 for AgNPs synthesized using *Eucalyptus globulus* leaf extract ([Velmurugan et al., 2024](#)). The decolorization of methylene blue was nearly 80% with AgNPs extracted from leaves of *Bambusa arundinacea* after 30 min of UV light exposure ([Jayarambabu et al., 2023](#)); whereas, recently, the AgNPs synthesized by the leaves of *Boerhaavia diffusa* showed 91.26% decolorization of methyl orange after 200 min exposure to sunlight ([Sudhakar et al., 2025](#)).

Altogether, these studies demonstrate that high degradation percentages do not necessarily indicate the relative performance of the plant mediated AgNP photocatalysts. When comparing the photocatalytic efficiency across studies, differences in the irradiation sources, irradiation times, loading of catalyst, initial dye concentration, solution pH, dimensions and experimental controls of the nanoparticles should also be considered.

The green-synthesized NPs show outstanding economic superior of recycle and long-range storage life compared to traditional chemical synthesis routes which would be an extremely promising long-acting protocol for water purification and

ecosystem protection. Different studies have shown the potential of plant-mediated AgNPs for photodegradation of various organic dyes. The reported degradation efficiencies vary depending on the plant source, dye type, nanoparticle properties, catalyst dose, irradiation conditions and reaction time. Representative studies on the degradation of various dyes using AgNPs are summarized in Table 4.

Table (4) Comparative synthesis conditions, characteristics, and photocatalytic performance of plant-mediated AgNPs.

Plant source	Extraction conditions	AgNP synthesis parameters	AgNP characteristics	Photocatalytic conditions	Degradation (%)	Reference
<i>Morinda tinctoria</i> leaves	10 g fresh leaves in 100 mL distilled water; heated at 60°C for 10 min and filtered	10 mL extract + 90 mL of 1 mM AgNO ₃ ; room temperature; pH 4.6–8.6 investigated	Mainly spherical/rod-shaped; 79–96 nm; crystalline AgNPs	MB (10 mg/L); 10 mg AgNPs in 100 mL; sunlight; 72 h	95.3%	(Vanaja <i>et al.</i> , 2014)
<i>Brassica oleracea</i> var. <i>botrytis</i> (cauliflower waste)	Cauliflower waste extract	3 mL extract; 0.5 mM AgNO ₃ ; pH 8.5; microwave irradiation at 600 W for 5 min	Average size 35.08 nm; surface area 19.22 m ² /g	MB; sunlight; 150 min	97.57%	(Kadam <i>et al.</i> , 2020)
<i>Jasminum</i> flower	20 g flowers in 100 mL distilled water; heated at 80°C for 3 h and filtered	Extract added gradually to AgNO ₃ solution; product centrifuged and dried	Crystalline AgNPs; SPR approximately 380–440 nm	10 mg AgNPs in 100 mL MB; sunlight; 120 min	78%	(Aravind <i>et al.</i> , 2021)
<i>Disporopsis longifolia</i> leaves/stems	10 g dried powder in 100 mL water; ultrasound extraction for 60 min; filtered	0.2 mL extract; 1.5 mM AgNO ₃ ; 40°C; 30 min	Mainly spherical; approximately 13–14 nm	MB, 5 mg/L; 20 mg AgNPs in 100 mL; sunlight; 240 min	~100%	(Tam <i>et al.</i> , 2022)
<i>Adhatoda vasica</i> leaves	15 g dried leaves in 100 mL water; heated at 65°C for 45 min and filtered	7 mL extract + 50 mL of 0.05 M AgNO ₃ ; pH 3; 25°C; 10 min	Spherical; 3.88–23.97 nm; mean ~11.36 nm	Amaranth; 100 mL dye solution; 15 mg AgNPs; sunlight; 60 min	97.7%	(Chaudhari <i>et al.</i> , 2023)
<i>Sambucus ebulus</i>	Phenolic extract; methanol removed by rotary evaporation before AgNP synthesis	12.5 mL extract + 25 mL of 20 mM AgNO ₃ ; pH 10–11; optimized at 85°C; reaction time ~4 h	Spherical; cubic structure; approximately 35–50 nm	Methyl orange; sunlight; 10 µL nanocatalyst; 11 min	95.89%	(Hashemi <i>et al.</i> , 2022)
<i>Eupatorium adenophorum</i> leaves	Shade-dried leaves; powdered; aqueous Soxhlet extraction; extract filtered and lyophilized	10 mL extract + 90 mL of 0.1 M AgNO ₃ ; 60–80°C; 400 rpm stirring	SPR around 400 nm; crystalline AgNPs characterized by XRD, SEM and DLS	Rhodamine B; sunlight; 90 min	78.69%	(Dua <i>et al.</i> , 2023)

However, there are still some concerns about the environmental safety of composite nanoparticles, in particular their potential toxicity and the cost of synthesis. Therefore, the use of non-toxic and readily available biological materials can make the synthesis process safer, more affordable and more environmentally friendly. This approach can also support the practical use of such systems while reducing their potential impact on the environment (Recio-Sánchez *et al.*, 2019).

5.3. Environmental toxicity and safety considerations

While plant-mediated synthesis provides a green pathway to form AgNPs, the products of such a green method should not be viewed as necessarily being environmentally safe. In the water, AgNPs may aggregate, settle, oxidatively dissolve, become sulfidated, and chlorinated, potentially altering the mobility and bioavailability of the NPs. The oxidative dissolution is of special importance because it can liberate Ag⁺ ions that can have a toxic effect in addition to the particle specific effect. Other reported adverse impacts include on microorganisms, algae, aquatic plants, zooplankton, and other aquatic organisms; severity of these impacts is highly dependent on particle size, degree of surface coating, concentration, duration of exposure, and water chemistry (Kang *et al.*, 2023; Yang *et al.*, 2024). The recovery of the catalyst, the residue of silver, the recovery of dissolved Ag⁺ after the treatment, and the possible release of silver during the repeated use, should therefore be taken into account in water treatment by photocatalytic degradation, in addition to the removal of the dye. Ecotoxicity testing under

environmentally relevant conditions and measurements of both total and dissolved silver would give a more realistic basis for evaluating the safety of AgNP-based treatment systems.

5.4. Limitations, standardization, and scale-up

Although considerable research has been conducted on the synthesis of AgNPs using plants, reproducibility is still a significant challenge. The chemical constituents of an extract may change depending on the plant species, part of the plant, geographical location, season, plant growth stage, storage, and extraction method. On the other hand, various or incomplete reaction parameters are reported in the literature such as pH, temperature, reaction time, AgNO₃ concentration, and extract to precursor ratio. Such sources of variation can hinder size, morphology, photocatalytic performance and surface chemistry of the nanoparticles to be reproduced across different laboratories. The data is not fully comparable because plant authentication, extraction yield, extract composition, synthesis conditions, purification procedures and characterization data are not consistently reported (Abegunde *et al.*, 2024). Scale-up brings its own set of challenges due to the possibility of changes in mixing parameters, heat transfer, mass transfer, and reaction kinetics as the process is scaled-up from milliliter scale batches to larger reactors. Other considerations when determining the economic feasibility of the process include plant material availability, extraction and purification costs, energy usage, recovery of nanoparticles, catalyst lifetime, and waste management. Accordingly, further research is needed to integrate process standardization, repeated-batch tests, catalyst-reuse trials, silver-leaching tests, and techno-economic evaluation to ensure the large-scale application of plant-mediated AgNP photocatalysis in wastewater treatment.

CONCLUSIONS

The green synthesis of nanoparticles using plants is one of the recent trends that has received wide attention in nanotechnology research, because plants have bioavailability, low cost and high environmental compatibility compared to traditional chemical methods. The plant extracts have a broad range of secondary compounds like phenols, flavonoids, alkaloids, and terpenes, which act as both reducing and stabilizing agents during the synthesis process and lead to the formation of stable synthetic nanoparticles with different physical and chemical properties. Results from recent studies indicate that the particle size, shape and distribution is directly influenced by the synthesis factors (plant extract concentration, temperature and pH) and therefore on the applied efficiency. Plant-based silver nanoparticles (AgNPs) have proven their effectiveness in multiple applications including medical fields as antimicrobials and therapeutic agents, in addition to their uses in electronics and the treatment of environmental pollutants. In a catalytic aspect, AgNPs serve as effective photocatalysts in the visible light region and accomplish degradation of complex structure of recalcitrant pigments into non-hazardous metabolites such water and carbon dioxide evolve as byproducts. However, there are still challenges related to the standardization of synthesis conditions and the reduction of variability in particle properties, which requires the development of advanced biotechnological strategies to more deeply understand biological mechanisms and improve the quality of large-scale synthesis. Accordingly, plant-based green synthesis is seen as one of the promising future paths that support the principles of sustainability and contribute to the development of safe and environmentally friendly nanotechnologies.

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