Green Synthesis of Silver and Silver Oxide Nanoparticles From Plants and Their Characterization

Anuj Kandwal, Shama Parveen, Rakesh Kumar Bachheti, Archana Bachheti, and Arun Kumar Khajuria

Abstract More contemporary synthetic approaches have been superseded by affordable and ecologically friendly nanoparticle (NP) production technologies. Green chemistry is environmentally safe, nontoxic, biocompatible, and financially productive. In the past, numerous research teams have produced silver and silver oxide nanoparticles from diverse plant extracts, and their findings have been widely reported. Green synthesis methods utilize microorganisms, plant extracts, or proteins as bio-capping and bio-reducing agents. They function as bio-nanofactories for material synthesis at the nanoscale size to create biogenic nanomaterials. Here, we have outlined the creation process, characterization, and composition of these plant-mediated silver oxide and silver nanoparticles made by plant-mediated synthesis. Green synthesis of silver and silver oxide nanoparticles depends on variety of parameters, such as extract concentration, exposure time, temperature, and pH. UV–visible spectroscopy, DLS, TEM, SEM, XRD, EDX, FTIR, etc. can successfully characterize plant-mediated silver and silver oxide nanoparticles. Future studies must concentrate on understanding the intricate mechanism of metal and metal oxide nanoparticle synthesis and designing nanoparticles that are less hazardous, healthier, and have precisely controlled dimensions and form. Additionally, silver release is more likely to occur in small-sized spherical silver nanoparticles. This review concludes that

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further research into the synthesis and characterization of metallic silver and silver oxide nanoparticles made via green synthesis is necessary to bring green synthesized products to the market.

Keywords Nanoparticles · Green route synthesis · Biogenic fabrication · Mechanism · Various methods

1 Introduction

Nanoscience is one of the encouraging research fields in novel science with marvelous applications in biology, physics, chemistry, and material science. Nanoscience and nanotechnology is a branch of science and engineering defined as the design, synthesis, characterization, and application of materials whose shape and size have been manipulated at the nanoscale. Particles smaller than 100 nm in any one dimension are usually referred to as "nanoparticles" (Husen & Iqbal, 2019; Kouvaris et al., 2012). High surface area-to-volume ratio, variable pore size, and high reactivity are some of the nanostructured materials' improved or pronounced characteristics that change particles' chemical, physical, thermal, mechanical, catalytic, and electromagnetic characteristics (Bachheti et al., 2019; Iravani et al., 2014; Painuli et al., 2020; Pal et al., 2011). Metallic nanoparticles (MNPs) play a crucial role in reforming human life and its environment. This draws immense interest from researchers owing to its large variety of potential applications in optical, biomedical, water treatment, electronics, cosmetics, agriculture fields, food technology, mechanical engineering, energy, polymer science, agriculture and environmental and health science (Bachheti et al., 2020, 2020a, 2020b, 2021, 2022; Chawla et al., 2023; Fu & Fu, 2015; Husen et al. 2019; Husen & Jawaid, 2020; Husen, 2022a, 2023a, 2023b, 2023c; Husen 2023a, 2023b; Husen & Siddiqi, 2023; Mandal et al., 2023; Taghiyari et al., 2023). Today, a significant portion of the nanomaterials employed in many industries utilize chemical and physical processes. Existing synthesis techniques are known to be costly and to involve chemicals that are harmful to the environment and human health, which include solvents made from organic materials, reduction agents, and stabilizers, which limits the practical application of these nanoparticles in therapeutic and scientific sectors (Shume et al., 2020). In order to reduce or altogether avoid the use of dangerous chemicals and prevent the development of superfluous and toxic byproducts, several research organizations are now engaged in finding affordable and environmentally safe nanoparticle synthesis procedures. The green synthesis technique offers the most advantageous replacement for the current chemical and physical ways of synthesis since it is less expensive, safer to use, and environmentally benign (Abate et al., 2023; Godeto et al., 2023; Gonfa et al., 2023; Zebeaman et al., 2023). Because botanical extracts contain biomolecules including protein, carbohydrates, and coenzyme precursors that can reduce metal ions, using them as reducing substances has also started to look interesting. Additionally, the developed nanoparticles are stabilized and capped by these biomolecules. In comparison to microbe-mediated production, plant-mediated synthesis is more scalable and quicker. It has also been shown to be effective, affordable, and easily accessible. Because of the aforementioned factors, manufacturing nanoparticles from plant sources has emerged as the most desirable and popular technique (Danish et al., 2021; Elemike et al., 2017).

Metallic NPs (silver, gold, zinc oxide, silver oxide, copper oxide, and titanium oxide) have been synthesized, studied, and utilized by researchers in numerous/frequent fields (Joshi et al., 2019; Leyu et al., 2023). Silver and silver oxide nanoparticles are an excellent choicer in nanotechnology in the field of biological systems for medical imaging and for treating diseases among different metallic nanoparticles (Gonfa et al., 2022; Jeevanandam et al., 2018). Silver oxide and silver NP have been extensively used for cellular delivery because of their versatile characteristics/properties like wide availability, deep functionality, good compatibility, potential for targeted drug delivery, and moderate release of drugs. Besides medical and pharmaceutical applications, metallic NPs widely used in everyday applications (Christian et al., 2008).

Recently, scientists' attention has switched to the use of plant extracts in the production of nanoparticles. This approach is attracting more interest than other biological systems because it offers a clear, practical, economical, secure, environmentally friendly, practical, and advantageous path to synthesizing MNPs of desired shape and size. The fact that plant extract-mediated synthesis of NPs is easier to maintain, more readily available, and safe to handle than microbial synthesis of NPs is a significant advantage. Different nanoparticles (Ag, Au, silver oxide, and TiO_2) of various shapes and sizes have been produced using various plant components, including leaves, peels, roots, stems, seeds, fruits, and flowers (Jana et al., 2000). The main benefit of plant-mediated MNP synthesis over chemical synthesis is that no additional protective agent is required in the former (Shekhawat et al., 2014). Moreover, it is easy to get plant extracts to develop a successful and environmentally friendly method for manufacturing industrial quantities of uniform metallic nanoparticles. Thus, the aim of this chapter is to provide in-depth information about the plant-mediated synthesis and characterization of ZnO nanoparticles.

2 Classification of Metallic Nanoparticles

Nanoparticles can be widely classified into two categories, namely, organic nanoparticles, which comprise carbon NPs (fullerenes), and inorganic NPs, comprising magnetics NPs of noble metals (like gold, silver, platinum) and semi-conductor NPs (like titanium oxide and zinc oxide, etc.). At present, interest in inorganic metallic nanoparticles (silver, gold, platinum, titanium oxide, silver oxide, zinc oxide) is growing intensively as they provide better material properties with functional adaptability and have been tested as potential tools for medical imaging for dealing with diseases because of their size features and superiority over chemical images (Khan et al., 2019).

Metallic NPs (silver, gold, zinc oxide, silver oxide silver oxide, copper oxide, titanium oxide) have been prepared, studied, and utilized by researchers, scholars, and scientists in numerous fields. Ag and silver oxide-based nanoparticles are of excellent choice and have excellent scope in nanotechnology and biological systems for medical imaging and treating diseases among the different metallic nanoparticles (Jeevanandam et al., 2018). Silver oxide and silver NP have been extensively utilized for cellular delivery because of their adaptable characteristics/properties like widespread accessibility, deep functionality, good compatibility, the potential for targeted drug administration, and moderate absorption of drugs. Besides medical and pharmaceutical applications, metallic NPs widely used in everyday applications (Christian et al., 2008).

The number of dimensions of materials that are outside the nanoscale (100 nm) range allows for the classification of nanoparticles into three categories, as follows (Tiwari et al., 2012).

(I) **Zero-dimensional nanostructured materials (O D)**
All three dimensions are measured within the nanoscale in zero-dimensional (0 D) nanostructured materials, i.e., all dimensions are smaller than 100 nm. Zero-dimensional NSMs can be either amorphous or crystalline. It can exhibit various shapes and forms. For example, nanoparticles, quantum dots, nanolenses, hollow spheres, and uniform particle arrays.

(II) **One-dimensional nanostructured materials (1 D)**
Only one dimension is outside the nanoscale in one-dimensional nanostructured materials, which may result in needle-like nanomaterials. They substantially impact nanoelectronics, alternative energy sources, and nanocomposite materials. For example, nanotubes, nanobelts, nanoribbons, nanowires, and nanorods.

(III) **Two-dimensional nanostructured materials (2 D)**
In this class, two dimensions are outside the nanoscale. They can exhibit plate-like shapes. Examples are nanofilms, nanowalls, nanoplates, nanodisks, nanoprisms, nanolayers, nanocoatings, and graphene. They are especially interesting not only for understanding the mechanism of nanoparticle growth but also for their investigation and applications in sensors, nanoreactors, photocatalysts, nanocontainers, and templates for two-dimensional structures for other materials.

3 General Methods of Metallic and Metal Oxide Nanoparticle Synthesis

Currently, various methods, including physical, chemical, and biological, are used to synthesize metallic nanoparticles (Mittal et al., 2013). From the structural point of view, there are two basic approaches for nanoparticles synthesis which involve "top-down" and "bottom-up" (Fig. 1). "Top-down" technique is usually achieved by physical methods, in which the size of starting bulk material is reduced by removing material until the desired nanoparticles are obtained. However, the serious drawback of this approach is the imperfection of obtained structure. The other method is "bottom-up" (atom by atom or molecule by molecule), usually achieved by chemical and biological methods, in which the atoms and molecules randomly assemble themselves into the desired nanoparticles (Arole & Munde, 2014). The main advantage of the bottom-up method is that the synthesized nanoparticles are free of structural defects. Scheme 1 shows several methods and strategies used to synthesize metallic NPs (Singh et al., 2018).

The physical methods used to synthesize MNPs include evaporation–condensation, spray pyrolysis, laser ablation, pulse wire discharge, sputtering, electron beam lithography, plasma, gamma radiation, and microwave irradiation (Tran & Le, 2018). The chemical methods such as chemical reduction of metallic salt, template method, reverse micelles method, polyol process, sonochemical method, electrochemical method, hydrolysis, wet chemical method, and tollens methods are generally used to synthesize metallic NPs. A stabilizing agent must be added in chemical approaches to stabilize dispersive nanoparticles. The use of toxic chemicals and high radiation levels harmful to the environment is a severe drawback of the chemical and physical approaches (Khandel & Shahi, 2018). Therefore, researchers need to develop green routes for the synthesis of MNPs.

Green chemistry, also called sustainable chemistry, is the scheme, development, and execution of chemical reactions and products that minimizes or eradicates the

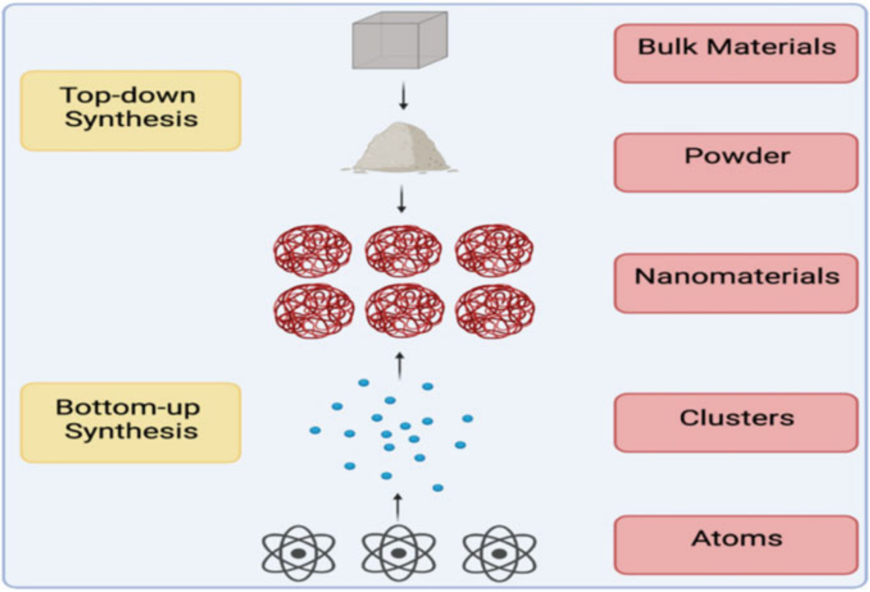
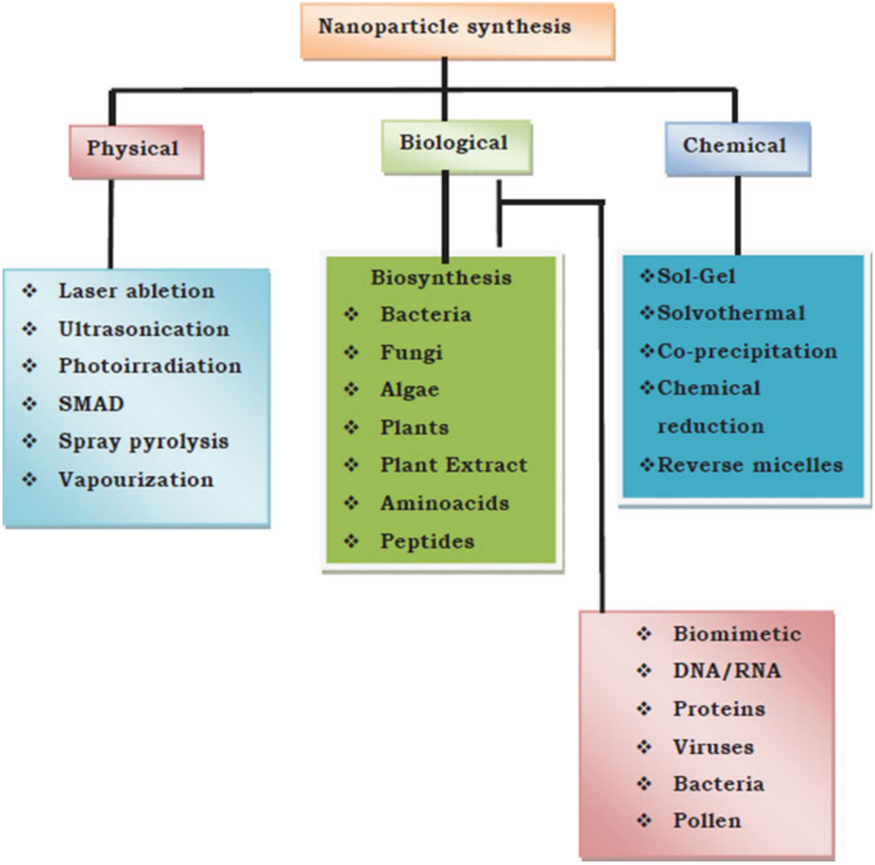


Fig. 1 Top-down and bottom-up approach for nanoparticles synthesis. Adopted from Alsaiari et al. (2023)



Scheme 1 Schematic representation of different methods to synthesize metallic nanoparticles

hazardous and toxic substances harmful to social life and the environment. It also focuses on energy-efficient processes. In recent years, the researcher has shifted their focus toward the biosynthesis of nanoparticles as it is green, cost-effective, feasible, rapid, sustainable, and environmentally benign. Biosynthesis of metallic NPs (bottom-up approach) is a bio-reduction method that uses naturally occurring eco-friendly substances such as plant extracts, vitamins, proteins, polysaccharides, biodegradable polymers, amino acids, microalgae, and microorganisms, including fungi and bacteria, as reducing, capping, and stabilizing agents. Bio-inspired methods are increasing steadily as they do not require hazardous toxic chemicals, high pressure, temperature, and energy (Heera & Shanmugam, 2015). The bio-enthused approach is very much close to the principles of nature, and it allows nature to synthesize stable MNPs.

4 Plant-Mediated Synthesis of Silver and Silver Oxide Nanoparticles

Recently, researchers have shifted their focus toward the biosynthesis of MNPs using plant extracts. This method is gaining more attention than other biological systems because it provides a clean, cost-effective, safe, eco-friendly, convenient, and beneficial route to synthesizing MNPs of desired shape and size. The significant advantages of plant extract-mediated synthesis of NPs over the microbial synthesis of NPs are that these are easy to maintain, readily available, and safe to handle. Different parts of plants, such as leaves, peel, roots, stem, seeds, fruits, and flowers, have been used to produce different nanoparticles (Ag, Au, silver oxide, TiO_2) of different shape and size (Jana et al., 2000). The major advantage of plant-mediated synthesis of MNPs over the chemical method is that in the former, there is no need for an additional protective agent (Shekhawat et al., 2014).

Several FTIR spectroscopic studies of plant-mediated NPs indicate that phytochemicals like flavonoids, alkaloids, terpenoids, polyphenols, polysaccharides, protein, and chlorophyll present in plant extracts act as reducing, capping, and stabilizing agents, and thus were believed to be responsible for the synthesis of Ag and silver oxide nanoparticles (Liu et al., 2017). The synthesis of bio-inspired nanoparticles results from the interaction of metallic salt with the plant extracts, which only takes place at optimum temperature, time, and pH (Kredy, 2018).

The most effective green synthesis technique for Ag and Ag_2O–NPs is using plant sources. The production of Ag and Ag_2O–NPs using plant-mediated synthesis takes less time and results in more stable nanoparticles than Ag and Ag_2O–NPs produced through microbe-mediated generation. The fact that botanical sources may be used easily, cheaply, and safely is crucial. They also include flavonoids that can stabilize the resultant nanoparticles (Husen et al. 2023d; Abbasi et al. 2020). The use of plant-derived materials has advanced to this point as more and more research teams have investigated the potential application of various plants for the manufacture of nanoparticles through the use of extracts of both aerial and beneath-the-ground parts, such as the roots, leaves, fruits, vegetables, and others (Ghotekar et al., 2020).

Silver nanoparticles were synthesized by using common and standard plant-mediated methods. At room temperature, aqueous plant extract and $AgNO_3$ solution were mixed in a fixed ratio in a 2 L Erlenmeyer conical flask. Then, the mixed solution was kept in a dark place for 72 h so that the synthesis of silver nanoparticles could take place. The solution turned a dark crimson-red color after 72 h, indicating the creation of Ag nanoparticles. To eliminate unreacted or uncoordinated components, the resulting solution was centrifuged for 20 min at 7500 rpm, rinsed with deionized distilled water, and then washed with ethanol. After being mashed in a mortar and pestle to create fine and homogeneous powdered graying black nanoparticles, the material was finally dried in an oven at 50 °C. Phytochemicals in plants are considered to mediate the synthesis of silver oxide nanoparticles. AgOH is produced initially as a result of the reaction among the hydroxyl groups (–OH) of the phytochemicals and the Ag+ from $AgNO_3$ before being changed into Ag_2O (Ravichandran et al., 2016; Sharma & Srivastava, 2020).

The roots and leaves of the plant contained various phytochemicals which plays an important role in reducing, capping, and stability of silver and silver oxide nanoparticles. For instance, *Ricinus communis* roots and leaves contained a variety of phenolic and flavonoid chemicals, including gallic acid, kaempferol-3-o-b-d-xylopyranoside, diethyl phthalate, kaempferol-3-o-b-d-xylopyranoside, 2-methyl, l-valine, triethyl citrate, quercetin-3-o-p-d-glucopyranoside, octadecanoic acid, 1-hexadecanol, and *n*-hexadecenoic acid; however, indole-3-acetic acid is the main component in root extract. Although due to the complicated chemical makeup of plants (extract), the precise method of metal nanoparticles by employing plant extract is uncertain. However, based on the above finding, a generic strategy for the creation of silver nanoparticles using three phytochemicals is given (see Fig. 2). With the release of hydrogen (reactive), keto form of the indole-3-actetic acid (present in the root extract) transforms into the enol form; the enol form, however, was unstable since it had two hydroxyl groups on the same carbon, and it changed back into keto form. Thus, silver nanoparticles are created when Ag^+ and Ag^0 combine as a result of the reactive hydrogen that has been released. Similar to this, triethyl citrate and flavonoid (quercetin-3-o-p-d-glucopyranoside) were regarded as reducing agents in the case of leaf extract. The phytochemicals (1-valine amino acid) and phenolic compounds play a significant role in the stability of metal nanoparticles, thus stabilized the silver nanoparticles (Huang et al., 2010; Rakhi & Gopal, 2012).

5 Characterization of Metallic Nanoparticles

Several techniques, such as UV–visible spectroscopy, SEM, XRD, DLS, EDX, TEM, FTIR, and TGA, can characterize metallic nanoparticles (Moond et al., 2023; Shaik et al., 2018).

In the preliminary stage, the formation of metallic nanoparticles is characterized by UV–visible spectroscopy. Metallic nanoparticles show the bright color and characteristic absorption band in the UV–visible region of the electromagnetic spectrum owing to a process known as surface plasmon resonance (SPR). Green-synthesized Ag and silver oxide nanoparticles show characteristic color and absorption UV–visible band, which is mainly dependent on their shape and size. Different surface plasmon resonance absorption bands in the range 300–700 nm are generally used to characterize different Ag (410–480 nm) and silver oxide (310–390 nm) nanoparticles of size less than 100 nm. A study revealed that the UV–visible spectrum of plant-mediated silver nanoparticles using *Allium cepa* extract has a sharp peak at around 413 nm. In another study, SPR peaks at around 422 and 447 nm were reported for the plant-mediated silver oxide NPs using *Vitex negundo* extract (Zargar et al., 2011).

X-ray diffraction (XRD) is a widely used technique for characterizing and identifying metallic nanoparticles' phase, crystalline nature, and crystalline structure).

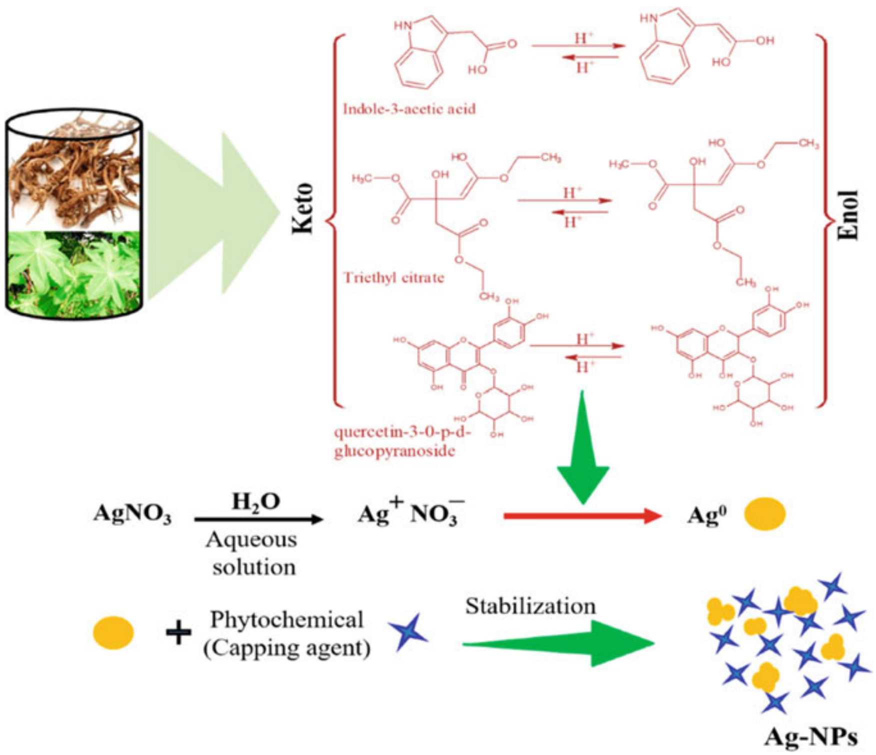


Fig. 2 Probable mechanism for plant-mediated synthesis of silver nanoparticles. Adopted from Gul et al. (2021)

In X-ray diffraction, X-rays enter the powdered sample, resulting in a diffraction pattern according to Bragg's equation $n\lambda = 2dSin\theta$. This diffraction pattern is compared with the standard data to obtain the crystal structures. In XRD pattern consists of diffraction peaks as a function of the diffraction angle 2θ. The size of metallic nanoparticles is determined by the Debye–Scherrer equation:

$$D = K\lambda / \beta \cos\theta$$

where D is the average crystallite size, λ is the X-ray wavelength, β is the full width at half maxima (FWHM), K is Scherrer's constant, and θ is Bragg's diffraction angle (Fig. 3).

Scanning electron microscopy (SEM) is a type of electron microscope that is used to produce the image of a sample and thus gives the morphology of metallic nanoparticles (Arjunan et al., 2012). In SEM, electron beams are generated from a filament (tungsten) and then accelerated toward a condenser lens by anode, where these are converged and then projected onto the specimen by the objective lens. These beams scan the surface sample in a raster pattern. The electron beam interacts with

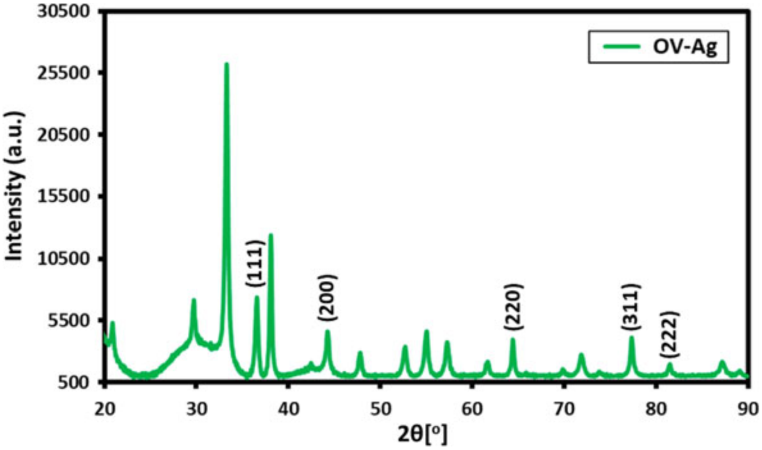


Fig. 3: XRD spectra of silver NP using *Origanum vulgare* leaf extract. Adopted from Shaik et al. (2018)

the atom in the sample, producing various signals and giving information about the surface morphology and composition of samples (Pradeep, 2007).

Energy-dispersive X-ray (EDX) analysis is a chemical microanalysis technique used to characterize the elemental composition of nanoparticles. SEM coupled with energy-dispersive X-ray spectroscopy (SEM–EDX) is widely used for surface analysis and elemental composition. EDX spectra measure the relative abundance of emitted X-rays from samples against their energy (Fig. 4). EDX spectrum shows the peaks at around 0.5 keV for oxygen and 3 keV for the elemental silver (Alaraidh et al., 2014).

Transmission electron microscopy (TEM) is a valuable and prominent microscopy approach that involves passing an electron beam through a specimen to create an image. Transmission electron microscopes can image at a substantially higher resolution than other microscopes due to the smaller de Broglie wavelength of electrons (Fig. 5). TEM can reveal the finest details of internal structure. High-resolution TEM can be used to analyze the structure and constitutional analysis of Ag and silver oxide nanoparticles (Ankamwar et al., 2005).

Fourier-transform infrared (FTIR) spectroscopy is used to identify the phytochemicals responsible for the capping, reducing, and effective stabilization of metallic nanoparticles. It is a technique that produces an IR spectrum of absorption or emission of a solid, gas, and liquid over a wide spectral range of 4000–400 cm^{-1} (Fig. 6).

For instance, silver nanoparticles were synthesized from the leaf extract of *Moringa oleifera,* and their antimicrobial and catalytic properties were evaluated (Sathyavathi et al., 2011). The absorption peak of silver nanoparticles at $\lambda_{max} =$ 460 nm was recorded by UV–visible spectrophotometer, XRD and FRSEM results confirmed the average size of NPs was less than 40 nm. FTIR study showed several stretching peaks at 3308, 1629, 1069, and 1029 cm^{-1} indicating the presence of

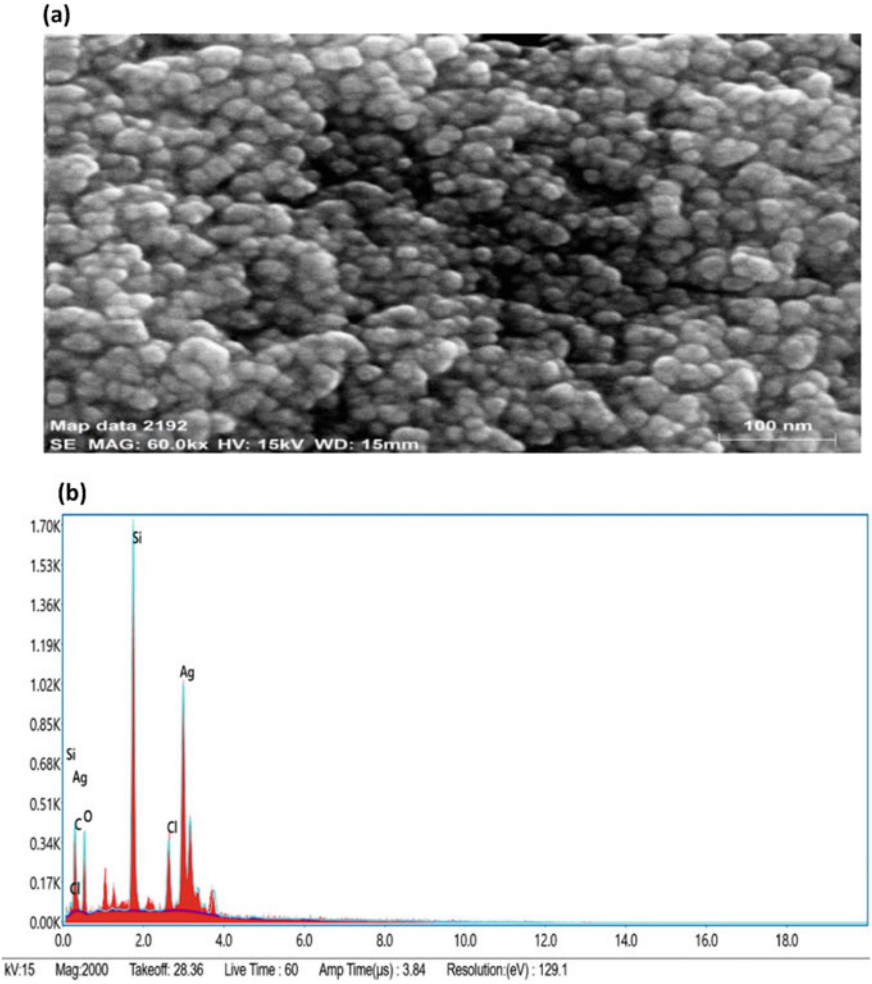


Fig. 4 **a** SEM image of Ag nanoparticles **b** EDX image of Ag nanoparticles using *Trigonella foenum-graceum* leaf extract. Adopted from Moond et al. (2023)

several functional groups acting as capping and stabilizing agents. In another study, Roy et al. (2017) reported the synthesis of silver NPs from the leaf extract of *Azadirachta indica* and the screening of these NPs for antioxidant and antibacterial activities. SPR peaks of these nanoparticles at $\lambda_{\text{max}} = 430$ nm were recorded by a spectrophotometer, particle size analyzer (PSA) showed the average size range of nanoparticles was 21.07 nm, and FTIR study confirmed the presence of phenolic compounds. In another report, spherical silver NPs were synthesized from *Abutilon indicum* leaf extract, and their antioxidant, antibacterial, and anticancer activity was investigated (Mata et al., 2015). TEM imaging showed the formation of spherical NPs with an average size of 70–75 nm, and XRD results revealed wurtzite hexagonal

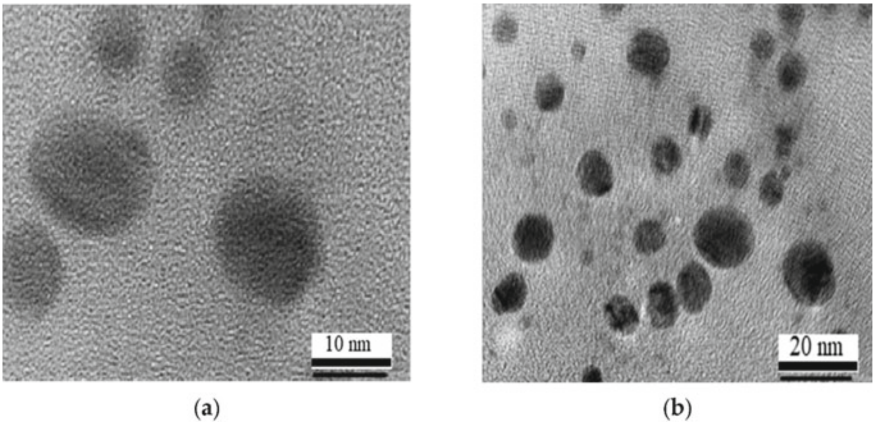


Fig. 5 TEM images of Ag nanoparticles using *Trigonella foenum-graceum* leaf extract. Adopted from Moond et al. (2023)

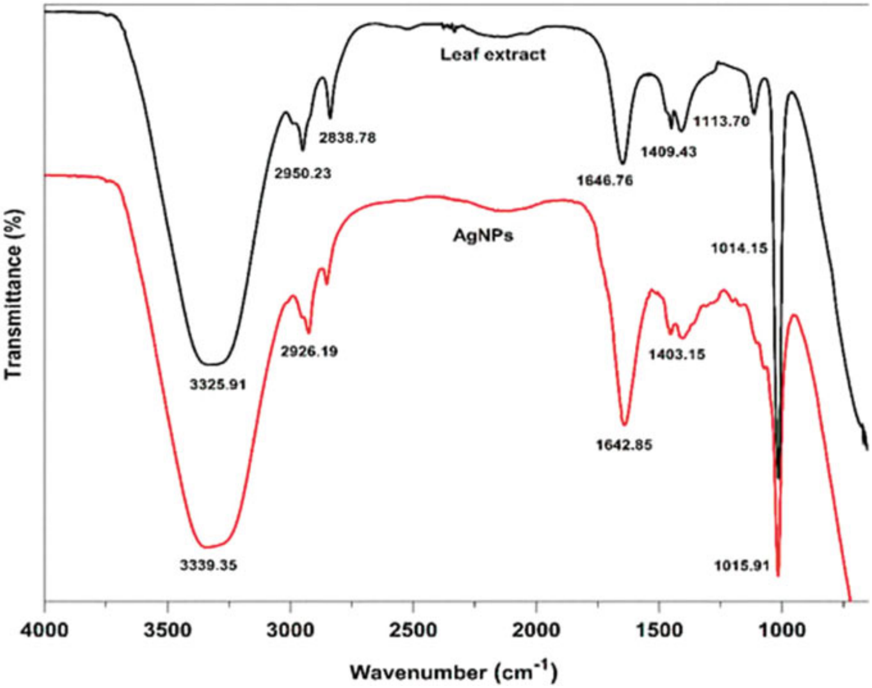


Fig. 6 FTIR spectrum of Ag nanoparticles using *Trigonella foenum-graceum* leaf extract. Adopted from Moond et al. (2023)

silver oxide NPs. FTIR spectrum showed a peak at 3291 cm^{-1} due to the presence of hydroxyl functional groups, while other peaks at 2930, 1663, 1530, 1239, and 459 cm^{-1} confirmed the presence of C-H, amide I and II groups, C-O bond, and metal–oxygen groups.

In order to create Ag_2O–NPs, Rashmi et al. (2020) combined separately milled plant powders of *Centella Asiatica* and *Tridax procumbens* using $AgNO_3$. Gotu kola, or *Centella Asiatica*, is part of the Apiaceae family. It is important in medicine and cosmetics because of the pentacyclic triterpenoids, which are asiaticoside, brahmoside, Asiatic acid, and Brahmic acid that it is said to possess. These substances can stabilize the resultant nanoparticles as well as decrease $AgNO_3$ to Ag_2O. The synthesized Ag_2O nanoparticles appear to have outstanding electrochemical capabilities, good photocatalytic activity for AO-8 under UV light, and antimicrobial properties. The generated nanoparticles, with a diameter of particles of 11–12 nm, are suggested by the results to have these qualities.

Using the hydroethanolic leaf extracts of the Ranunculaceae family's medicinal plant, *Helleborus odors*, Sutan et al. (2021) created Ag_2O–NPs in a bottom-up manner. Using a 1:1 mixture of crude hydroethanolic leaf extracts and $AgNO_3$, the Ag_2O–NPs were created. The reaction was allowed to run its course for 24 h in the dark at room temperature.

The gathered nanoparticles were identified as Cytogen toxic leaf extracts of papaya (*Carica papaya*) and fenugreek (*Trigonella foenum-graecum*). Separate mixtures of fenugreek leaf and papaya leaf extracts were combined with $AgNO_3$, which was then agitated at room temperature for 8 h to produce Ag_2O–NPs with a particle size range of 19.4–30.4 nm. These Ag_2O-NPs were then tested for hemolytic activity.

Shah et al. (2019) used *Paeonia emodi* leaf extracts combined with $AgNO_3$ while constantly stirring at 55 °C for 1 h 30 min. The resultant nanomaterials were investigated for their potential as photocatalytic and antibacterial agents. According to Suresh et al. (2018), the plant Pavetta indica Linn was employed to create Ag_2O–NPs. In order to create distorted cubic-shaped nanomaterials with a size less than 50.5 nm, leaf extracts were combined with an $AgNO_3$ solution and agitated continuously for 24 h at 100–120 °C. These particles were then examined for their ability to reduce inflammation and for their phytochemical content.

As a reaction mediator and capping agent, Muthukumar et al. (2022) used Amaranthus sp. leaf extract to create Ag_2O–NPs in the shape of husks. Aqueous leaf extract of Amaranthus sp. was gradually added to $AgNO_3$ solution with constant magnetic stirring at 35 °C for 15–20 min to produce Ag_2O–NPs. According to Muthukumar et al. (2022), Amaranthus sp. leaf extract was utilized as a capping agent and reaction mediator in forming Ag_2O nanoparticles in the shape of husks. Other reports of green synthesis of Ag and silver oxide NPs from the various parts of plant extract are illustrated in Table 1.

Table 1 Plant-mediated synthesis of silver and silver oxide nanoparticles of some important medicinal plants

Plant used	Characterization technique	Nanoparticle synthesized	Key references
Acalypha indica	XRD, EDS, SEM, HRTEM	Ag	Krishnaraj et al. (2010)
Aerva lanata	TEM, EDS, FTIR, XRD	Ag	Balashanmugam et al. (2014)
Allium cepa	UV–VIS, XRD, SEM,	Ag	Bouqellah et al. (2019)
Allium sativum	UV–VIS, TEM,	Ag	El-Refai et al. (2018)
Aloe vera	HRTEM	Ag	Vélez et al. (2018)
Alstonia scholaris	DLS, FTIR, XRD, UV–VIS,	Ag	Shetty et al. (2014)
Azadirachta indica	TEM, DLS, FTIR, UV–VIS	Ag	Ahmed et al. (2016)
Berberis vulgaris	XRD, UV–VIS, FTIR, DLS	Ag	Behravan et al. (2019)
Carica papaya	TEM, XRD, FTIR, SEM, UV–VIS	Ag	Balavijayalakshmi and Ramalakshmi (2017)
Cinnamon zeylanicum	UV–VIS, HRTEM, EDX	Ag	Anjum et al. (2019)
Clerodendrum serratum	UV–VIS, TEM,	Ag	Patil and Mengane (2016)
Datura stramonium	FTIR, EDAX, TEM, XRD, UV–VIS,	Ag	Gomathi et al. (2017)
Desmodium gageticum	FTIR, EDAX, TEM, UV–VIS, SEM	Ag	Thirunavoukkarasu et al. (2013)
Diospyros montana	SEM, XRD, EDAX, FTIR, TEM, DLS, UV–VIS	Ag	Bharathi et al. (2018)
Eugenia stipitata	TEM, XRD, SEM, UV–VIS	Ag	Kumar et al. (2016a)
Ficus carica	XRD, TEM, DLS, UV–VIS	Ag	Kumar et al. (2016b)
Justicia adhatoda	UV–VIS, TEM,	Ag	Bose and Chatterjee (2015)
Kalanchoe pinnata	TGA, FTIR, DSC, XRD, EDX, SEM, PSA, UV–VIS	Ag	Phatak and Hendre (2015)
Petroselinum crispum	TGA, FTIR, DSC, XRD, EDX, SEM, TGA, XPS, DLS, UV–VIS	Ag	Talabani et al. (2021)
Parthenium hysterophorus	FTIR, TGA, DSC, TEM	Ag	Ahsan et al. (2020)

(continued)

Table 1 (continued)

Plant used	Characterization technique	Nanoparticle synthesized	Key references
Mimosa pudica	TEM, XRD, EDX, SEM, UV–VIS, FTIR	Ag	Fatimah and Mutiara (2016)
Mulberry	TEM, FTIR, XRD, UV–VIS	Ag	Chunfa et al. (2018)
Musa paradisiaca	TEM, FTIR, XRD, UV–VIS	Ag	Anbazhagan et al. (2017)
Sambucus nigra	TEM, XRD, UV–VIS	Ag	Moldovan et al. (2016)
Sida cordifolia	UV–VIS, ZETA POTENTIAL, EDAX, SEM, FTIR, TEM	Ag	Srinithya et al. (2016)
Thevetia peruviana	EDX, TEM, SEM, FTIR, XRD, UV–VIS,	Ag	Oluwaniyi et al. (2016)
Tinospora cordifolia	EDX, XRD, SEM, FTIR, UV–VIS	Ag	Selvam et al. (2017)
Zingiber officinale	TEM, FTIR, XRD, UV–VIS	Ag	Yang et al. (2017)
Ziziphus oenoplia	EDAX, XRD, DLS, FTIR, TEM, UV–VIS	Ag	Soman and Ray (2016)
Panicum miliaceum	UV–VIS, FTIR, TEM, TGA, XPS, EDX,	Silver oxide	Velsankar et al. (2022)
Centella Asiatica	XRD, UV–VIS, FTIR, SEM, EDX,	Silver oxide	Rashmi et al. (2020)
Cleome gynandra	UV–VIS, ZETA POTENTIAL, SEM, FTIR, TEM, DLS,	Silver oxide	Mani et al. (2021)
Helleborus odorus	UV–VIS, XRD, TEM, EDX	Silver oxide	Şuţan et al. (2021)
Herniaria hirsuta	UV–VIS, FTIR, XRD, SEM,	Silver oxide	El-Ghmari et al. (2021)
Trigonella foenum-graecum	UV–VIS, FTIR, TEM, SAED	Silver oxide	Ashokraja et al. (2017)
Amaranthus sp.	UV–VIS, XRD, SEM, DLS	Silver oxide	Muthukumar et al. (2022)
Diospyros montana	UV–VIS, ZETA POTENTIAL, EDAX, SEM, FTIR, TEM,	Silver oxide	Sujatha et al. (2023)
Pavetta indica Linn	XRD, SEM, EDX	Silver oxide	Suresh et al. (2018)
Artocarpus heterophyllus	UV–VIS, XRD, FTIR, DLS, TEM	Silver oxide	Sharma and Srivastava (2020)
Lawsonia inermis	UV–VIS, EDAX, XRD, SEM, FTIR	Silver oxide	Fayyadh and Jaduaa Alzubaidy (2021)

(continued)

Table 1 (continued)

Plant used	Characterization technique	Nanoparticle synthesized	Key references
Daphne alpina	XRD, SEM, EDX, FTIR	Silver oxide	Haq et al. (2021)
Thunbergia mysorensis	UV–VIS, FTIR, XRD, SEM, TEM,	Silver oxide	Kokila et al. (2022)
Cyathea nilgirensis	FTIR, XRD, SEM, EDX	Silver oxide	Pradheesh et al. (2020)
Salix integra	UV–VIS, XRD, XPS, TEM, FTIR	Silver oxide	Patel and Joshi (2023)
Zephyranthes rosea	FTIR, TEM, SAED, EDX, XPS, XRD	Silver oxide	Maheshwaran et al. (2020)
Rhamnus virgata	FTIR, XRD, SEM, EDX, DLS, UV–VIS	Silver oxide	El-Ghmari et al. (2021)
Eupatorium odoratum	UV–VIS, XRD, SEM, TEM	Silver oxide	Elemike et al. (2017)

6 Challenges and Future Perspectives

The most frequently studied and utilized nanomaterials are undoubtedly silver nanoparticles. Green synthesis approaches have garnered a lot of interest recently among the various ways to produce silver nanoparticles since they are easy, effective, economical, and ecologically safe. In order to effectively use the biosynthesized silver nanoparticles for potential applications, it is necessary to obtain insight into the various inevitable challenges that must be addressed in the future. Metal and metal oxide nanoparticles have various properties that can be greatly influenced by their physical and chemical properties, especially their size, shape, and composition. This, in turn, can have a positive impact on their health benefits. Additionally, the metallic nanoparticle's typical size has a direct impact on both their catalytic and antibacterial properties (Chi et al., 2019; Ferdous & Nemmar, 2020; Hong et al., 2016; Yin et al., 2020). Although plant-mediated synthesis has received greater attention recently because it is a green strategy, it is still a novel concept that is in the early stages of research. In order to effectively use the plant-mediated silver and silver oxide nanoparticles for potential applications, it is necessary to obtain insight into the following inescapable issues that must be addressed in the future.

The shape and size of the silver nanoparticles produced by plants have varied greatly. To effectively manage the shape, size, and monodispersity of nanoparticles, it is necessary to experiment with and validate a variety of parameters, such as extract concentration, exposure time, temperature, and pH. Additionally, silver release is more likely to occur in small-sized spherical silver nanoparticles. Silver nanoparticles less than 10 nm are easily able to infiltrate bacterial cells, alter cell permeability, and cause cell damage. A significant issue in addition to this is the toxicity of metal nanoparticles. According to reports, the use of metal NPs in various industries has had extremely damaging impacts on both human health and the environment. For instance, prolonged exposure to silver can cause eye and skin discoloration and bluish-gray skin. Additionally, recent studies appear to support the idea that some bacteria are less susceptible to silver nanoparticles or are resistant to them. The mechanism behind the mechanism of silver nanoparticles is still poorly understood and now in a dormant state. In the future, attention should be paid to thorough investigations that identify the biochemistry of the bioactive molecules involved in capping and reducing during the creation of nanoparticles. In plant-mediated biosynthesis, different outcomes from the extract of the same plant species gathered from different parts of the world are expected due to differences in their makeup. This problem can be solved by correctly identifying the variety of phytochemicals present in plant extract and then researching how they affect capping and decreasing. Studies on the production of silver nanoparticles to date have solely used laboratory-scale experiments. For mass or industrial production to be possible, more optimization effort is required. The potential of biosynthesized silver nanoparticles for various applications has been shown in several research. Future research is necessary to assess the toxicity of biosynthesized silver nanoparticles, their biocompatibility (with cells and tissues), their safety for the environment (soil, water, and air), their accumulation in plants and animals, and their long-term effects on human and agricultural crop health. In comparison to conventional techniques, biogenic production of nanoparticles is more affordable. However, there is still room to cut costs, which are mostly caused by metal salts, microbial media, and downstream processing in biosynthesis. This can be resolved in the future by taking waste recycling into account as a different cost-saving measure.

7 Conclusion

Silver and silver oxide nanoparticles are the most desirable nanomaterials for various applications, including electrical, catalytic, antibacterial, and other biological activities. The literature for understanding the production and characterization of silver and silver oxide nanoparticles utilizing plant extracts is summarized in the current review. The use of plant extract in the synthesis of silver and silver oxide nanoparticles is advantageous due to its lower environmental impact and ability to create vast numbers of nanoparticles. Plant extracts may function in creating silver and silver oxide nanoparticles as both reducing and stabilizing agents. The use of plant extract in synthesizing silver oxide nanoparticles has advantages over other physical and chemical approaches since it is secure, environmentally benign, and easy to implement. UV–visible spectroscopy, DLS, TEM, SEM, XRD, EDX, and FTIR can successfully characterize these nanoparticles. Plants have a huge potential for producing silver and silver oxide nanoparticles with the desired shape and size that have a vast potential for use. In a nutshell, future studies must concentrate on understanding the intricate mechanism of metal and metal oxide nanoparticle synthesis and designing nanoparticles that are less hazardous, healthier, and have precisely controlled dimensions and form. Additionally, silver release is more likely to occur in small-sized spherical silver nanoparticles. Furthermore, the necessity to use plant-based metallic NPs more frequently in related disciplines must also be taken into consideration.

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