Green Route Synthesis and Characterization Techniques of Silver Nanoparticles and Their Biological Adeptness

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ABSTRACT: The development of the most reliable and green techniques for nanoparticle synthesis is an emerging step in the area of green nanotechnology. Many conventional approaches used for nanoparticle (NP) synthesis are expensive, deadly, and nonenvironmental. In this new era of nanotechnology, to overcome such concerns, natural sources which work as capping and reducing agents, including bacteria, fungi, biopolymers, and plants, are suitable candidates for synthesizing AgNPs. The surface morphology and applications of AgNPs are significantly pretentious to the experimental conditions by which they are synthesized. Available scattered information on the synthesis of AgNPs comprises the influence of altered constraints and characterization methods such as FTIR, UV−vis, DLS, SEM, TEM, XRD, EDX, etc. and their properties and applications. This review focuses on all the above-mentioned natural sources that have been used for AgNP synthesis recently. The green routes to synthesize AgNPs have established effective applications in various areas, including biosensors, magnetic resonance imaging (MRI), cancer treatment, surface-enhanced Raman spectroscopy (SERS), antimicrobial agents, drug delivery, gene therapy, DNA analysis, etc. The existing boundaries and prospects for metal nanoparticle synthesis by the green route are also discussed herein.

INTRODUCTION

Metal nanoparticles (NPs), due to their exceptional biological and physicochemical properties, have devoted particular/increasing attention to their use in emerging constituents for various applications.1 Among several metal nanoparticles, silver nanoparticles (AgNPs) are one of the most dynamic and interesting nanomaterials that have gained significant attention in the arena of nanotechnology.2 AgNPs and their nano-composites have created marvelous potential and noteworthy applications in diverse fields of nanotechnology, particularly in biomedical therapeutics (OR biomedical and therapeutic researches), MRI contrast agents, drug delivery, and biomedical devices for the detection of numerous alarming diseases or complications.3 Moreover, biomedical and other numerous applications of AgNPs are worth noting here since they have become an advanced material for consumer interest. AgNPs have gained popularity in industrial sectors, including textiles, food industries, feminine/female hygiene products, healthcare products, cosmetics, water purification plants, and environmental pollution control. AgNPs are also most widely used for thermal, electronics, engineering, energy, and magnetic field applications.4,5

The success of AgNPs lies in their advantageous amalgamation of physicochemical properties. These materials have several advantages, such as their large surface area to volume ratio, their ability to be attached to ligands with diverse functionalities to obtain custom-tailored properties, their toxicity toward pathogens, their ability to kill cancer cells, and their catalytic properties.4,6 Surface plasmon resonance (SPR) is the main characteristic of metal NPs, which can be influenced by some altered parameters like the shape and size of particles and the dielectric constant of the reaction mixture. AgNPs exhibit SPR peaks between 400 and 480 nm.7 Their extinction coefficients are 105 to 106 times higher than ordinary molecular chromospheres. Due to the weaker coupling to interbond transitions, the SPR for Ag is more intense than for any other metal NPs. The SPR frequency of AgNPs can also be altered from the visible to near-infrared by twisting their shape and size. Such exceptional properties have encouraged various studies and applications of AgNPs. Furthermore, the Ag-based compounds are consid-
erably more affordable than the Au-based ones. Therefore, AgNPs are considered a significant class of nanomaterials.

Several approaches have been studied for AgNP synthesis: (i) physical method, (ii) chemical method, (iii) photochemical method, and (iv) biological method (Figure 1). Each technique has several benefits and difficulties. The most common difficulties are the cost, scalability, and particle size distribution, which are briefly discussed in Table 1. Among the existing techniques, the chemical approaches have been frequently used for AgNP fabrication. These approaches offer a relaxed way to synthesize AgNPs. The chemical procedure of AgNPs in solution frequently works with the following three main components: (i) metal precursors (usually AgNO$_3$), (ii) reducing agents (i.e., ethylene glycol) to reduce metal ions into the metal atom, and (iii) stabilizing/capping agents (i.e., PVP) to regulate the development of NPs and stop them from aggregating.

The use of toxic chemicals in their chemical synthesis is a major concern as they show adverse effects on the environment as well as on living beings. Recently, remarkable attention has been paid to the synthesis of AgNPs via a greener route. Keeping in mind the need for sustainable nanomaterial synthesis, a lot of novel routes have been optimized based on the bioinspired reduction and, in general, termed biological methods. Many unusual biological entities have been investigated for the biogenic reduction of metal ions, in particular, bacteria, fungi, algae, simple amino acids, sugars, biodegradable polymers, vitamins, and plant extracts. These materials which are used for the production of NPs offer several benefits such as being benign, less toxic, recyclable, and secure, particularly by considering their use in food technology and medicine. These biological methods incorporate different philosophies of green chemistry, such as the use of renewable and nonhazardous raw materials, the avoidance of waste production, the use of greener solvents, and decreasing energy expenditure. Hence, there have been definite inventions toward the expansion of sustainable strategies and standards for developing eco-friendly nanomaterials. These nanomaterials have been prepared in combination with the accomplishment of green chemistry principles. Therefore, many new opportunities are available for synthesizing new green AgNPs which can be utilized for many applications.

The biological synthesis of AgNPs produced by living organisms is primarily founded on the principle of chemical synthesis. The only difference is the replacement of the stabilizer and reducing agent by molecules. These agents can be derived from microorganisms such as plants, yeasts, fungi, and bacteria. In summary, AgNPs can be synthesized by using

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**Figure 1.** Different methods of AgNPs synthesis.

**Table 1.** Synthesis of AgNPs Using Different Methods: Advantages and Disadvantages

| Synthesis Methods | Synthesis Principle | Advantages | Disadvantages |
|-------------------|---------------------|------------|--------------|
| Physical method   | Physical method for the AgNPs synthesized by using physical energy to harvest AgNPs with a narrow size distribution. | Radiation is used as a reducing agent, so no dangerous chemicals involved produce a large number of silver nanoparticles in a single process within a random distribution. | Expensive, less yield along with high consumption of energy, contamination of solvent, and random distribution. |
| Chemical method   | Silver ions reduce to the silver atoms by using chemical reducing agents. | Simple production, economics, and high yield. | Less use of capping agents for AgNP synthesis is toxic and hazardous; the manufactured particles require further purification as their surfaces are contaminated with chemical sediments; lack of regular sizes; require more steps to stop self-aggregation; and the release of hazardous byproducts during synthesis. |
| Photochemical method | Using photochemically generated intermediates, production of metal course and reduction of metal ions. | A clean process with good spatial resolution and convenience. | High costs and experimental environment are required. |
| Biological method | The reduction of silver ions to silver atoms by using biomolecules derived from living organisms. | Cost-effective and abundance of raw materials. | Les use of capping agents for AgNP synthesis is toxic and hazardous; the manufactured particles require further purification as their surfaces are contaminated with chemical sediments; lack of regular sizes; require more steps to stop self-aggregation; and the release of hazardous byproducts during synthesis. |

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ACS Omega 2022, 7, 27004−27020

https://doi.org/10.1021/acsomega.2c01400
a wide variety of biological techniques which are also considered eco-friendly and economic. The role of biological materials is found to provide a higher rate of reduction of metal ions at ambient temperature and pressure. Among the various biological entities used for NPs synthesis, the plant extract is a comparatively spontaneous approach since it does not require any special treatments like isolation, culture, and culture maintenance. Additionally, the synthesis of plant extract mediated AgNPs tends to be quicker than microorganisms, which is highly economic and comparatively easier for the bulk synthesis of NPs.

However, AgNPs exhibit an exceptional antibacterial activity that has attracted global attention to develop more efficient nanomaterials. An outstanding antimicrobial activity has been expressed by AgNPs against a number of microorganisms along with multi-drug-resistant bacteria. The improved antibacterial activity of AgNPs has become extremely valuable and needed in the pharmaceutical and medical industries. AgNP incorporation into a number of products has been reported, such as cosmetics, dressings, clothing, foods, and dental products. The antibiotic potential of AgNPs is directly connected to their mode of action, which can directly attack microorganisms in multiple assemblies simultaneously with the same dose to provide a chance and strength to execute the bacteria.

Here, we present the applications and a greener way to synthesize AgNPs. Many exceptional articles have already been reported on NP synthesis and their functionalization. Therefore, in this review, we do not mean to deliver ample analysis on this topic; instead, we will emphasize the facts that are of the utmost importance to AgNP synthesis by using plant extracts. Their biological aptness and interaction with biomolecules are also discussed in this manuscript.

**Green Route for AgNP Synthesis.** The three foremost ideas for AgNP synthesis in a greener mode are solvent selection, an ecologically pleasant reducing material, and a nonhazardous stabilizing material. To be energy proficient, the production methods must be conducted at neutral pH and ambient pressure and temperature. The biological specimens emerge as the best fit for stimulating such natural chemical environments. In the last few decades, several biological techniques have been applied for AgNP synthesis. These techniques have originated as possible options since they are found to be eco-friendly, economic, and simple techniques. It has also been identified that a lot of microorganisms can offer either intra- or extracellular inorganic ingredients that can be used as biodegradable nanofactories for the construction of nanomaterials and more predominantly for AgNP synthesis. The bulk synthesis of NPs by using microorganisms and biomolecules is always considered as an alternative to the chemical method not only for AgNPs but also for other metallic NPs. Several such studies which are biological, economic, ecofriendly, greener, and nontoxic have been reported for a greener synthesis of AgNPs.

Many approaches developed in the biosynthesis of metal NPs by using microorganisms, however, face many drawbacks, such as microbe culturing and better control over shape, crystallinity, and size distribution. The kinetic rate of the biological synthesis of NPs is also slow and not monodispersed; therefore, such difficulties have inundated the approaches. The innovative understandings obtained from strain choice and conditions of reaction optimization such as concentration, pH, temperature, incubation time, and genetic material quantity are required for the execution of biological approaches on a large scale. Meanwhile, many articles have been published on the green technique synthesis of AgNPs with a required morphology and size by using extracts obtained from different plant parts. Further, the most demanding method for large-scale production of AgNPs is the use of plant extracts with low maintenance needed. Plant extracts always carry biologically active molecules which can act as reducing and capping agents for NP synthesis, which extends their applications in the biological field. The biological methods employing green NP synthesis are therefore considered as the best tools because they confirm their nontoxic and biocompatible applications. The metallic NPs of Ag, Au, Cu, and Pd have already been synthesized by using materials that are benign, nontoxic, and ample, such as vitamin B2, tea, vitamin C, coffee extracts, beer juice, red grape, blueberry, blackberry, turmeric extracts, pomegranate, orange peel, and leave extracts of various plants.

**Plant Extracts Used for AgNP Synthesis.** Nowadays, the synthesis of nontoxic NPs by using plant extracts has opened many new routes of synthesis. Many plant extracts obtained from various plants and their excellent applications for the biosynthesis of NPs are well reported. Previously, it was known that the plants have the ability to hyperaccumulate and biologically reduce metal ions. With such exceptional properties, such plants are an eco-friendlier route for the biosynthesis and detoxification of NPs. The plant extracts are made up of terpenoids, bioactive alkaloids, polyphenols, phenolic acids, proteins, and sugars that are well-known for their reductive activity and are mainly accountable for reducing metal ions and stabilizing them. These bioactive molecules constitute an abundance of different organic compounds with carboxyl, hydroxyl, and carboxylic functional groups which facilitate the complexation of the metallic ions like Ag, Au, Pt, and Cu. The hydroxyl groups are oxidized to carbonyl groups by metal ions which themselves get reduced to elemental metal. The conversion of the hydroxyl groups to carbonyl groups via oxidation can be induced by dissolved oxygen in the aqueous system. The complexation of Ag ions by hydroxyl groups of starch and its successive reduction by aldehyde groups are well reported. Mohan and co-workers reported a simplistic approach for AgNP synthesis using Acacia gum (0.5% w/v) under a mild environment. They found that, initially, when Ag ions were mixed with aqueous acacia gum, an ion-exchange process occurred, where the carboxylate group of the acacia gum glycoprotein was transformed into −COOAg. Afterward, these −COOAg were converted into AgNPs and stabilized by polysaccharide polymer chains of the acacia gum. Puiso et al. used lingonberry and cranberry juices and recognized that the presence of phenolics, anthocyanins, and benzoic acid in the juices was accountable for the AgNP reduction and stabilization. Bar et al. synthesized AgNPs by using Jatropha curcas latex as a reducing and capping agent, where major latex components such as curcacyc line A, curcacyc line B, and curcin were responsible for the synthesis and stability of AgNPs. As the carbonyl groups of peptides and amino acids of these natural latex components have strong empathy to bind with metals and ions, the protein can act as an encapsulating agent, thus protecting AgNPs from accumulation. Pandey et al. established the presence of strong communication between the Ag particles and oxygen of −OH groups available in the gum polysaccharides by studying the FTIR spectra of AgNPs. This proved that the presence of
the –OH group in the gum polysaccharide had the superior ability to synchronize with Ag⁺ ions. The Saraca indica flower extract is rich in flavonoids, and the oxidation of the hydroxyl groups present in the flower extract by Ag⁺ ions led to AgNP development. From aldehyde to carboxylic acid, the oxidation for Ag⁺ ion reduction is due to the presence of flavanones or terpenoids found in the flower extract. Shankar and co-workers reported AgNP synthesis and Au core–Ag shell bimetallic NPs by using neem extract. The AgNPs were found to be polydisperse, and a large percentage of AuNPs had plate-like morphology. Their FTIR peaks for AuNPs were observed at 1608, 1384, and 1076 cm⁻¹, which indicated the existence of terpenoids or flavanones adsorbed on the NP surfaces. Reducing sugars present in neem extract were also accountable for the metal ion reduction. Park et al. report on polysaccharides and phytochemicals revealed how heparin, chitosan, cellulose, starch, alginic acid, and dextran work as reducing and capping agents for AgNP preparation. Jun et al. reported AgNP crystal formation by Polygala tenuifolia root extract. The FTIR band for AgNPs obtained at 1637 cm⁻¹ is considered responsible for the reduction of Ag⁺ ions. The FTIR band for AgNPs was observed to be polydisperse, and a large percentage of AuNPs had plate-like morphology. Their FTIR peaks for AgNPs were observed at 1608, 1384, and 1076 cm⁻¹, which indicated the existence of terpenoids or flavanones adsorbed on the NP surfaces. Reducing sugars present in neem extract were also accountable for the metal ion reduction. Park et al. report on polysaccharides and phytochemicals revealed how heparin, chitosan, cellulose, starch, alginic acid, and dextran work as reducing and capping agents for AgNP preparation. Jun et al. reported AgNP crystal formation by Polygala tenuifolia root extract. The FTIR band for AgNPs obtained at 1637 cm⁻¹ is considered responsible for the reduction of Ag⁺ ions.

**Preparation of Plant Extract.** In general, we classify extraction methods into two groups: (i) conventional methods and (ii) green technique methods. Maceration, infusion, digestion, decocation, percolation, reflux, and Soxhlet extraction are common conventional methods. These methods are simple and easy to set up, but large volumes of extracting solvent, longer extraction time, and less efficient extraction yield are their main drawbacks. Meanwhile, there has been remarkable development in the extraction methods with the introduction of green techniques, including pressurized liquid extraction (PLE), supercritical fluid extraction (SFE), ultrasound-assisted extraction (UAE), and microwave-assisted extraction (MAE). These techniques require less extraction solvent and less extraction time with efficient extraction yield. However, these techniques require a highly equipped and expensive experimental setup. A brief summary of the various methods of extraction is reported in Table 2.

**Stepwise Procedure for AgNP Synthesis by Using Plant Extracts.** The stepwise method followed by several researchers for the biological AgNP synthesis by using plant extracts has been summarized as follows and presented in Figure 2:

- Fresh, healthy, and mature plant parts are selected and washed frequently with tap water followed by deionized water to remove surface contaminants.
- Cleaned plant parts are sliced into fine pieces, air-dried in the shade for several days or at a definite temperature in a hot air oven for a definite time, and pulverized into fine powder.
- Powdered plant material can then be extracted with water or organic solvents by following different techniques, such as simple boiling for some minutes, microwave- and ultrasound-assisted extraction, etc.
- The extract is vacuum-dried and concentrated using a rotary evaporator.
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- The reaction mixture is then kept undisturbed until a reddish-brown color forms from the colorless AgNO₃.

| Table 2: Commonly Used Methods for the Extraction of Bioactive Components from Plant Extracts |
|-----------------------------------------------|
| Method                  | Extraction solvent | Volume consumed | Extraction time | Extraction temperature | Extraction efficiency |
|--------------------------|--------------------|-----------------|-----------------|------------------------|-----------------------|
| Maceration               | Water, aqueous     | Large           | Long (hours to days) | Under heat             | Low                   |
| Soxhlet Extraction       | Water, organic     | Large           | Long            | Under heat and pressure| High                  |
| Presurized liquid extraction | Organic solvents | Large           | Long            | Under heat and pressure| High                  |
| Microwave-assisted extraction | Organicsolvents | Large           | Long            | Under heat and pressure| High                  |
| Supercritical fluid extraction | Organic solvents | Large           | Long            | Under heat and pressure| High                  |
| Ultrasound-assisted extraction | Organic solvents | Large           | Long            | Under heat and pressure| High                  |

https://doi.org/10.1021/acsomega.2c01400
ACS Omega 2022, 7, 27004−27020
solution. This indicates the formation of AgNPs. This process can be carried out at room temperature or varying temperatures as per requirements.

- The free particles are then washed and purified by centrifugation.
- To eliminate extra silver ions, the silver colloids are washed multiple times with deionized water.
- Further, the AgNPs so prepared are lyophilized and kept in tight-packed vials under ambient conditions for their characterization and application.

**Mechanism of AgNP Formation by Using Plant Extract.** Plant extract mediated AgNP synthesis is generally started by mixing the extract with a AgNO$_3$ salt solution at room temperature. The reaction is too fast and visibly confirmed by observing the color change observation in vessels. This marks the formation of AgNPs. The nucleation of the reduced metal ions from monovalent to divalent oxidation states starts initially. Immediately after this step, it is followed by the periodic development of neighboring particles to form bigger nanoparticles via noncovalent interactions which are thermodynamically stable, while extra metal ion reduction continues. Multiple shapes and morphologies such as cubes, polygons, wires, etc. are obtained by the progressive aggregate development of NPs. At the final step of the synthesis, the plant extracts stabilize the NPs and result in a more energetically stable morphology.

Depending on the plant or plant material from which it was extracted, the plant extract comprises a variety of bioactive chemicals. In general, plant extracts contain flavonoids, terpenoids, and phenols, but proteins, glycosides, and polysaccharides have also been involved in nanoparticle formation. Depending on the plant or plant material from which it was extracted, the plant extract comprises a variety of bioactive chemicals. In general, plant extracts contain flavonoids, terpenoids, and phenols, but proteins, glycosides, and polysaccharides have also been involved in nanoparticle formation. The functional components of these bioactive compounds operate as reducing and stabilizing agents for the nanoparticle synthesis. Therefore, plants are considered as biochemically rich sources for NP synthesis. Figure 3 depicts the mechanism of AgNP formation using plant extracts.

**Factors Affecting AgNP Synthesis by Using Plant Extracts.** During AgNP synthesis, the concentration of plant extract and metallic salt, reaction time, pH, and temperature considerably manipulate the quality and morphology of NPs."Kellkawi and co-workers" investigated the synthesis of AgNPs using Mentha pulegium extracts through optimized method conditions with various extraction solvents (water, 70% ethanol, and absolute ethanol) and different concentrations of plant extract and metal ions. Their findings show that methanolic and aqueous extracts formed stable anisotropic nanoparticles with narrow size distribution below 50 nm, while ethanolic extracts synthesized significantly unstable AgNPs. Furthermore, the rate of nanoparticle synthesis with ethanolic extract was remarkably weaker than the two others. In addition, the stability of AgNPs decreased by increasing the plant extract concentration or by adding AgNO$_3$ concentration, and the rate of the reaction grew.

The concentration and composition of plant extracts can considerably disturb the quality and yield of the products. Therefore, for reaction optimization, the choice of an appropriate plant extract with a suitable concentration may be a critical step. Additionally, the fractionation of plant mixtures by using variable solvents may simplify the reaction control and interpretation of the results.

**Synthesis of Silver Nanoparticles Using Amino Acids.** Protein building blocks are amino acids that play a considerable role in metabolism and are oxidized by a range of oxidizing agents. Their reducing nature has been studied and reported by many scientific groups around the world for the purpose of NP synthesis. Since the overall charge of an amino acid in the aqueous solution depends on the pH of the medium, the AgNP formation rate could be managed by increasing or decreasing the pH by using amino acids. Roy et al. used cysteine as a reducing and capping agent for AgNP preparation. They found that the prepared AgNPs were stable for over one month and exhibited antimicrobial activity. Csapo and co-workers synthesized citrate-stabilized AgNPs functionalized with i-cysteine. They reported that AgNPs were only stable at pH > 7, while at pH < 7, an increase in the degree of aggregation was observed. Selvakannan et al. investigated the synthesis of AgNPs using Mentha pulegium extracts through optimized method conditions with various extraction solvents (water, 70% ethanol, and absolute ethanol) and different concentrations of plant extract and metal ions. Their findings show that methanolic and aqueous extracts formed stable anisotropic nanoparticles with narrow size distribution below 50 nm, while ethanolic extracts synthesized significantly unstable AgNPs. Furthermore, the rate of nanoparticle synthesis with ethanolic extract was remarkably weaker than the two others. In addition, the stability of AgNPs decreased by increasing the plant extract concentration or by adding AgNO$_3$ concentration, and the rate of the reaction grew.

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observed that tyrosine can act as an excellent reducing agent under alkaline conditions.

The Ag⁺ reduction on AgNPs at pH > 10 occurs because of the ionization of the tyrosine phenolic group, which can reduce Ag⁺ ions and itself gets converted to a semiquinone structure. Nidyaa et al. synthesized AgNPs functionalized with L-glutamic acid (Glu) using sodium borohydride (NaBH₄). Jacob et al. conveyed the synthesis of water-soluble AgNPs under alkaline conditions by Ag⁺ ion reduction using tryptophan as a reducing agent. The authors modified the AgNP surfaces by functionalizing them with different concentrations of tryptophan. The researchers observed a shifting of the AgNP SPR band from 400 to 540 nm, indicating the replacement of BH₄⁻ ions adsorbed on the surface of AgNPs by tryptophan, thus destabilizing the AgNPs. Rafey et al. synthesized AgNPs by using aspartic acid and hexadecyltrimethylammonium bromide (HTAB) as reducing and stabilizing agents, respectively, in the presence of aqueous NaOH. When the same experiment was performed in the absence of NaOH, there was no AgNP construction; this indicated that the presence of OH⁻ was necessary for Ag⁺ ion reduction. This study also depicted the absorption of Ag⁺ ions on the Ag-O surface due to the interaction between the Ag⁺ and OH⁻ ions. The aspartic acid plays a significant role in this reduction through an electron transfer mechanism from the α-carboxylate group of aspartic acid to Ag⁺ ions. It was also found that the growth of the spherical AgNPs is due to the α-COOH group of aspartic acid. Khan and co-workers studied the multidimensional role of cysteine as a reducing, cross-linking, stabilizing, and buffering agent during the growth of AgNPs. They used aqueous CTAB as a cationic micellar medium and studied the rate of AgNP formation with increasing cysteine concentration. They found that increasing the cysteine concentration decreased the rate of AgNP formation, whereas increasing CTAB concentration and Ag⁺ ions did not affect the reaction rate. Matos et al. conducted Xe light irradiation experiments with 21 different amino acids and used them as reducing and stabilizing agents for AgNP synthesis. They found that only five amino acids, namely, tyrosine, methionine, tryptophan, cysteine, and histidine, successfully produced AgNPs. The authors also reported that no illumination or heating was required for AgNP synthesis using tryptophan, and the addition of sodium hydroxide was sufficient. Chemical structures of some common sugars, polysaccharides, and amino acids present in plant extracts are presented in Figure 4.

**Analytical Techniques for the Characterization of AgNPs.** Many techniques have been used to characterize nanoparticles (NPs). These techniques have allowed researchers to gain further knowledge of the NP properties. Here, we provide a brief insight into the use of the following techniques, which were found to be beneficial during several characterization research studies: UV–vis spectroscopy, Fourier transform infrared spectrometry (FTIR), X-ray diffraction (XRD), and nuclear magnetic resonance (NMR).

**FTIR Spectroscopy.** FTIR spectroscopy is a well-established and a continually developing technique, which offers many advantages such as being rapid, high throughput, and nondestructive as well as being able to analyze a variety of samples. FTIR spectroscopy has been utilized in industry and research (Figure 5). Complex molecules, for example, the molecules attached to the AgNPs, have been detected by using this analytical technique.

FTIR spectroscopy works by exposing an IR beam to the sample of interest. IR radiation is then absorbed by the functional groups within the sample, resulting in vibrations in one of the following manners: stretching, bending, deformation, or a blend of vibration modes. IR spectroscopy in the mid-IR involves photons of wavenumbers ranging between 4000 and 600 cm⁻¹ becoming excitable, causing the molecule of interest to leave the vibrational ground level. Excitation of the target molecule can only occur if the energy of the photon is equivalent to the difference in energy between the ground and excited states. Thermal relaxation then causes the excited molecules to return to their ground state. Detection of this transition can be achieved by the absorption of photons that have energy equivalent to the difference in energy of the relevant vibrational levels. The vibrations mentioned here are referred to as fundamental vibrations. For these vibrations to be visible, coupling with a changing dipole moment must occur, and the wavenumber of the incident radiation must be identical to the vibrational wavenumber. Fundamental vibrations fall into four main categories: stretching vibrations, planar bending vibrations, out of plane bending vibrations, and torsion vibrations.

FTIR spectroscopy has been used within a diverse range of applications due to its multiplex and high throughput. FTIR spectroscopy has been used for material evaluations and identifications. Many green silver nanoparticle studies have utilized FTIR as a technique for analyzing the structures of AgNPs. The results of FTIR analysis of AgNPs synthesized using green silver nanoparticles showed a high absorption band at 3590 cm⁻¹ (O–H str.), 3070 cm⁻¹ (C–H str.), 1670 cm⁻¹.
(C=O str.), and 1525 cm$^{-1}$ (N–H bend, amide I) in some recent studies. By capping the AgNPs, the proteinaceous substance prevents agglomeration. The stretching vibrations of AgNPs cause the absorption bands at 816 and 630 cm$^{-1}$, as shown in Figure 6.

The use of Cocos nucifera in the green synthesis of AgNPs has been described previously by Uddin et al.\textsuperscript{84} It can be noted from the results that three significant peaks occurred in the spectra at 3450, 1645, and 1089 cm$^{-1}$. Furthermore, Al Masoud et al.\textsuperscript{86} demonstrated the use of FTIR to detect biomolecules for reducing Ag$^+$ ions and capping the ginger-extract-produced bioreduced AgNPs (Figure 7). The findings from this study showed that the functional groups can be detected from the synthesized AgNPs, and significant peaks can be detected at 1057, 1386, 1620, and 3417 cm$^{-1}$, which corresponded to primary alcohols and NO$_3$, and C–N stretching vibrations of aliphatic and aromatic amines, respectively, can be detected.

Furthermore, another study was performed by Awad et al.\textsuperscript{87} In this research, the authors prepared green nanoparticles from Trigonella foenum-graecum, and green NPs synthesized from silver nanoparticles were then examined using FTIR. The results showed significant absorption bands of AgNPs and Trigonella foenum seed extracts. The peaks from this study were observed around 3264, 1636, and 1961 cm$^{-1}$, which corresponded to $\cdot$OH, NH, and $\equiv$C–H, respectively.

UV–Visible Spectroscopy. UV–visible spectroscopy is an extremely helpful tool that can be used for the primary characterization of the synthesized nanomaterials (Figure 8). UV–vis has been employed to examine the synthesis and stability of AgNPs. Many benefits are associated with its use, such as being time efficient, simple, and specific to various kinds of NPs. It is also important to particle characterization of colloidal suspensions. Moreover, spectroscopy does not need to be calibrated. The optical properties of AgNPs make them very sensitive to specific light frequencies. The conduction and valence bands in AgNPs appear to be very close to each other, where electrons can move freely and instigate a surface plasmon resonance (SPR) absorption band. The AgNP absorption is influenced by the size of particles, dielectric medium, and chemical surroundings. The amount of metal NPs, sized between 2 and 100 nm, is recorded with surface plasmon peaks. The presence of NPs is confirmed by SPR peaks in the visible region.\textsuperscript{92–94}

A study carried out by Nazima et al.\textsuperscript{95} concluded that the average peak for AgNPs was observed at 430 nm (Figure 9). In addition, the average particle size of the nanoparticles was examined at 58 ± 0.05 nm using dynamic light scattering (DLS).

A research study conducted by Alomar\textsuperscript{96} focused on the use of a green chemistry technique to produce eco-friendly NPs using Peganum harmala leaves. UV–visible spectroscopy was applied to characterize silver nanoparticles (AgNPs), and a sharp peak was detected at 350 nm (Figure 10). For neem, aloe vera, Indian mint, and guava leaves, Alex et al.\textsuperscript{97} observed
A study carried out by Rani et al.\textsuperscript{84} saw the use of a green approach to synthesize highly stable spherical AgNPs. This study involved the use of UV–visible spectroscopy to examine the stability of nanoparticles over three months, where a sharp band between 420 and 430 nm was detected. Parit et al.\textsuperscript{86} conducted a further green study and reported the existence of two distinct peaks at 363 and 426 nm when synthesizing nonspherically shaped AgNPs.

Nuclear Magnetic Resonance (NMR) Spectroscopy. One of the main nondestructive molecular characterization techniques is NMR which analyzes the chemical environment of the nuclei and gives extensive information about the surface structure. This technique is now recognized as one of the most flexible and efficient methods for characterizing the structure of surface ligands. Moreover, NMR is employed to describe the surface modification of nanomaterials to prove ligand immobilization on the nanomaterials, by taking either a qualitative or quantitative approach. One of the disadvantages of NMR spectroscopy and imaging, compared with other modalities, is that it needs much more samples than small molecules as a result of the bulk nanomaterial dilution of surface ligands since the weight percentage of surface ligands drops exponentially by the growth of particle size.\textsuperscript{99} Furthermore, it is worth mentioning that line broadening is observed in nanoparticle-related ligands, and this can lead to obscure peak assignment and integration. The results depict that larger nanoparticles experience more severe line broadening in comparison with the smaller ones, speculated to be as a result of either homogeneous or heterogeneous line broadening.\textsuperscript{100} NMR can be applied to samples in all different physical and chemical states, including samples in gaseous, liquid, and solid phases. Despite not being a typical technique for characterizing nanoparticle surfaces, in numerous cases nanoparticle surfaces can be examined either directly or indirectly through chemical functionalization.\textsuperscript{101,102} State-of-the-art 2D NMR techniques, including diffusion and ordered spectroscopy, and advanced 2D NMR techniques, such as diffusion-ordered spectroscopy (DOSY), nuclear Overhauser effect spectroscopy (NOESY), total correlated spectroscopy (TOCSY), heteronuclear single-quantum correlation spectroscopy (HSQC), and rotating frame nuclear Overhauser effect spectroscopy (ROESY), are specifically practical and efficient to gain extra information on nanomaterial surfaces.\textsuperscript{103} The role of capping ligands in determining particle shape is also probed by using NMR spectroscopy analysis. On the whole, under definite reaction conditions, by employing NMR, in both solution and solid phases, the chemical conversion of NP precursors can be displayed with a high spatial and chemical resolution, for various metal identities; this is beneficial for a better understanding of the reaction mechanisms for NP synthesis. NMR is over and above useful for screening the process and intended products of ligand exchange when the initial capping ligands are required to be replaced.\textsuperscript{103}

X-ray Diffraction. XRD is a technique that can sharply analyze the structure and conformation of nanomaterial surface ligands as well as map their positions. Nanocrystals, besides atomically precise nanoclusters which have a well-defined molecular formula nature of the phase, lattice parameters, crystalline grain size, and ligand composition, are magnificent samples of nanomaterials for studying the total structure of the ligand shell.\textsuperscript{104,105} Bragg’s law is the underlying principle of the XRD technique, which is grounded in the wide-angle elastic scattering of X-rays. In other words, the crystal forms several diffraction patterns when it is exposed to X-rays. These patterns reproduce the physicochemical characteristics of the materials’ crystal structures. For example, in a powder specimen, diffracted beams normally come from the sample and represent its structural physicochemical properties. Each material owns its unique diffraction pattern, which can be defined and identified by comparing the diffracted pattern to the Joint Committee on Powder Diffraction Standards

![Figure 9](https://doi.org/10.1021/acsomega.2c01400) Using Cyprus rotundas, the UV–visible spectrum of AgNPs (reprinted with permission from ref 95).

![Figure 10](https://doi.org/10.1021/acsomega.2c01400) UV–visible absorption spectra of green synthesized AgNPs made with an aqueous Peganum harmala leaf extract (reprinted with permission from ref 96).

SPR bands of AgNPs at 446, 456, 443, and 347 nm, respectively. In another study, in which Al Masoud et al. prepared green NPs from ginger, an absorbance peak was observed at 434 nm (Figure 11). \textsuperscript{86}

![Figure 11](https://doi.org/10.1021/acsomega.2c01400) Absorption spectra of produced AgNPs in the ultraviolet–visible range utilizing ginger extract (reprinted with permission from ref 86).
(JCPDS) library’s reference database. Moreover, the diffracted beams can demonstrate the purity or imperfections of the sample. Therefore, this technique is generally employed to characterize and identify bulk and nanomaterials as well as forensic specimens and industrial and geochemical sample materials. Apart from the benefits, it has several drawbacks, including crystal growth problems and the obtained results which only refer to an individual conformation/binding state. Regarding electron diffractions, diffracted X-rays have a lower beam intensity.\textsuperscript{108,109} The research conducted by Khan et al. revealed that the existing method of wet chemical solution for preparing silver nanoparticles and their thin films is simple, convenient, and feasible, which permits the silver nanoparticle synthesis of spherical shape and fairly narrow size distribution. A face-centered cubic crystalline phase of silver with the lattice constant of 0.4085 nm is seen in the X-ray diffraction pattern produced by the scattering of X-rays from the sample. According to FETEM analysis, the average particle size is 17.5 nm which is in good agreement with XRD results. The average crystallite size of magnetite NPs, based on Upadhyay et al.’s findings, was in the range of 9−53 nm using X-ray line broadening. The broadening of XRD peaks was mostly a result of particle/crystallite size and lattice strains other than instrumental broadening.\textsuperscript{110} Figure 12 illustrates the FCC crystalline structure of green produced AgNPs utilizing \textit{G. resinifera} plant extract. At lower concentrations, the (122) and (231) planes dominated, whereas the (111), (200), (220), and (311) planes dominated at higher concentrations.\textsuperscript{94}

**Scanning Electron Microscopy (SEM).** The advancement of several high-resolution microscopy techniques has fueled interest in nanomaterials research by probing objects on a very microscopic scale with a highly energetic electron beam (Figure 13). SEM is a surface imaging approach capable of discerning varied particle sizes, size distributions, nanomaterial forms, and the surface morphology of manufactured particles at the micro- and nanoscales, among other electron microscopy techniques.\textsuperscript{111} Nanoparticles with morphologies less than 10 nm can be identified by using modern high-resolution SEMs. This imaging technique deals with backscattered electrons (BSEs),\textsuperscript{112} which helps to study not only the surface morphology of the NPs but also their interaction with other systems.\textsuperscript{113,114}

Many depositions of AgNP studies, like deposition on silica spheres,\textsuperscript{115} on polyester fibers,\textsuperscript{116} or on linen,\textsuperscript{117} were reported by using SEM micrographs. The energy beam range of 1−30 keV is utilized to get complementary information.\textsuperscript{112,118,119} The sample cross section and imaging studies can be conducted by adding a Ga\textsuperscript{+} as a focused-ion beam (FIB) to the SEM instrument.\textsuperscript{120} The major problem with SEM is that the nonconducting sample charging affects the quality of the image and therefore its interpretation. An advanced version of SEM is an environmental scanning electron microscope (ESEM), which is one of the best techniques that can investigate the charging effect due to water vapor presence in the microscopic chamber. The wet approach stops the dehydration of samples and other changes like size reduction, shape change, and cracking, so it is enormously applicable for the biological investigation of suitable samples.\textsuperscript{115,118} Finally, the lower signal-to-noise ratio and spatial resolution are the major drawbacks of SEM in comparison to transmission electron microscopy (TEM).\textsuperscript{112} Agressott et al.\textsuperscript{122} described the manufacture of AgNPs using fungus, with SEM pictures showing AgNPs of various sizes and spherical forms, as seen in Figure 14.

**Transmission Electron Microscopy (TEM).** Transmission electron microscopy (TEM) is the most advanced and expensive technique for NP characterization and surface studies (Figure 15). Generally, it generates information about particle size, shape, and arrangement. Depending on the requirement and technology, TEM exists in different forms to which CTEM (conventional TEM), HRTEM (high-resolution TEM), and STEM (scanning TEM) can be included.

Mostly, the aggregation of NPs is one of the main difficulties in investigations of electron microscopy (EM). The HRTEM performance is based on the reflection of the interference of the electron beam by the analyzing sample. Even the atomic
Nanoparticle–Biomolecule Interaction. The nanoparticle–biomolecule interaction is an interface between nanomaterials and biological systems where the organic and synthetic sciences merge into a new science with diverse biological applications (Figure 16). This new interface is dedicated to the safe use of nanotechnology and nanomaterial design. This nanobiointerface can be easily understood by understanding the molecular components and dynamic forces responsible for these interactions. Two major responsible components are: (i) the composition of the NP and its surface functionality and (ii) the changes that occur at the solid–liquid interface when the NPs interact with the surrounding components. The major interacting forces arise from repulsive electrostatic double-layer interactions, and attractive van der Waals short-range forces arise from steric hindrance, charge, and solvent interactions.\textsuperscript{126,127}

The relations between the AgNPs and biomolecules such as proteins and DNA seem to signify some of the identical principles as those between colloidal particles. Here, the van der Waals, electrostatic, salvation, and hydrophobic forces are still applied, but since the events here occur at the nanoscale, they require special consideration\textsuperscript{126,128–130} (Figure 16). Currently, across the globe, researchers are working on the specific properties of nanoparticles having: (i) diverse shapes, (ii) high crystallinity, and (iii) selective surfaces, which are essential for causing hydrophilic/hydrophobic behavior with increased stability in harsh environmental conditions like variable pH, high ionic strength, and many more. With these updates on AgNPs, their interaction with biomolecules thus cannot be overlooked due to its immense potential usage in biological applications and the growing significance of developing the nanotoxicology field, which addresses the safety of these engineered AgNPs. Due to the large surface area and surface functionalization, the NPs when interacting with proteins can easily interrupt their native conformation, thereby disturbing the protein function (Figure 16).

The electrostatic interactions that are hydrophobic interactions and specific chemical interactions are common in AgNPs and protein interactions. Protein’s selective interaction with a variety of nanomaterials under different conditions has...
| plant species      | parts used        | extraction technique                                                                 | bioactive components                                                                                                                                                                                                                                                                                                                                                           | agnps specification                      | potential application                                           | reference |
|--------------------|-------------------|--------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------|---------------------------------------------------------------|-----------|
| Acacia leucorrhæa  | stem bark         | Soxhlet extraction with water.                                                       | amino acids, carbohydrates, alkaloids, tannins, glycosides, flavonoids, and steroids                                                                                                                                                                                                                                                                                                                                                     | polydispersed, sphere-shaped, 17–29 nm | antibacterial activity                                      | 5         |
| Acacia cyanophylla | leaves, flower,   | Boiled with water at 60 °C for 15–20 min with constant shaking.                      |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | polydispersed, sphere-shaped, 88.11 nm | antibacterial activity                                      | 135       |
|                    | and stem          |                                                                                        |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                                          |                                                               |           |
| Arinaæa flavum     | tuber              | Macerated with methanol for 4 days.                                                  | phenolic compounds                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | sphere-shaped, 5–8 nm                   | antibacterial activity                                      | 7         |
| Artemisia quattæsis| aerial part        | Boiling with 50% ethanol at 60 °C for 10 min.                                         | flavonoid and phenolic acids                                                                                                                                                                                                                                                                                                                                                                                                                   | sphere-shaped, 5–25 nm                  | antibacterial, antioxidant, and cytotoxic activity          | 136       |
| Carissa carandas   | leaf               | Boiling with water at 85 °C for 60 min with continuous stirring at 200 rpm.            |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | sphere-shaped                           | antitumor, anti-inflammatory, and antioxidant activity    | 9         |
| Caesalpinia gilliesii | leaf            | Maceration with 70% methanol.                                                        | phenolics and flavonoids                                                                                                                                                                                                                                                                                                                                                                                                                         | sphere-shaped, 3–6 nm                   | antibacterial activity and antitumor activity              | 137       |
| Chrysanthemum indicum | flower         | Simple boiling with water for 5 min.                                                | flavonoids, terpenoids, and glycosides                                                                                                                                                                                                                                                                                                                                             | polydispersed, sphere-shaped, 37.71–71.99 nm | antibacterial activity, lactate dehydrogenase (LDH) activity, and no cytotoxic activity | 42        |
| Cymbopogon citratus | leaf              | Simple extraction with cold water followed by centrifugation.                      | alkaloids and flavonoids                                                                                                                                                                                                                                                                                                                                                                                                                         | polydispersed, cuboidal, and rectangular-shaped, 15–65 nm | antibacterial activity                                     | 138       |
| Euphræasia officinalis | leaf            | Simple boiling with water for 30 min followed by centrifugation.                    | iridoids, flavonoids, phenolic acids, and ethereal oils                                                                                                                                                                                                                                                                                                                                                                       | quasi-sphere-shaped, 40.37 ± 1.8 nm     | anticancer activity, antibacterial activity, and antibiofilm activity | 139       |
| Hylanthæus ennaægermus | stem bark       | Boiled with ethanol.                                                                 |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                                          | scavenging, antiurolithiatic, and antidiabetic activity     | 140       |
| Otostegia persica  | leaf              | Maceration with ethanol (98%) for 24 h with shaking at room temperature.              | essential oils, phenolics, terpenoids, and flavonoids                                                                                                                                                                                                                                                                                                                                                                                      | sphere-shaped, 23.4–53.2 nm             | scavenging, antibacterial, antifungal, and anti-inflammatory activity | 1         |
| Polygala tenufolia | root              | Ultrasound-assisted extraction with 70% ethanol.                                     | flavonoids                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | spherical and irregularly shaped, 12–15 nm | antibacterial activity                                      | 62        |
exposed that the mechanism of selective AgNP interaction with a specific binding site of the protein is attributed to electrostatic interactions.\textsuperscript{131} The protein interaction with AgNPs causes permanent alterations, instability, and secondary structure of the protein. Generally, the $a$-helix gratified is reduced, while the $\beta$-sheet content is increased.\textsuperscript{132} When the NP surfaces are functionalized with charged ligands, their interaction with the protein can denature or unfold it, while in the case of a neutral ligand, the protein retains its structure.\textsuperscript{133,134} Gel electrophoresis can also be a significant tool to scrutinize the NP–biomolecule interaction.

**Potential Biological Activities of Plant-Based AgNPs.** The biological activities of plant extract based AgNPs are discussed and reported in Table 3. Their sources and plant name along with active biocomponent are provided and later on discussed in brief.

Kora et al.\textsuperscript{135} explained the usefulness of plant extracts and developed an eco-friendly and facile technique for AgNP synthesis using a reducing and stabilizing agent, natural biological polymer, and gum kondagogu (Cochlospermum gossypium), respectively. The synthesized AgNPs expressed considerable antibacterial action against both Gram +ve and –ve bacteria. The AgNPs also exhibited effective antibacterial activity against both Gram +ve and –ve bacteria when they synthesized AgNPs from aqueous extract of gum olibanum as reducing and stabilizing agents.\textsuperscript{142} Abdel-Halim and co-workers synthesized AgNPs using KBr/thiourea dioxide-initiated guar gum/polyacrylamide grafted copolymer.\textsuperscript{143} Guar gum (Cyamopsis tetragonoloba) was also used by Pandey et al.\textsuperscript{144} for AgNP synthesis with a particle size of <10 nm. They used AgNPs as an optical sensor for ammonia detection with a detection limit of 1 ppm. The concentration of the guar gum and Ag$^+$ ions is the key factor in determining the size distribution and morphology of the AgNPs. They investigated that with increasing Ag$^+$ ion concentration the size of AgNPs increased, and at higher concentrations, they formed clusters. Interestingly, it was observed that by keeping the Ag$^+$ ion concentration constant and increasing the gum concentration the size of the spherical AgNPs increased without any cluster formation.

Velusamya and co-workers synthesized AgNPs from antibacterials using Neem gum (Azadirachta indica) (at 0.1–0.5% w/v) with a size of <30 nm. Thakur et al. reported AgNP synthesis using Acacia arabica gum with superior antimicrobial activity.\textsuperscript{145} Similarly, Kora et al. synthesized AgNPs with a proficient antibacterial activity using gum Tragacanth (Astragalus gumiimmer) as a reducing and stabilizing agent.\textsuperscript{146} They concluded that the AgNP size could be restricted by changing the reaction time and gum concentration.

The sunlight effect on the stability and toxicity of AgNPs layered with PVP and gum Arabic were conveyed by Cheng et al.\textsuperscript{147} They observed that after sunlight irradiation the AgNPs aggregated, but to a different degree depending on their coated surfaces. The UV content of sunlight and strong oscillating dipole–dipole interaction were identified as the driving forces of AgNP aggregation and destabilization, respectively. Mewada et al.\textsuperscript{148} used neem gum (Azadirachta indica plant exudate) (2% w/v) for biological AgNP synthesis.

These AgNPs were orbicular in shape, with an oscillating size between 15 and 20 nm, and expressed antimicrobial action against E. coli and S. aureus. Ahmed et al.\textsuperscript{149} used Azadirachta indica (Neem) aqueous leaf extract as a reducing and capping agent for AgNP preparation. Fajar et al.\textsuperscript{150} used textiles for AgNP preparation. Similarly, Chandra et al. used green tea leaves from different altitudes of Eastern Nepal to prepare AgNPs.\textsuperscript{151} These AgNPs exhibited antimicrobial behavior concerning both S. aureus and E. coli. When excited at 280 and 300 nm, the AgNPs show emission peaks at 561 and 600 nm, respectively, which did not change the occurrence of flavonoids in the extract. A broad spectrum of antimicrobial activity has been exhibited by AgNPs.

Caffeine is a widely used behaviorally active drug. It can form a complex when it is coordinated with metal ions and reduce them to their corresponding metals. Khan et al. reported how CTAB regulates the shape of AgNPs in the presence of neem leaf extract as a green reducing agent.\textsuperscript{152} By changing CTAB concentration, they produced monodispersed AgNPs, which were earlier polydispersed spherical with exciting shapes: triangle, flat, and plate-like hexagonal. Dubey and co-workers\textsuperscript{153,154} used leaf extract of Rosa rugosa SPR at 451 nm for the AgNP synthesis. The produced AgNPs remained typically spherical with a regular size, that is, 12 nm, and had negative zeta potential.

Banker et al.\textsuperscript{155} magnificently prepared AgNPs using banana peel extract at pH 3, but the AgNPs formed aggregates after 15 days with antimicrobial activity. Dipankar et al.\textsuperscript{156} synthesized AgNPs using Iresine herbstii leaf aqueous extracts and showed promising antibacterial and scavenging activity along with cytotoxicity against the cervical cell line HeLa. Vidhu et al.\textsuperscript{157} produced AgNPs using Saraca indica flower extract, expressing catalytic activity toward methylene blue (MB) degradation by NaBH$_4$.

The cytotoxicity caused by AgNPs is due to the oxidative stress and Ag-ion release. Based on electron spin resonance (ESR) results, the AgNP active surfaces can directly induce the free radical generation, and the termination of AgNPs into Ag ions activates the hydroxyl radical production.\textsuperscript{158} By using a high concentration of AgNPs, the epithelial cell morphology can be modified to rounded and fusiform shape. This is because AgNPs trigger the oxidative stress which can decrease the glutathione and superoxide dismutase that finally lead to apoptosis by elevating fragmentation of DNA.\textsuperscript{159} Furthermore, AgNPs can interrupt cell membrane integrity and cause lysosomal swelling and even lyosomal rupture.\textsuperscript{160} AgNPs and released Ag ions always prefer to interact with thiol groups. In the cytoplasm, many molecules are present which contain thiol groups, cells, and inner mitochondrial membranes, and they can target silver ions or AgNPs.\textsuperscript{161} The cell membrane damage leads to cytoplasmic content leakage, while the lysosomal rupture releases cathepsins into the cytoplasm where they are responsible for activating apoptosis. Once damaged, mitochondria impair electron transfer, obstruct adenosine triphosphate (ATP) synthesis, activate oxidative stress, and stimulate mitochondrial-dependent apoptosis.\textsuperscript{159,160}

### CONCLUSIONS AND FUTURE DIRECTIONS

In summary, the cost-effective and eco-accommodating green synthesis dominates chemical and physical methods because it is effectively used for bulk synthesis. Currently, the development of eco-friendly methods by green chemistry for AgNP preparation is needed. Microorganisms, including bacteria and multifaceted eukaryotes, can be used for NP synthesis of specific shapes and sizes. The low rates of synthesis and the restricted shapes and sizes of NPs created have caused us to focus on investigating plant consumption. The AgNP
synthesis utilizing plant extracts can lead to additional biological bodies which can overwhelm lethargy/fatigue syndrome in microorganisms, and subsequently their culture can reduce the perspective toward the NP formation. The hygienic occupied atmosphere, well-being, environmental protection, minor consumption, and balanced products are the other benefits of NP synthesis from plant extracts. Fundamental methods of characterization are often typically applied for routine analysis to assert the presence of ligands on the surface of nanomaterials, including comprehensive nuclear magnetic resonance spectroscopy analysis, FTIR, XRD, and UV−vis spectroscopy. It is anticipated that AgNP applications will grow broadly, but there are many applications which need to be explored with respect to their resources in the environment and their potential long-term impacts on living organisms. We believe that in the near future a greener and more biosynthesized AgNP will open many new windows toward biomedical applications, such as “nanodrugs”. We hope that the use of AgNPs will extend to water purification and as SPR enhancers. These AgNPs have potential to be used in energy storage devices which will solve the current energy crisis globally. Additional investigations are still required to understand this complex mechanism by using microorganisms in order to control the shape and size of synthesized AgNPs. The AgNPs have materialized in the current and forthcoming era, with a diversity of applications including therapeutics, cardiovascular implants, dentistry, medicine, agriculture, biosensors, etc.

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Notes
The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

N.K.S. acknowledges the Science and Engineering Research Board, Government of India, grant no. SERB/CHE/2021/142 for funding. We also express our sincere gratitude to Shri Maneklal M. Patel Institute of Sciences and Research, Kadi Sarva Vishwavidyalaya, Gandhinagar, Gujarat, India for providing necessary facilities.

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Silver Nanoparticles by Using Polygala Tenuifolia Root Extract as a Green Synthesis of Silver Nanoparticles Using Flower Extract of Compounds from Medicinal Plants and Herbs

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