

Review

Biogenic Synthesis of Silver Nanoparticles, Characterization and Their Applications—A Review

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Abstract: With the growing awareness for the need of sustainable environment, the importance of synthesizing and the application of green nanoparticles has gained special focus. Among various metal nanoparticles, silver nanoparticles (AgNPs) have gained significant attention. AgNPs are synthesized conventionally by physical and chemical methods using chemicals such as reducing agents, which are hazardous to environment due to their toxic properties, provoking a serious concern to create and develop environment friendly methods. Thus, biological alternatives are emerging to fill gaps, such as green syntheses that use biological molecules taken from plant sources in the form of extracts, which have shown to be superior to chemical and physical approaches. These biological molecules derived from plants are assembled in a highly regulated manner to make them suitable for metal nanoparticle synthesis. The current review outlines the wide plant diversity that may be used to prepare a rapid and single-step procedure with a green path over the traditional ones, as well as their antifungal activity.

Keywords: silver nanoparticles; biological synthesis; characterization techniques; applications



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1. Introduction

“Nanotechnology” is the newest and one of the most promising and active areas of modern research. The technology deals with the design, synthesis, and manipulation of particles size ranging from 1–100 nm [1]. Within this size range, the chemical, physical, and biological properties change in the fundamental way of both individual atoms and their corresponding bulk material [2]. This very small size increases the surface area-to-volume ratios of particles. The nanoparticles synthesized using plant extract have gained huge consideration in recent years due to their remarkable properties and wide range of applications in catalysis [3], plasmonic [4], optoelectronics [5], biological sensor [6], water treatment, pharmaceutical applications [7], and agriculture and crop protection [8]. Stunning growth in this emerging technology has opened novel fundamental and applied frontiers, including the synthesis of nanomaterial and utilization of their physicochemical and optoelectronic properties [9]. The application of nanotechnology has increased in large number of areas such as optics, mechanics, chemical industries, space industries, electronics, energy science, single electron transistors, light emitters, nonlinear optical devices, photo-electrochemical, catalysis, biomedical, cosmetics, drug/gene delivery, and food and feed [10–14]. Among various nanoparticles used for all the above-mentioned purposes, the metallic AgNPs are contemplated as the most promising, as they possess remarkable antimicrobial properties due to their greater surface area to volume ratio, which is of curiosity for researchers due to the growing microbial resistance against metal ions and antibiotics and the development of resistant strains [15]. Nanoparticles are seen as a solution to many technologies and environmental challenges [10,16–18]. The biological synthesis methods of NPs reduce hazards to the global efforts. The development and

implementation of these sustainable processes should adopt the fundamental principles of green chemistry. These principles draw attention on maximizing the efficiency of chemical processes without compromising the safety concern of the products.

2. Silver Nanoparticles

Among the various metallic nanoparticles, AgNPs are one of the most promising products in the nanotechnology industry. The development of consistent processes for the synthesis of AgNPs is an important field of current nanotechnology research. AgNPs have a wide range of use because of their unique characteristics such as optical, electrical and magnetic properties, which can be incorporated into antibacterial, antiviral, and antifungal applications, composite fibers, biosensor materials, cosmetic products, food industry uses, and electronic components [19,20]. The AgNPs are also reported as medical and pharmaceutical agents that have directly encountered by a human system in such products as shampoos, detergents, soaps, toothpaste, and cosmetics [21]. The biomedical use of AgNPs includes their application as antibacterial [22], antifungal [23], anti-inflammatory [24,25], antiviral [26], and anti-diabetic agents [27]. In recent studies, AgNPs were also reported in the diagnosis and treatment of cancer and as drug carriers by either active or passive mechanisms [28]. The antibacterial effects of silver have been noticed since antiquity and, in a variety of applications, silver is currently used to control bacterial growth including in dental work, catheters, and burning wounds. It is widely known that Ag ions and Ag-based compounds are highly toxic to microorganisms, showing strong biocidal effects [29]. Due to the optical properties of AgNPs, these are mainly used in photonic devices and in molecular diagnostics. An increasing application is the use of AgNPs for antimicrobial coatings. Many textiles and biomedical devices contain AgNPs that continuously release a low level of silver ions to provide protection against bacteria [30]. AgNPs were used as catalysts for the reduction of many aqueous aromatic nitro compounds in which NaBH_4 alone could not reduce aromatic nitro compounds. NaBH_4 was reported to enhance the catalytic activity of AgNPs by reducing the oxide layer to regenerate the fresh surface of the silver particles [2].

3. History and Concept of Nanotechnology

The history of nanoparticles is quite long and, during the last two decades, major developments within nanoscience have taken place. In 1970, Norio Taniguchi coined the term “nanotechnology.” But the concept of nanotechnology was initially defined by Nobel Prize winner Richard Feynman in his renowned address at the California Institute of Technology on 29 December 1959. The topic of nanoparticles was mentioned in one of his articles published in 1960 titled “There is Plenty of Room at the Bottom.” He pointed out that if a single bit of information required only 100 atoms, then all the books ever written could be kept in a cube with sides measuring 0.02-inch in length [31].

The nanoparticles are being used in many sectors including in the biomedical field, water treatment, the electrical industry, biological textiles, chemistry, and human health. Depending upon shape and size, colloidal metal particles play a critical role in different applications, including in the preparation of magnetic, electronic devices, wound healing, antimicrobial gene expression, and the preparation of biocomposites, the noble metal colloids having the specific optical, catalytical, and electromagnetic properties [32]. Nanotechnology is a recent invention in scientific research, but its basic concepts have been developed over a long period of time [33], since people have been coating glass windows with tiny coloured metal particles for a long time, particularly silver, to create a glassy yellow colour.

4. Classification of Nanoparticles

Nanoparticles are classified mainly into two categories: inorganic and organic nanoparticles. Carbon nanoparticles (fullerenes) are one of the organic nanoparticles. On the other hand, inorganic nanoparticles contain gold and magnetic nanoparticles and silver and semiconductor nanoparticles such as titanium dioxide and zinc oxide. There is an increasing

interest in inorganic nanoparticles, as they offer superior material properties with functional usefulness. Due to their small structure and benefits over chemical imaging agents and medications, they have been investigated as a possible instrument for medical applications as well as for treating diseases. Gold nanoparticles have been widely employed in imaging, medication delivery, and biological target thermostherapy [34]. Inorganic nanoparticles such as metallic and semiconductor nanoparticles show core optical properties which may augment the transparency of polymer-particle composites. For those reasons, inorganic nanoparticles have gained much interest in studies devoted to optical properties in composites [35].

5. Methods of AgNP Synthesis

In AgNPs synthesizing and stabilization, several physical and chemical methods have been used. In recent years, Nanoparticle synthesis is one of the most fascinating areas of scientific research, and there is an increasing focus on manufacturing nanoparticles in environmentally acceptable ways (green chemistry). Mixed-valence polyoxometalates, polysaccharides, Tollens, irradiation, and biological processes are examples of green synthesis approaches that have advantages over traditional methods which use chemical agents that are detrimental to the environment. This chapter addresses the synthesis of AgNPs using physical, chemical, and green methods. The various types of methods used for the synthesis of nanoparticles are represented in Figure 1.

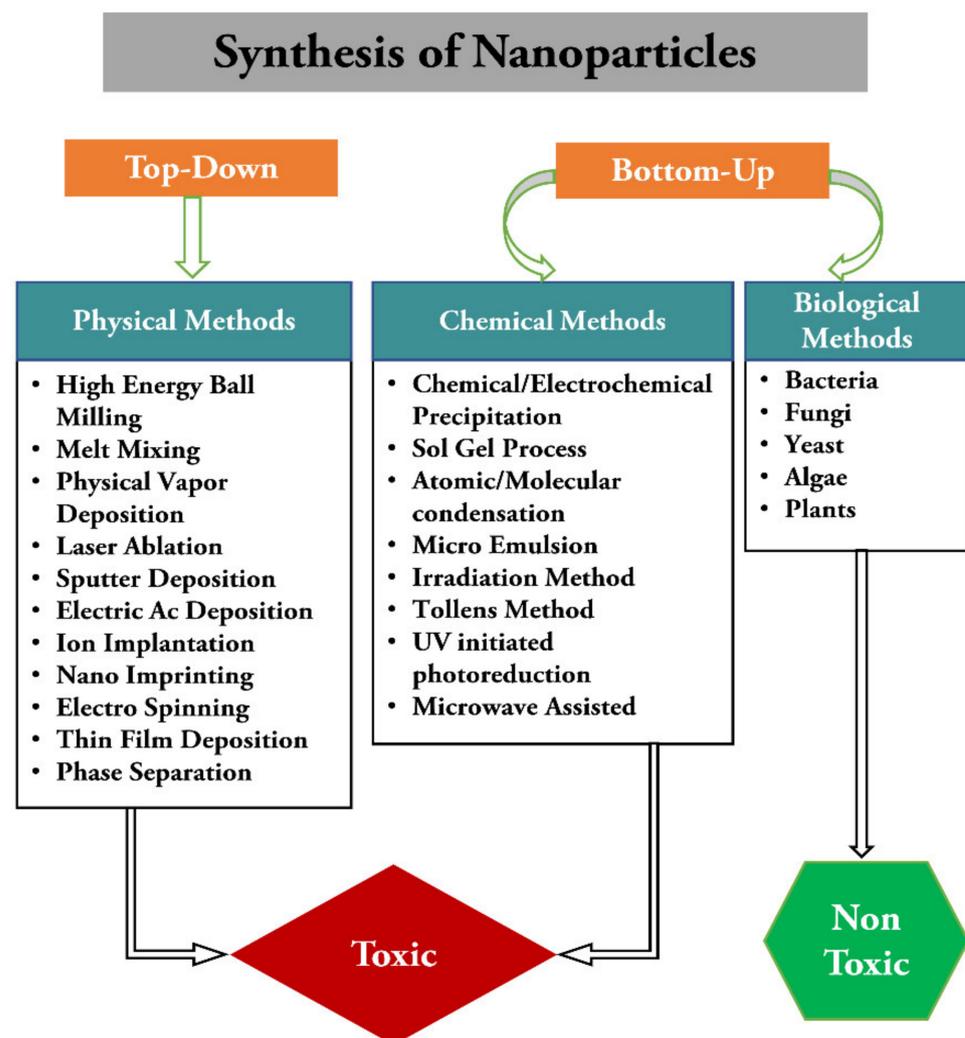


Figure 1. Different types of method used for the synthesis of nanoparticles.

5.1. Physical Methods

In physical processes, there are various methods including plasma arcing [36], ball milling [37], thermal evaporation [38], spray pyrolysis [39], ultra-thin films [40], electron irradiation [41], pulsed laser desorption [42], lithographic techniques [43], sputter deposition [44], layer by layer growth [45], and the diffusion flame [46] synthesis of nanoparticles. In these methods, the nanoparticles synthesized by evaporation condensation, which could be conducted in a tube furnace at atmospheric pressure and is used to make metal nanoparticles.

The starting material within a boat centered at the furnace is vaporized into a carrier gas. The evaporation/condensation technique has previously been used to synthesize various nanoparticles, including Au, PbS, Ag, and fullerene. However, utilizing a tube furnace to make AgNPs has a number of disadvantages, including the fact that a tube furnace occupies a large space and need a high energy input while increasing the environmental temperature around the source material, and it takes a lot of time to gain thermal stability. In addition, a typical tube furnace requires power using up to more than several kilowatts and a pre-heating time of several tens of minutes to attain a stable operating temperature. Furthermore, AgNPs have been synthesized with the laser ablation of metallic bulk materials in solution [47–51]. One of the biggest advantages of laser ablation compared to another physical methods for synthesizing metal nanoparticles is the absence of chemical reagents in solutions. Therefore, pure colloids can be produced by this method which will be useful for more applications [52].

5.2. Chemical Methods

In chemical processes, nanoparticles are synthesized using several methods such as electro-deposition, sol-gel process [53] chemical solution deposition [53], chemical vapor deposition [54,55], the Langmuir Blodgett method, the soft chemical method, catalytic route, hydrolysis [56], co-precipitation, and the wet chemical method. Chemical reduction is the most common method for synthesis of AgNPs. Various organic and inorganic chemicals have been used as reducing agents; sodium borohydride (NaBH_4), elemental hydrogen, sodium citrate, ascorbate, Tollens reagent, *N,N*-dimethylformamide (DMF), polyol process, and poly (ethylene glycol)–block copolymers are used for the reduction of silver ions (Ag^+) in non-aqueous or aqueous solutions. The above-mentioned chemicals reduce silver nitrate into AgNPs. Silver ions (Ag^+) are reduced into metallic silver (Ag^0) by reducing agents, which is followed by agglomeration into oligomeric clusters. Capping agents are also used for size stabilization of the nanoparticles. These clusters eventually lead to the formation of metallic colloidal silver particles [57,58]. A lot of nanoparticles can be synthesized in a short span of time, which is one of the biggest advantages of this method. It is needed to use protective reducing agents to stabilize nanoparticles to avoid their agglomeration during the course of AgNPs preparation and protect the nanoparticles that can be absorbed on or bind onto nanoparticle surfaces [54]. Surfactants having functionalities for interactions with particle surfaces (e.g., thiols, amines, acids, and alcohols) can stabilize particle development and protect particles from precipitation, agglomeration, or losing their surface features. Polymeric substances such as poly (vinyl alcohol), poly (vinyl pyrrolidone), poly (methacrylic acid), poly (ethylene glycol), and polymethyl methacrylate have been shown to be efficient nanoparticle stabilizers [59].

These conventional methods use high radiation and concentrated reducing and stabilizing agents that are hazardous to human health and non-ecofriendly by-products. As a result, biological nanoparticle synthesis is a one-step bio-reduction process that consumes less energy to synthesize eco-friendly NPs [60]. Biological approaches rely on environmentally favorable resources such as plant extracts, bacteria, fungus, and microalgae such as cyanobacteria, diatoms, and seaweed [61,62].

5.3. Biological Methods

Nanoparticle synthesis by biological methods is a growing area of nanotechnology [63]. Plant extracts [64], bacteria [65], and fungus [66] are some eco-friendly resources for the biological synthesis of nanoparticles. As this synthesis of AgNPs does not employ the use of hazardous chemicals, it provides a variety of advantages in terms of environmental benefits and compatibility for pharmaceutical and other biological applications. Green synthesis has been proven to be better to conventional approaches in term of being cost-effective, nontoxic to the environment, and easily scaled up for large production [67].

5.3.1. Synthesis of AgNPs Using Bacteria

In 1999, Klaus and colleagues reported the first evidence of bacterial-mediated AgNP production and detected AgNP aggregation inside the cells of *Pseudomonas stutzeri* AG259, a bacterium isolated from a silver mine [68].

Rapid synthesis of AgNPs using keratinase was obtained from a novel keratin-degrading bacterial strain, *Bacillus safensis* LAU 13. UV spectrophotometry showed the maximum absorbance at 409 nm. The FTIR results indicated that proteins were the capping and stabilization molecules in the synthesis of AgNPs. The XRD data showed that the particles are crystalline in nature with an average size of ~8.3 nm and have a face-centred cubic phase. These particles were used against clinical isolates of *E. coli* and showed effective antibacterial activity [69]. AgNPs of spherical shape were synthesized using *Bacillus methylophilic* DC3, isolated from the soil of Korean ginseng, a traditionally known oriental medicinal plant in Korea. The synthesized AgNPs were characterized using FE-TEM and the particles showed sizes in the range of 10–30 nm. The UV-vis absorption spectrum showed the maximum absorbance peak at 416 nm. In recent contributions, the synthesis of nanoparticles using bacteria including *Pseudomonas deceptionensis*, *Weissella oryzae* [70], *Bacillus amyloliquefaciens*, *Bacillus licheniformis*, and *Rhodobacter sphaeroides* [71–73] was reported. The extracellular synthesis of AgNPs was reported with the use of bacteria such as *Acinetobacter calcoaceticus* [74], *Gluconobacter roseus* [75], *Klebsiella pneumonia* [76], *Salmonella typhimurium* [77], *Pseudomonas aeruginosa* [78], *Xanthomonas oryzae* [79], and *Rhodococcus* sp. [80].

5.3.2. Synthesis of AgNPs Using Fungi

Extracellular synthesis of AgNPs using *Fusarium oxysporum* can be carried out in several kinds of materials, such as cloths [81]. The filamentous fungus *Aspergillus fumigates* is known for the rapid synthesis of AgNPs ranging from 5 to 25 nm [82]. The fungus, *Aspergillus flavus*, accumulated AgNPs on the surface of its cell wall in 72 h when challenged with a silver nitrate solution. After being dispersed by ultrasonication, these nanoparticles had an absorption peak in the UV-visible spectrum at 420 nm, which corresponded to the plasmon resonance of AgNPs. According to transmission electron micrographs of nanoparticles in aqueous solution, the fungus produced relatively monodisperse AgNPs with an average particle size of 8.92 ± 1.61 nm.

The formation of metallic silver has been confirmed by X-ray diffraction analysis of the nanoparticles. The Fourier transform infrared spectroscopy confirmed the presence of protein as the stabilizing agent surrounding the AgNPs [83]. The intracellular synthesis of AgNPs using fungus *Fusarium oxysporum* has been investigated. It was observed that, when exposed to the fungus, the aqueous silver ions are reduced in the solution, thereby leading to the formation of an extremely stable silver hydrosol. The size of AgNPs is in the range of 5–15 nm, and the proteins secreted by the fungus stabilize them in solution [84]. Mukherjee describes a unique biological approach for the manufacture of AgNPs using the fungus *Verticillium*. When the fungal biomass was exposed to aqueous Ag⁺ ions, the metal ions were reduced intracellularly, resulting in the production of AgNPs with diameters of 25 ± 12 nm. According to electron microscope investigation of thin sections of fungal cells, the silver particles were generated below the cell wall surface, perhaps due to metal ion reduction by enzymes present in the cell wall membrane [85].

It is also proclaimed by the extracellular biosynthesis of AgNPs using a common fungus, *Alternaria alternata*. These nanoparticles were assessed for their part in increasing the antifungal activity of fluconazole against *Candida albicans*, *Phoma glomerata*, *Trichoderma* sp., *Phoma herbarum*, and *Fusarium semitectum*. In the study, it was concluded that the antifungal activity of fluconazole was increased against the test fungi in the presence of AgNPs [86].

5.3.3. Synthesis of AgNPs Using Algae

The aqueous extract of *Pithophora oedogonia* was used for the synthesis of AgNPs. The synthesis process was considerably more rapid, and the generation of silver was reached for a few minutes. In the UV-vis spectrum, the maximum absorbance peak was observed at 445 nm. The SEM and DLS analysis of colloidal AgNPs revealed a size of 34.03 nm. The EDX spectroscopy revealed strong signals in the silver region and confirmed the presence of Ag. The FTIR analysis of the nanoparticles indicated the presence of protein, which was regarded as a capping agent surrounding the AgNPs [64]. Fresh *Caulerpa racemosa*, marine algae, was used in the synthesis of AgNPs. The reduction of silver nitrate was conducted at room temperature by the extract. The surface plasmon absorbance peak observed at 413 nm was revealed by UV-visible absorption spectroscopy. The FT-IR analysis revealed the possible functional groups responsible for the reduction and stabilization of the nanoparticles. The particles are crystalline in nature and 5–25 nm in size, as found by XRD and TEM analyses [87]. Spirogyra was also used for the synthesis of AgNPs. In UV-vis absorption spectrum the peak was observed at 430 nm. The synthesized AgNPs were uniform and 17.6 nm in size, as revealed by SEM. AgNPs can act as a powerful antibacterial agent against various pathogenic bacteria, which was confirmed by MIC and MBC results [88].

5.3.4. Synthesis of AgNPs Using Plant Entities

The plant entities use as in production assembly of AgNPs has gained attention because of its rapid, non-pathogenic, eco-friendly, and economical protocol, and it provides a single step technique for the biosynthesis of nanoparticles. The reduction and stabilization of silver ions by combination of biomolecules which are already recognized in the plant extracts such as proteins, amino acids, enzymes, polysaccharides, tannins, phenolics, terpenoids, alkaloids, saponins, and vitamins are medicinally important and environmentally benign, yet chemically complex structures [89,90]. A large number of plants reported to the synthesis of AgNPs are mentioned (Table 1) and discussed concisely in the presented review (Figure 2). The following steps are involved in the production of nanoparticles: the plant of interest is collected from the accessible area, rinsed thoroughly two to three times with tap water to remove both epiphytes and necrotic plants, and then cleaned again with deionized water to remove related debris. The plant components are cleaned and dried in the shade for 10–15 days before being pulverized. Around 10 g of dry powder is soaked in 100 mL deionized distilled water and boiled using the hot percolation process to produce the plant extract. After that, the infusion is filtered until no insoluble material is left in the extract.

Table 1. Silver nanoparticles synthesized using plants.

Plants	Size (nm)	Plant's Part	Shape	Applications	References
<i>Acalypha indica</i>	10–50	Leaves	-	Cytotoxic effects against MDA-MB-231, human breast cancer cells	[91]
<i>Agastache mexicana</i> and <i>Tecoma stans</i>	16–20	Leaves	Spherical	-	[92]
<i>Aloe vera</i>	70	Leaves	Spherical	Antifungal activity	[93]

Table 1. Cont.

Plants	Size (nm)	Plant's Part	Shape	Applications	References
<i>Alternanthera dentate</i>	50–100	Leaves	Spherical	Antimicrobial activity	[94]
<i>Andrographis paniculata</i>	67–88	Leaves	Spherical	Hepatocurative activity	[26]
<i>Artocarpus elasticus</i>	5.81	Stem bark	Spherical	-	[95]
<i>Avicennia marina</i>	60–95	Leaves	-	Mosquito larvicidal activity	[96]
<i>Barleria cristata</i>	25–30	Leaves	Spherical	Mosquitocidal and biotoxicity activity	[97]
<i>Boerhaavia diffusa</i>	25	Leaves	Spherical, FCC	Antibacterial activity	[98]
<i>Boswellia serrate</i>	7–10	Gum	Spherical	Antibacterial activity	[99]
<i>Brassica rapa</i>	16.14	Leaves	Anisotropic shaped	Antiangiogenic activity	[25]
<i>Cassia javanica</i> L.	100	Leaves	Spherical	Antibacterial activity	[100]
<i>Cestrum nocturnum</i>	20	Leaves	Spherical	Antioxidant and antibacterial	[101]
<i>Cleome viscosa</i>	20–50	Fruit	Spherical	Antimicrobial activity	[102]
<i>Coleus aromaticus</i>	26–27	Leaves	Spherical	Larvicidal toxicity against dengue and filariasis vectors	[103]
<i>Cucurbita maxima</i> , <i>Moringa oleifera</i> and <i>Acorus calamus</i>	30–70	Petals, leaves, rhizome	Roughly spherical	Anticancer activity against epidermoid A431 carcinoma	[104]
<i>Delphinium denudatum</i>	85	Roots	Spherical, FCC	Dielectric properties	[105]
<i>Descurainia sophia</i>	30	Seeds	Spherical	Antibacterial and antifungal activity	[106]
<i>Dillenia indica</i>	11–24	Fruit	Spherical	Antibacterial activity	[74]
<i>Dimocarpus Longan Lour</i>	20–35	Peel	-	Anticancer effects against prostate cancer (PC-3) cells	[107]
<i>Dionaea muscipula</i>	5–10	Whole plant	Quasi-spherical	Antioxidant	[108]
<i>Diospyros sylvatica</i>	10	Roots	Spherical	Antimicrobial activity	[109]
<i>Elaeagnus umbellata</i>	40	Whole plant	Spherical	Antimicrobial	[110]
<i>Encostemma axillare</i>	15–20	Leaves	Spherical	-	[111]
<i>Enteromorpha compressa</i>	4–24	Seaweed	Spherical	Biomedical properties	[112]
<i>Gracilaria corticata</i>	18–46	Seaweeds	Spherical	Antifungal activity	[113]
<i>Gymnema sylvestre</i>	20–30	Leaves	Spherical	Antibacterial activity	[114]
<i>Hybanthus enneaspermus</i>	25.2	Whole plant	Spherical, hexagonal, triangular	Larvicidal activity	[115]
<i>Lantana camara</i>	53.5	Flower	-	-	[116]
<i>Lantana trifolia</i>	<50	Leaves	Spherical	Antibacterial activity	[117]
<i>Lathyrus</i> sp.	117	Seeds, Sepal	Spherical	Antifungal activity	[118]
<i>Stachys lavandulifolia</i>	16	Fruit	-	Antimicrobial	[119]
<i>Malus domestica</i>	7.3	Leaves	Irregular	Anticancer activity	[120]
<i>Musa paradisiaca</i>	23.7	Banana peels	Spherical	Antimicrobial activity	[121]
<i>Myrmecodia pendan</i>	10–20	Leaves	Spherical, FCC	-	[122]
<i>Nauclea latifolia</i>	12	Fruit	Irregular	Antimicrobial and antioxidant	[123]
<i>Ocimum Sanctum</i>	10–20	Leaves	Spherical	Antibacterial activity	[124]
<i>Olea europaea</i>	90	Leaves	Spherical	Cytotoxic effect on MCF-7 cells	[125]
Olive leaf	20–25	Leaves	Spherical	Antibacterial activity	[126]
<i>Parkia speciosa</i>	31	Leaves	Spherical	Antibacterial, antioxidant and photocatalytic activity	[127]
<i>Phyllanthus pinnatus</i>	61.45	Stem	Spherical	Antibacterial activity	[128]
<i>Pistacia atlantica</i>	10–50	Seed	Spherical, FCC	Antibacterial activity	[129]
<i>Pistacia atlantica</i>	40–60	Leaves	Spherical	Antioxidant, cytotoxicity and antibacterial activity	[130]
<i>Pteridium aquilinum</i>	30–40	Leaves	Spherical	Mosquitocidal and antiplasmodial activity	[131]
Reishi Mushroom	15–22	Mushroom	Spherical	Antifungal activity	[132]
<i>Rosa canina</i>	13–21	Leaves	Spherical	Antioxidant, antibacterial, antifungal and DNA cleavage activity	[133]

Table 1. Cont.

Plants	Size (nm)	Plant's Part	Shape	Applications	References
<i>Rosmarinus officinalis</i> Linn.	10–33	Leaves	Spherical	Antimicrobial activity	[134]
<i>Sinapis arvensis</i>	14	Seeds	Spherical	Antifungal activity	[135]
<i>Solanum trilobatum</i>	15–20	Leaves	Cubic and hexagonal	Antidandruff activity	[136]
<i>Syzygium alternifolium</i> (Wt.)	20	Fruit	Spherical	Antimicrobial activity	[137]
<i>Talinum triangulare</i>	13.86	Leaves	Spherical	Electrochemical, antimicrobial and antioxidant activity	[138]
<i>Tephrosia purpurea</i>	20	Leaves	Spherical, FCC	Antibacterial activity	[139]
<i>Terminalia cuneata</i>	25	Barks	Distorted spherical	Catalytic action in reduction of direct yellow-12 dye	[140]
<i>Terminalia arjuna</i>	10–50	Leaves	Spherical	Catalytic action in reduction of MO, MB, 4NP and CR dyes	[90]
<i>Thevetia peruviana</i>	18.1	Leaves	Spherical	Antimicrobial activity	[141]
<i>Thevetia Peruviana</i>	10–30	Latex	Spherical, tubular, irregular	-	[142]
<i>Thymbra spicata</i>	7	Leaves	spherical	Catalytic reduction	[143]
<i>Tradescantia pallida</i>	98	Leaves	Spherical	Antibacterial activity	[144]
<i>Viburnum lantana</i>	20–80	Leaves	Spherical, FCC, uniform	Antibacterial Activity	[145]

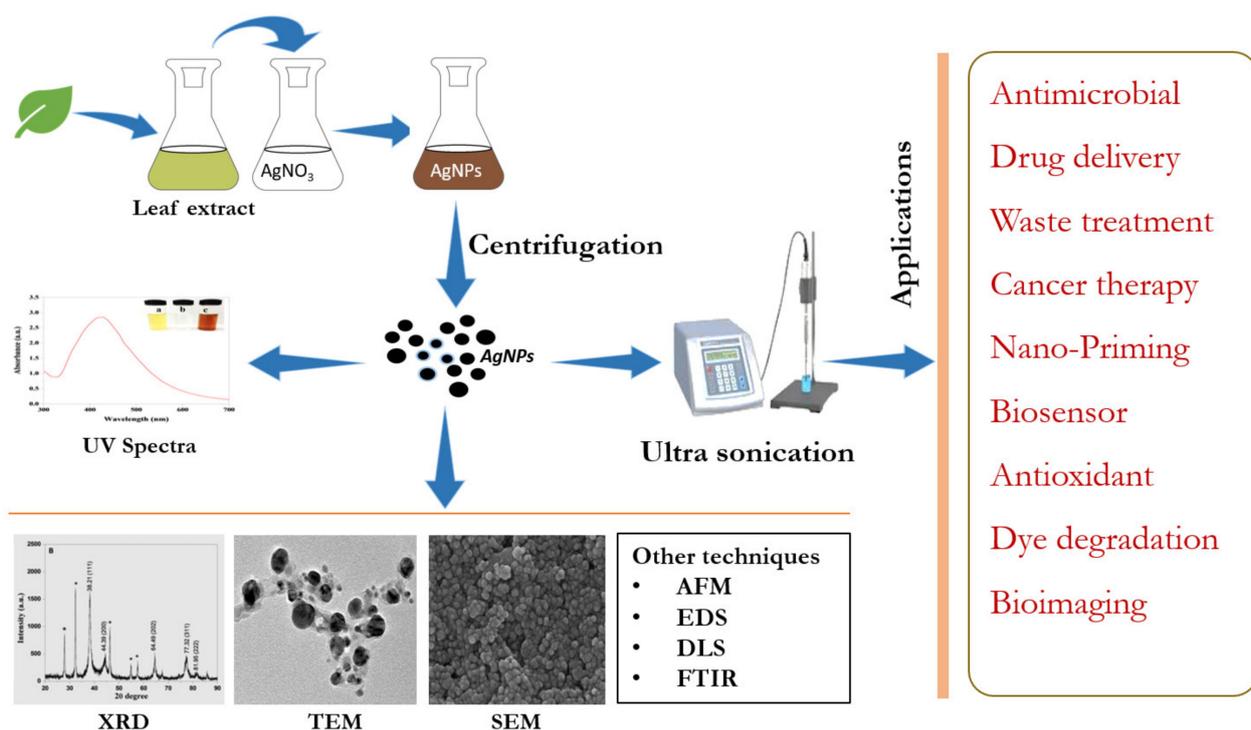


Figure 2. Graphical representation of the mechanism of plant-mediated synthesis of silver nanoparticles and their application.

The addition of a few milliliters of plant extract to 10^{-3} M AgNO₃ solution induces the reduction of pure Ag⁺ ions to Ag⁰, which can be surveilled by measuring the UV-visible spectra of the solution at regular intervals [146]. A huge range of plants and their respective plant parts had been utilized for the synthesis of AgNPs. The green synthesized spherical shaped AgNPs with a size of 31.83 nm was observed using the aqueous rhizome extract of *Acorus calamus*. The FTIR analysis of these particles revealed that the reduction and capping

of the AgNPs are due to the presence of aromatic amine, phenol/alcohol, and carbonyl groups in *Acorus calamus* extract. These nanoparticles exhibit antibacterial activity against *Bacillus cereus*, *Staphylococcus aureus*, and *Bacillus subtilis* and also evaluate its antioxidant and anticancer activity [147].

Calliandra haematocephala leaf extract was used as reducing agent for green synthesis of AgNPs. The extracellular synthesis of AgNPs is rapid, simple, eco-friendly, and cheaper in cost. The reduction of particles was primarily characterized by UV-visible spectrophotometry, and the SPR peak was identified to be at 414 nm. The SEM and XRD analyses revealed an average particle size of 70 nm with a face-centred cubic structure. The presence of element silver was determined by energy-dispersive spectroscopy (EDS). The stability of AgNPs was characterized by zeta potential, which is an equally negative charge (−17.2 mV) on particle surfaces. The antibacterial activity of these nanoparticles was evaluated against *E. coli* pathogenic bacteria [148]. *Lantana camara* was also used for the synthesis of AgNPs. Colorless to a brown–yellow colour of the solution are the visual indications of the nanoparticle formation. The crystalline nature of the particles was confirmed by X-ray diffraction (XRD) and selected area electron diffraction (SAED) patterns. The TEM analysis revealed that the average particles size was 14 nm. The FTIR results showed the involvement of the functional groups of *Lantana camara* leaf extract in the reduction and capping of AgNPs. The formation of AgNPs was also confirmed by X-ray photoelectron spectroscopy (XPS). These nanoparticles also exhibit an effective antibacterial activity against *Bacillus* and *Pseudomonas* [149].

Dried roasted seed extract of the plant *Coffea arabica* was mixed with silver nitrate solution in order to obtain AgNPs. The reduction of the silver was complete when the colour of the solution (AgNO_3 + extract) changed from light to dark brown. The spherical- and ellipsoidal- shaped particles ranging from 20–30 nm were exhibited in TEM observation. The primary characterization of these particles by UV-vis absorption spectroscopy showed the maximum absorption at 459 nm. AgNPs are highly crystalline in nature and a cubic face-centred lattice was revealed by the XRD analysis. The EDX spectrum confirmed the presence of elemental silver. The test for the antibacterial activity of AgNPs on *E. coli* and *S. aureus* indicated a reduced bacterial growth with the development of well-defined inhibition zones [150]. In the study of Ahmed et al., AgNPs were synthesized at room temperature using an aqueous extract of *Skimmia laureola* leaves. The colour of the mixture was changed from pale yellow to dark brown during the synthesis process. In UV-vis absorption spectroscopy evaluation, the synthesized AgNPs showed SPR at around 460 nm. The spherical and hexagonal shapes and crystalline nature of AgNPs with size 25 nm were confirmed by SEM and XRD analysis. Reduction of this particle was mainly due to bioactive compounds of leaf extract of *S. laureola* such as triterpenoids, skimmidiol, and coumarins. Moreover, AgNPs showed remarkable potential against various Gram-positive and Gram-negative human pathogenic bacteria [151].

The stable and spherical AgNPs were synthesized using *Rosmarinus officinalis* Linn. leaf extract. Leaf extracts of *R. officinalis* have dual properties of stability and emulsifying agents. The structure and morphology of the biologically synthesized AgNPs analyzed by UV-visible, FT-IR, SEM, TEM, and XRD. Maximum absorbance at 450 nm confirmed the formation of AgNPs. AgNPs were spherical and crystalline in nature, with sizes ranging within 10–33 nm, examined by SEM, TEM, and XRD analysis, respectively. These particles had highly antibacterial and antifungal activities [134]. AgNPs were also synthesized using plant leaf extracts of *Ocimum tenuiflorum*, *Solanum tricobatum*, *Syzygium cumini*, *Centella asiatica*, and *Citrus sinensis*. The average particles size of 28 nm, 26.5 nm, 65 nm, 22.3 nm, and 28.4 nm were measured by AFM analysis corresponding to *Osmium tenuiflorum*, *Solanum tricobatum*, *Syzygium cumini*, *Centella asiatica*, and *Citrus sinensis*, respectively. These quasi-spherical-shaped AgNPs showed the highest antimicrobial activities against *Staphylococcus aureus*, *Pseudomonas aeruginosa*, *Escherichia coli*, and *Klebsiella pneumonia* pathogenic bacteria [152]. *Zizphora tenuior* extract has been successfully used to made AgNPs, which are spherical shaped and 8–40 nm in size. Synthesized AgNPs were charac-

terized by various techniques such as UV-visible spectroscopy, FTIR, XRD, SEM, and TEM. This biogenic reduction of silver ions is environmentally benign. FTIR spectroscopy revealed that the reduction of nanoparticles was due to the involvement of alkaloids, phenolic compounds, terpenoids, and other stabilizing functional groups [153]. AgNPs were synthesized by Dipankar et al. using *Iresine herbstii* leaf extract, and then the formation of the nanoparticles was observed when the color of the reaction mixture turned brownish grey after 7 days of incubation. UV-vis absorption spectroscopy showed maximum absorbance at 460 nm, indicating the formation of Ag nanoparticles. SEM and EDX images showed pure and polydispersed spherical particles 44–64 nm in size and face-centred cubic in shape. FTIR analysis revealed the presence of plant biomolecule that might be responsible for the reduction of the into the nanoparticles. The synthesized AgNPs via green route exhibited strong antioxidant activity as well as cytotoxicity against HeLa cervical cell lines [154]. The root extract of *Panax ginseng* was used to synthesize silver and gold nanoparticles. Reduction of silver nitrate was conducted within 2 h of reaction time at 80 °C. AgNPs were synthesized successfully within 5 min of reaction time by reduction of auric acid at 80 °C. Synthesized gold and AgNPs was spherical shaped and 10–30 nm in size, as evident by characterization using various techniques such UV-Vis absorption spectroscopy, FE-TEM, EDX, and XRD. In addition, AgNPs showed a potent antibacterial activity against *Bacillus anthracis*, *Vibrio parahaemolyticus*, *Staphylococcus aureus*, *E. coli*, and *Bacillus cereus* [155]. The leaf extract of *Elephantopus scaber* L. was used to synthesize AgNPs. By the TEM analysis, it was found that synthesized nanoparticles were in spherical shapes with average particles sized 78 nm. It was observed in the DPPH assay that the AgNPs possessed antioxidant activity. Thus, it can be used as a potential free radical scavenger [156]. AgNPs were rapidly synthesized by Krishnaraj et al. using the leaf extract of *Acalypha indica*, and the formation of nanoparticles was noticed within 30 min [157]. The formation of stable AgNPs at various concentrations of AgNO₃ gives mostly spherical particles with a diameter ranging from 15 to 50 nm. In the pursuit of making the nanoscale-research greener, the orange peel (*Citrus sinensis*), a common by-product of the food processing industry, has been utilized; it has reductive potency i.e., has been reported to prepare biopolymer template “green” AgNPs. TEM imaging revealed well-dispersed spherical particles of 3–12 nm size. It was also interesting to note that the highest fraction of particles had a diameter of 6 nm [158]. The aqueous extract of *Abutilon indicum* leaves caused a rapid reduction of AgNO₃ into AgNPs. Formation, stability, size, and shape of the AgNPs were monitored by UV-vis spectrophotometer, TEM, SEM, and XRD [159]. In recent reports, these nanoparticles have been synthesized using the leaf extract of *Melia dubia* and were tested on the human breast cancer (KB) cell line. AgNPs showed remarkable cytotoxicity against the KB cell line [120].

Stachys lavandulifolia and *Lathyrus* sp. was also used to synthesize AgNPs with an average size of 7 and 11 nm, respectively. Reduction of the silver nitrate solution was indicated by colour change into dark brown and auburn after treating with extract. UV-vis absorption spectroscopy showed a strong SPR peak at 440 and 420 nm for *S. lavandulifolia* and *Lathyrus* sp., respectively. For the synthesis of AgNPs proteins, polyhydroxy functional groups were involved, as highlighted by FTIR report. These nanoparticles were used as an antifungal agent against *Dothiorella sarmentorum*, and the mycelium growth was inhibited as increasing the density of AgNPs [118]. Dwivedi et al. reported a facile and rapid biosynthesis of AgNPs from an obnoxious weed *Chenopodium album*. The leaf extract was prepared and successfully used for the synthesis of AuNPs and AgNPs having the size in the range of 10–30 nm. The spherical nanoparticles were observed at a higher leaf extract concentration, as inferred from the TEM imaging [160]. The AgNPs were formed after three hours of incubation at 37 °C using an aqueous solution of 1 mM silver nitrate.

Cymbopogon citratus (commonly known as lemon grass), a native aromatic herb from India and also cultivated in other tropical and subtropical countries, showed a strong antibacterial effect against *E. coli*, *P. aeruginosa*, *P. mirabilis*, *S. Somenei*, *Shigella flexaneri*, and *Klebsiella pneumonia* [161]. AgNPs were synthesized through the reduction of silver nitrate solution by aqueous extract of *Azadirachta indica* leaves by Prathna et al., and the growth

kinetics of AgNPs was scrutinized having a size of 10–35 nm. By an easy green method using the thermal treatment of aqueous solutions of silver nitrate and natural rubber latex extracted from *Hevea brasiliensis*, colloidal AgNPs were synthesized. The AgNPs presented diameters ranging from 2 nm to 10 nm and had a spherical shape with an FCC crystalline structure [162].

6. Techniques Used for Characterization of Nanoparticles

Nanoparticles are characterized according on their size, shape, surface area, and disparity [107]. In many applications, the uniformity of these parameters is essential. The following are the most prevalent techniques for identifying nanoparticles: dynamic light scattering, scanning electron microscopy, transmission electron microscopy, UV-visible spectrophotometry, atomic force microscopy, Fourier transform infrared spectroscopy, powder X-ray diffraction, and energy-dispersive spectroscopy [163].

For the characterization of silver and gold nanoparticles, wavelength ranges of 400–450 nm [164] and 500–550 nm [105] are used, respectively. The characterization of the surface charge and the size distribution of the particles suspended in a liquid solution were demonstrated by DLS [107]. Electron microscopy such as SEM and TEM are commonly used for morphological characterization at the nanometer-to-micrometer scale [165]. TEM has a 1000-time higher resolution compared with the SEM. FTIR spectroscopy is a useful technique for characterizing the surface chemistry [166]. Table 2 shows various nanoparticle characterization techniques. FTIR is used to identify organic functional groups of plants biomolecules (e.g., hydroxyls, carbonyls) adhering to the surface of nanoparticles, as well as other surface chemical residues. The XRD technique is used to determine the crystal structure, characterization, and phase identification of nanoparticles [167]. In this technique, X-rays penetrate the nanomaterial, and the generated diffraction pattern is compared to standards to obtain structural information. Using energy-dispersive spectroscopy, the elemental composition of metal nanoparticles is established [168].

Table 2. Different nanoparticles characterization techniques and techniques-related information.

Techniques	Characterization Techniques	Information Provided
Microscopy	AFM	Size, morphology, surface texture, electrical, and mechanical properties
	STM	Elemental and molecular composition
	SEM	Surface, size, shape morphology, and crystallographic composition
	TEM	Elemental composition and electrical conductivity
X ray-based techniques	XAS, XRF, XPS, XRD	Surface, crystallographic, and elemental composition
Light Scattering Spectroscopic techniques	UV-visible DLS FTIR	Particle size, aggregation, structure, and surface chemistry

7. Plant Biomolecules Responsible for Bio-Reduction of Silver Ions

Several secondary metabolites and enzymes have relatively advanced the formation of metallic nanoparticles from the corresponding ionic compounds. The reduction reaction mainly involved plant biomolecules (secondary metabolites) such as sugars (polysaccharides), proteins, pigments, organic compounds, and plant resins. Plants' natural products are involved in the reduction reaction to synthesize green nanoparticles. These secondary metabolites are known as key sources for controlling various acute diseases [169]. The proposed reduction reaction validated that the secondary metabolites are the main factors for the biosynthesis of metallic nanoparticles. The plant extracts contain numerous functional groups such as C-C (Alkenyl), C-N (amide), OH (phenolic and alcohol), N-H (amine), C-H, and COOH (carboxylic group). It is mainly symbolized as plant-secondary metabolites and

might be micro- and macro biomolecules [170]. These chemical compounds are extensively involved in the synthesis of nanoparticles. *R. hymenosepalus* leaf extract enhances nanoparticle synthesis at room temperature with rapid reaction kinetics. As a result, the solvent extract of *R. hymenosepalus* is high in polyphenols such catechins and stilbenes molecules, which function as reducing and stabilising agents in the synthesis of AgNPs [171]. The ecofriendly technique was used to synthesis nanoparticles from secondary metabolites such as phenolics [172], proteins [29], polysaccharides [164,173], flavonoids, and tannins [174].

8. Factors Influencing the Synthesis of Nanoparticles

The size and shapes of nanoparticles depend on the hydrogen ion concentration. It was reported that *Aloe vera* extract produced Au-Ag core nanoparticles in various sizes and shapes by fluctuating the pH of the solvent medium [175]. Highly stable AgNPs synthesized using plant extracts have been reported in some studies. Surprisingly, the synthesized nanoparticles were found to be stable under a wide pH range (2–10) due to their high zeta potential [160,176]. On the other hand, the temperature is also one of the most stimulating factors for the nanoparticle's biosynthesis with different size and shapes. However, in the case of AgNPs, very few studies have reported that temperature controls the shape of the synthesized nanoparticles [177]. Generally, AgNPs were successfully synthesized only at room temperature [40,178]. The study of Raju et al. regarding the synthesis of AgNPs using *Cymbopogon flexuosus* extract concluded that at the high reaction temperature, particles will lead to higher spherical shaped, whereas at low reaction temperatures, they mostly increase the nano triangle formation [179]. Generally, the difference in morphology is due to the percentage/amount of the salt solution in the reaction mixture. The salt concentration could be changed with the reduction ability and sizes. Some environmental factors, such as chemical and physical parameters, controlled metallic crystal structure using the plant biomass as substrates [180]. In addition, to plant extract and substrate concentration, the reduction reaction time (minutes-hours) is one of the factors affecting the shape, size, and stability of AgNPs to some extent. For a better synthesis of AgNPs, reaction parameters such as plant extract concentration, metal ion solution concentration, plant extract to metal ion solution concentration ratio, exposure period, pH, and temperature were adjusted [127,181]. One can make uniform sized AgNPs with better particle stability by adjusting one or more parameters [182]. These findings clearly show that plant extracts generated AgNPs at a significantly quicker pace than other methods. The production methodology followed green chemistry methods, and the generated nanoparticles were shown to be more stable, biocompatible, and useful. In light of these advantages, it is generally agreed that plant extracts are superior candidates for the biogenic production of nanoparticles, particularly AgNPs [62,183]. Figure 3 shows different types of factors affecting the morphology of nanoparticles.

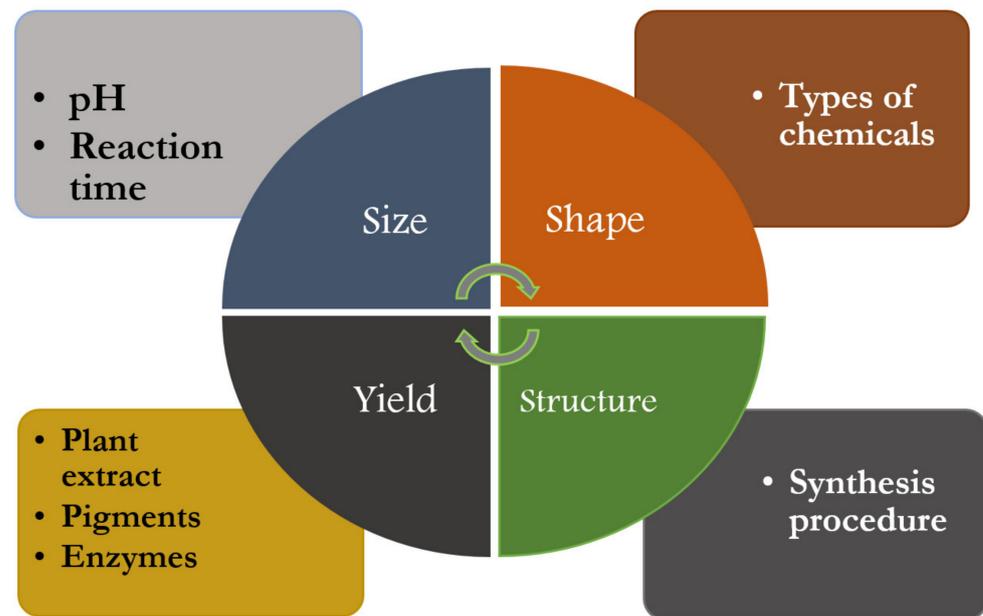


Figure 3. Different types of factors affecting the morphology of nanoparticles.

9. Application of AgNPs

9.1. Antifungal Activity

Antifungal activity of the AgNPs against fungal pathogens is mostly indefinite. Nevertheless, it was reported that these nanoparticles had significant antifungal activities against *T. mentagrophytes* and *Candida* species (such as *C. albicans*, *C. tropical*, *C. glabrata*, *C. parapsilosis*, and *C. krusei*). AgNPs disrupt fungal cell wall structure and lead to significant damage to fungal cells [37,184]. *Aspergillus oryzae* (plant disease caused) and *Candida albicans* were used for determining anti-fungal activities of AgNPs by the disk diffusion method on the surface of Sabouraud Dextrose Agar inoculated with 1.0×10^5 (CFU/mL) of a spore suspension of fungi. The Petri plates cultured with *A. oryzae* were incubated at 30 °C for 24–48 h, while the plates cultured with *C. albicans* were incubated at 32 °C for 24–48 h. The disks impregnated with AgNPs suspension (solubilized in 5% DMSO) of AgNPs doses (20, 40 and 80 mg/disk) were dispensed at different positions on the agar plate [185]. At the end of the incubation period, antifungal activities of AgNPs were determined as the diameter of the zone of inhibition. AgNPs had potent antifungal agents determined using in vitro Petri dish assays of *Bipolaris sorokiniana* and *Magnaporthe grisea*. The assay revealed that AgNPs had a significant effect on these two fungal pathogens. Effective concentrations of the silver compounds inhibiting colony formation by 50% were higher for *B. sorokiniana* than for *M. grisea*. These two fungi causing diseases on perennial ryegrass (*Lolium perenne*) were significantly reduced by AgNPs, further confirmed by colony formation chamber inoculation assays. For the most part, silver ions and nanoparticles effectively reduced disease severity with an application at 3 h before spore inoculation, but their efficacy significantly weakened when applied at 24 h after inoculation. The in vitro evaluations of AgNPs influence the colony formation of spores and disease progress of plant-pathogenic fungi. The plant efficacy of silver ions and nanoparticles is much greater with the preventative application, which may promote the direct contact of silver with spores and germ tubes and inhibit their viability [184].

Narayanan and Park (2014) studied the antifungal activity of AgNPs synthesized using turnip leaf (*Brassica rapa* L.) extract. Agar disc diffusion method was used to demonstrate antifungal activity against *Gloeophyllum abietinum*, *Chaetomium globosum*, *G. trabeum*, and *Phanerochaete sordida*. In this method, the sterile paper disc loaded with 2 and 4 mg/10 mL of synthesized AgNPs showed slight to moderate inhibition of wood-degrading fungal growth by forming a crescent-shaped inhibition zone around discs combined with nanoparticles.

However, the disc loaded with 4 mg of chemically-synthesized AgNPs showed significant inhibition of fungi [25].

Gracilaria corticata mediated synthesized AgNPs used to evaluate antifungal activity against *Candida* species. An amount of 30 μ L of the nanoparticle solution was well sufficient to inhibit *Candida albicans* and *C. glabrata*. AgNPs showed good antifungal activity as compared with standard reference antifungal drug Nystatin [109]. It is a well-known fact that antifungal activity of AgNPs is likely to be well associated with its high surface-to-volume ratio with enhanced antimicrobial effect [185,186]. Plant-based AgNPs are found to be involved in membrane destruction, damage to fungal intercellular components, and cell activity in *Candida* sp. [187]. Commercially available antifungal medications have limited therapeutic applicability, as well as higher side effects and a slower recovery from microbial illness. As a result, adverse effects such as liver damage, renal failure, nausea, elevated body temperature, and diarrhoea might occur after taking commercial medications. Nanoparticles were used to create a new and effective antimicrobial medication. The multifunctional AgNPs exhibit potential antifungal action and successfully destroy spore-producing fungi.

By treating with metallic nanoparticles, significant changes were observed in the fungal cell membrane structure [188]. Using a combination of AgNPs and fluconazole, *Phoma glomerata* and *Trichoderma* sp. were destroyed. Furthermore, the biosynthesized AgNPs have potent antifungal action against the various phytopathogenic fungi, such as *Fusarium oxysporum* [6], *Alternaria alternata*, *Sclerotinia sclerotiorum*, *Macrophomina phaseolina*, *Rhizoctonia solani*, *Botrytis cinerea*, *Curvularia lunata* [181], *A. flavus*, and *A. fumigatus* [189]. Placing fungal mycelia from the zone of inhibition on PDA plates was used to test the vitality of the fungus. Normal fungal mycelia untreated with AgNPs grew quickly after 48 h, but fungal mycelia from the zone of inhibition of newly produced AgNPs expanded poorly at both doses. Antifungal activity of AgNPs against some of the fungi are mentioned in the Table 3.

Table 3. Antifungal activity of biologically synthesized silver nanoparticles.

Plant	Test Organism	Method	Reference
<i>Aaronsohnia factorovskyi</i>	<i>Fusarium solani</i>	Poisoned food technique	[190]
<i>Aloe vera</i>	<i>Aspergillus</i> sp. and <i>Rhizopus</i> sp.	Agar disc diffusion method	[93]
<i>Amaranthus retroflexus</i>	<i>Macrophomina phaseolina</i> , <i>Alternaria alternata</i> and <i>Fusarium oxysporum</i>	Poison food technique	[191]
<i>Ananas comosus</i>	<i>Fusarium verticillioides</i> , <i>Aspergillus flavus</i> and <i>Alternaria alternata</i>	Well diffusion assay on malt extract agar	[192]
<i>Argimone mexicana</i>	<i>Aspergillus flavus</i>	Food poisoning	[193]
<i>Brassica rapa</i> L.	<i>Gloeophyllum abietinum</i> , <i>G. trabeum</i> , <i>Chaetomium globosum</i> , and <i>Phanerochaete sordida</i>	Agar disc diffusion assay	[79]
<i>Camellia sinensis</i>	<i>Aspergillus flavus</i> and <i>A. parasiticus</i>	Agar disc diffusion method	[194]
<i>Gracilaria corticata</i> (sea weeds)	<i>Candida albicans</i> and <i>C. glabrata</i>	Agar disc diffusion method	[109]
<i>Ligustrum lucidum</i>	<i>Setosphaeria turcica</i>	Paper Disk Diffusion Assay	[195]
<i>Malva parviflora</i>	<i>Helminthosporium rostratum</i> , <i>Fusarium solani</i> , <i>Fusarium oxysporum</i> , and <i>Alternaria alternata</i>	Poisoned food technique	[190]
<i>Melia azedarach</i>	<i>Verticillium dahlia</i>	Poisoned food technique	[196]
<i>Ocimum sanctum</i>	<i>Candida albicans</i> , <i>Candida glabrata</i> , and <i>Candida tropicalis</i>	Broth dilution method	[122]
<i>Passiflora caerulea</i>	<i>Trichophyton mentagrophytes</i> , <i>T. rubrum</i> , <i>E. floccosum</i> , <i>M. audouinii</i> , <i>M. Canis</i>	Agar disc diffusion method	[197]
<i>Peganum harmala</i>	<i>Fusarium oxysporum</i> , <i>Alternaria alternata</i> , and <i>Trichoderma</i>	Disc diffusion assay	[198]
<i>Phyllanthus urinaria</i> , <i>Pouzolzia zeylanica</i> , and <i>Scoparia dulcis</i>	<i>Aspergillus niger</i> , <i>Aspergillus flavus</i> , and <i>Fusarium oxysporum</i>	Poisoned food technique	[199]
<i>Prunus cerasifer</i>	<i>Aspergillus niger</i> , <i>A. flavus</i> , <i>A. fumigatus</i> , <i>A. terreus</i> , <i>Penicillium chrysogenum</i> , <i>Fusarium solani</i> and <i>Lasiodiplodia theobromae</i>	Kirby–Bauer disc diffusion assay	[200]
<i>Sinapis arvensis</i>	<i>Neofusicoccum parvum</i>	Mycelium growth inhibition test	[135]
<i>Stachys lavandulifolia</i> and <i>Lathyrus</i> sp.	<i>Dothiorella sarmentorum</i>	Agar dilution method	[118]
<i>Teucrium polium</i> L.	<i>Fusarium oxysporum</i>	Poisoned food technique	[201]
<i>Tropaeolum majus</i> L.	<i>Trichoderma viridiæ</i> , <i>Mucor</i> spp., <i>Aspergillus niger</i> and <i>Candida albicans</i>	MIC	[202]

9.2. Application of Nanoparticles in Agriculture

Attempts to apply nanotechnology in agriculture have begun as a result of the rising knowledge that traditional agricultural approaches will not increase a farm's production. Despite being the backbone of third-world countries, agriculture is regrettably experiencing a number of global difficulties, including climate change, population growth, urbanization, resource sustainability, and environmental concerns. Traditional agricultural methods erode soil quality, contribute to eutrophication of aquatic ecosystems, and necessitate additional fertilizer usage, irrigation, and higher energy inputs in order to sustain productivity on degraded soil. As a result, there is a lot of interest in employing nanotechnology in agriculture these days, since it has a lot of potential for revolutionizing traditional agricultural techniques and food production with revolutionary technologies. Nanobiosensors and other smart delivery systems will also aid the agricultural industry in the combat against various crop infections and provide a cost-effective way to release pesticides and fertilizers in a regulated and site-specific manner [203]. However, there is still a lack of knowledge on nanomaterial fate and impacts in agricultural systems. The introduction of nanosensors can aid in calculating the quantity of agricultural inputs required by signaling the nutrient or water status of crop plants, allowing farmers to apply nutrients, water, or crop protection (insecticide, fungicide, or herbicide) only where necessary [204]. Moreover, nano-pesticides, nano fungicides, and nano-herbicides are being used in agriculture [205]. In affluent countries, nanolabeled water filters have been employed to clean up waste areas [206]. According to Karn et al. (2009), the usage of nano-encapsulated fertilizers may regulate fertiliser consumption based on crop requirements and reduce pollution [207]. Bhattacharyya et al. (2011) explored nanotechnology's uses in a variety of disciplines, including nano-food, nano-food packaging, and nano-farming, as well as its consequences on the environment. In general, scientific applications of nanotechnology have the potential to significantly alter the agricultural system through enhanced production [35]. This can only be accomplished by allowing for greater plant input management and conservation. The greater public knowledge of the benefits and problems of rising nanotechnology and its products, the more likely the technology will be accepted. As a result, nanotechnology may become a necessary and crucial component of future agriculture and food production.

Applicability and phytotoxicity of silver nanomaterials in agriculture are well debated by the EPA [6,208]. As reported by Bergeson (2010a), there are more than 100 pesticides that contain AgNPs as antimicrobial agents [208]. However, the toxicity of nanosilver to humans and ecosystem is a major concern. Lu et al. (2010) have reported that the citrate-coated colloidal AgNPs were not cytotoxic, genotoxic, or phototoxic to humans; however, citrate-coated AgNPs in powder form were toxic [209]. The authors argued that this could be because of the "chemical change of spherical AgNPs in the powder to form silver oxides or ions". Interestingly, by coating powdered AgNPs with biocompatible polyvinyl pyrrole, the phototoxicity was repressed [207]. To reverse the toxicity of nanomaterials, exploring such biocompatible coatings would increase the chances of applying nanomaterials in plant germination and growth. Research is also needed to investigate the adverse effect of such coatings on the desired seed/plant properties and the effectiveness of nanomaterials. Figure 4 shows many other applications of biologically synthesized nanoparticles in different areas.

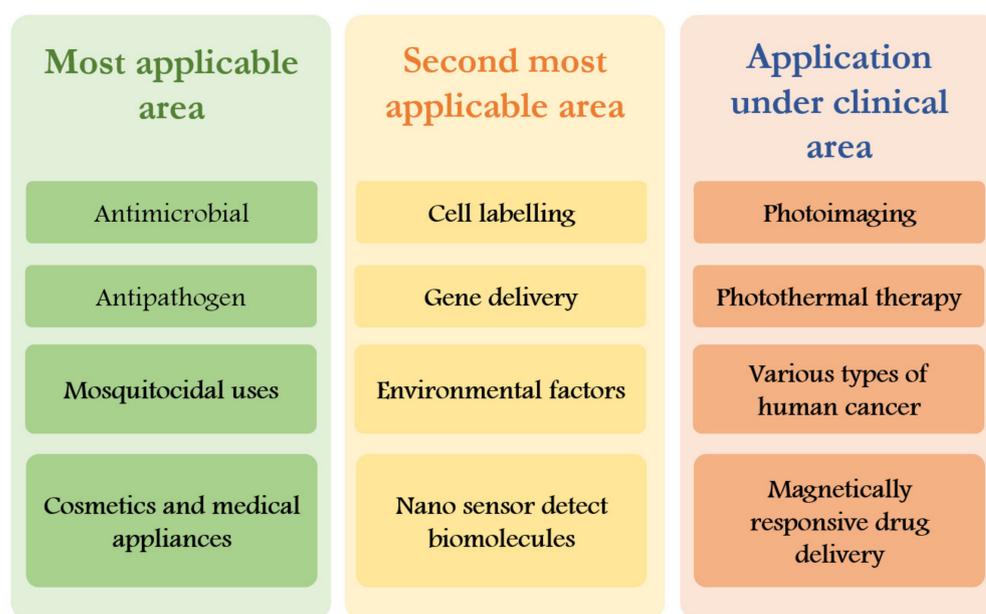


Figure 4. Application of biologically synthesized nanoparticles in various fields.

10. Conclusion and Future Perspective

Due to the diverse properties, functionalities and wide applications of silver nitrate nanoparticles, biogenic AgNPs stand out as one of the most versatile materials. The AgNPs synthesized from metallic silver by using various methods are generally used in food, consumer products, and medical products because of their antibacterial, antifungal, and antioxidant activity. Silver has been most considerably studied and used since ancient times to prevent spoilage and fight infections. Biogenic synthesis of AgNPs offers several advantages over chemical and physical methods, such as single pot, cost effectiveness, ecofriendliness, easily scaling up for large scale production, and no need to use high pressure, energy, temperature, and hazardous chemicals. The delivery of nanoparticles based on nanotechnology has given propitious results for enhanced plant growth, nutrition, and plant disease resistance, and this has been accomplished through the site-specific delivery of essential nutrients and fertilizers with the help of controlled-release formulations of nanoparticles. Nanoencapsulation allows for the slow and sustained release of the active substances and provides better penetration, thus improving the herbicide application. The yield of staple food crops is much lower while the food demand is increasing day by day. For sustainable agriculture, the commercialized nanoparticles need to be applied to augment the growth and yield of crops.

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Conflicts of Interest: The authors declare that the work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

AFM: Atomic Force Microscopy; Ag, Silver; AgNO₃, Silver Nitrate; AgNPs, Silver nanoparticles; Au, Gold; CFU, Colony-Forming Unit; CR, Congo Red; DLS, Dynamic Light Scattering; DMF, *N,N*-dimethylformamide; DMSO, Dimethyl Sulfoxide; DPPH, 2,2-Diphenyl-1-Picrylhydrazyl; EDS, Energy-Dispersive Spectroscopy; EPA, Environment Protection Agency; FCC, Face-Centered Cubic; FE-SEM, Field Emission Scanning Electron Microscopy; FE-TEM, Field Emission Transmission Electron Microscopy; FTIR, Fourier Transformed Infrared Spectroscopy; HRTEM, High-Resolution Transmission Electron Microscopy; MB, Methylene Blue; MO, Methyl Orange; mV, Mili Volt; NaBH₄, Sodium Borohydride; PbS, Lead Sulphate; SAED, Selected Area Electron Diffraction; SEM, Scanning Electron Microscopy; SPR, Surface Plasmon Resonance; STM, Scanning Tunneling Microscope; TEM, Transmission Electron Microscopy; UV-vis, Ultra Violet Visible Spectroscopy; XAS, X-ray Absorption Spectroscopy; XPS, X-ray Photoelectron Spectroscopy; XRF, X-Ray Fluorescence; 4NP, 4-Nitrophenol.

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