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REVIEW

Biogenic Silver Nanoparticles as Next-Generation Green Catalysts for Multifaceted Applications

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Abstract

In the field of material sciences, nano-based formulations have attracted the attention of researchers, as they are highly suitable for applications in different fields. Conventionally, physical and chemical techniques have been employed to synthesize silver nanoparticles (AgNPs). However, they use hazardous and poisonous ingredients, which are toxic to human health and the environment. Therefore, it necessitates the development of an eco-friendly and economical method for the fabrication of silver nanoparticles. Biogenic AgNPs have been synthesized using plants and microorganisms due to the presence of reducing agents such as metabolites and enzymes in their extracts. The size, shape, and other properties of the biogenic AgNPs have been characterized using various biophysical techniques. AgNPs are widely used to treat infections and diseases in humans and plants. They have demonstrated antifungal and antibacterial activities and, therefore, have been applied in various therapeutic applications like the treatment of cancer, wound dressing, orthopedic and cardiovascular implants, and dental composites. Biogenic AgNPs have been applied for the remediation of environmental pollution, including that of water and air via the detoxification of synthetic dyes and other contaminants. They have improved seed germination and plant growth after application as nanofertilizers and nano-pesticides, as well as in masking the effects of stress. This review describes various biological routes used in the green synthesis of silver nanoparticles and their potential applications in agricultural, environmental, and medical fields.

Keywords Green synthesis · Silver nanoparticles · Antimicrobial · Therapeutic · Catalysis

Introduction

Nanotechnology is one of the most dynamic, novel, and active research areas in the twenty-first century. It refers to the ability to handle objects at a nanometer scale ranging from 1 to 100 nm by monitoring, manipulating, and controlling matter for useful applications. According to the National Nanotechnology Initiative of the USA, nanotechnology is "science, engineering and technology undertaken at the nanoscale level where special phenomenon permits creative applications in a wide range of sectors" [1]. It involves merging techniques and protocols from other fields, such as physics, biology, and biochemistry. As a result, novel methodologies and new materials have been created [2]. The synthesis of nanoparticles (NPs) has become a significant research area due to their widespread applications in the medical field, including diagnostics and therapies [3].

Among all the NPs, silver nanoparticles (AgNPs) are of great interest due to their broad range of applications in microbiology, food technology, parasitology, pharmacology,

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chemistry, and cell biology [4, 5]. NPs possess novel and unique physical properties, such as high surface area-to-volume ratio and structural stability [6]. In contrast with the bulk materials used to prepare them, NPs have outstanding magnetic, optical, mechanical, and catalytic properties. These can be altered by carefully modulating the shape, size, synthesis conditions, and functionalization of the NPs [7]. Depending on their morphology and chemical properties, they can be broadly categorized into inorganic NPs (ZnO_2, Fe_2O_3, TiO_2, and CaO), carbon-based NPs (graphene, carbon nanotubes, and fullerenes), nano-polymers (nanowires, nanorods, and polymeric nanotubes), metallic (Cu, Ag, and Au) and quantum dots [8]. The research on metal nanoparticles is the foremost field of nanotechnology due to their use in cosmetics, cancer therapy, therapeutics, and molecule-based detections [9, 10]. During the last two decades, silver and certain other noble nanoparticles have received considerable attention due to their exceptional characteristics, such as having a sustainable surface area when compared to bulk materials, despite having similar chemical compositions [11]. Nanosized metallic particles are unique, and their high surface–volume ratio substantially impacts their physicochemical and biological properties [11, 12].

Consequently, AgNPs have been employed in a broad range of applications, including consumer goods, electrical batteries, information storage, catalysis, healthcare, biolabeling, antimicrobials, DNA sequencing, and contamination control [8–11]. Numerous textiles, wound dressings, and biomedical devices have recently incorporated AgNPs. The “top-down” and “bottom-up” approaches are commonly applied for the fabrication of nanostructures. They differ from each other in the technique employed and precursor used. The top-down approach involves the size reduction of bulk material through various techniques such as mechanical milling, spray pyrolysis, pulse wire discharge, cutting, and evaporation [13]. Laser ablation and evaporation–condensation are the two most crucial and widely used physical methods for nanoparticle synthesis in this approach [14].

Evaporation-based synthesis uses a tube furnace in which the precursor material is vaporized in a carrier gas. Nanoparticles of different materials, such as Au, PbS, Ag, and fullerene, have already been reported [15]. Fabrication of AgNPs by evaporation has a few demerits, as it requires a high amount of energy for heating during operations and consumes a lot of space [11]. Polydispersed AgNPs could be synthesized through evaporation via small ceramic heaters. These evaporate the foundation material and produce spherical nanoparticles [16]. In laser ablation, metal colloids are produced without the application of chemical solvents, making them environmentally friendly. Usually, the reaction in a physical method occurs in a solvent-free solution. By adjusting the ablation efficiency and characteristics (size and shape) can be controlled. Additionally, the purity of nanoparticles synthesized is relatively high with robust antimicrobial activity and reactivity. Generally, NPs are of a uniform size and shape, but controlling their characteristics is difficult. The narrow size distribution of AgNPs additionally benefits the physical approaches over chemical ones [13].

By contrast, the bottom-up approach is the assembly of nanosized building blocks, such as molecules and particles, by chemical reduction, photochemical, solvothermal, coprecipitation, bioreduction, and microwave. It fabricates atoms into nanoparticles using either chemical or biological methods [17]. It involves electrochemical methods, pyrolysis, chemical reduction, irradiation-assisted chemical methods, and others. Of these, chemical reduction is most commonly used for the synthesis of AgNPs. The morphology of the nanoparticles, such as their shape and size, plays a significant role in controlling their properties [18]. Metal precursors, and reducing, stabilizing, or capping agents are the typically main components needed for this approach. Sodium citrate, ascorbate, elemental hydrogen, sodium borohydride, N, N-dimethylformamide (DMF), Tollens’ reagent, and poly(ethylene glycol) block copolymers are employed as reducing agents [19].

Stabilizing agents, including surfactants, ligands, or polymers like polyvinylpyrrolidone and polyethylene glycol, have specific functional groups. The concentration of the salt solution as precursor material affects the size of the AgNPs [20]. The introduction of reducing agents reduces the metal precursors. In chemical reduction, silver ions (Ag^+) are transferred with electrons from the reducing agents to produce Ag^0; these metallic forms coalesce to form AgNPs. The most frequently employed salt for producing AgNPs is silver nitrate, as it is more chemically stable than others and is easily accessible [21]. One of the chief advantages of this method is the synthesis of a substantial amount of nanoparticles within a short duration [11]. However, chemical methods have several drawbacks despite producing a high concentration of nanoparticles. For instance, the waste generated is huge and the nanoparticles synthesized are more often contaminated due to the use of toxic solvents [22]. Both the environment and human health are endangered by the use of toxic chemicals [17, 18, 22]. In extreme situations, sodium borohydride as a reductant and stabilizer may result in breathing problems and fluid accumulation in the lungs. Extremely high exposures may harm the neurological system [23, 24]. Moreover, altering the chemical concentrations and reaction conditions can change the morphology of the nanoparticles synthesized. However, for specific applications, these nanomaterials may face certain limitations or difficulties: (i) a lack of understanding of the basic mechanism, (ii) toxicity, (iii) stability under harsh conditions, (iv) requirement of skilled operators, and (v) challenges in device assembly. Therefore, to overcome the limitations of these conventional approaches, “green synthesis” is gaining enormous attention in technology, research, and material sciences [24]. Due to its affordability, environmental friendliness, ease of scaling up for large-scale nanoparticle synthesis, and no requirement for harmful chemicals as well as high energy, green synthesis offers to overcome the limitations of physical and chemical methods. It allows for improved manipulation, crystal growth control, and stability. It has prompted the design of novel synthesis methods for the precise control of the shape and size of AgNPs, which would be useful in applications [25].

For the synthesis of AgNPs, three fundamental methodologies: chemical, physical, and biological processes (Table 1) are operated globally [26, 27]. Chemical methods are the most common yet have fewer benefits. Chemical methods for the synthesis of AgNPs are plentiful and extremely common. They use water or organic solvents for the synthesis of AgNPs. Their major shortfall is they are not green methods. Reagents that are used for the synthesis of AgNPs, like oleyl amine, are dangerous to aquatic life and harmful to the environment. Therefore, it is evident that the chemical synthesis of AgNPs, though straightforward and efficient, violates some principles of green chemistry, mainly due to the reliance on chemicals toxic to humans. In a world moving toward attaining sustainable development goals, chemical methods are not practical options for the large-scale synthesis of silver nanoparticles. In terms of greenness, physical methods show more promise, but biological methods seem to maintain the principles of green chemistry the most [28–30]. Therefore, biological methods are the green and suitable alternatives to physical and chemical methods for AgNP synthesis [29, 30]. Certain constituent biomolecules and enzymes of living organisms, such as algae, plants, microbes, and even animals, play a significant role in nanoparticle synthesis, helping the reduction of Ag^+ to form AgNPs. The principal benefit of biological synthesis is the purity and safety of the resultant nanoparticles [31].

Biogenic AgNPs have been applied as green catalysts in medicine, agriculture, and environmental remediation [8]. Green AgNPs have demonstrated antifungal and antibacterial activities against animal, human, and plant pathogens [9–11]. These nanoparticles are widely used in the treatment of cancer and as a protective covering for medical equipment like catheters. Biogenic AgNPs are also useful in the remediation of environmental pollutants, including organic and inorganic pollutants [24, 28]. Detoxification of synthetic dyes and other contaminants has been demonstrated using AgNPs. Biogenic AgNPs are also useful in improving seed germination and plant growth as nanofertilizers and nanopesticides as well as to overcome stress. Therefore, this review article describes the biogenic synthesis of AgNPs and their applications as green catalysts in biomedical, agricultural, and environmental fields.

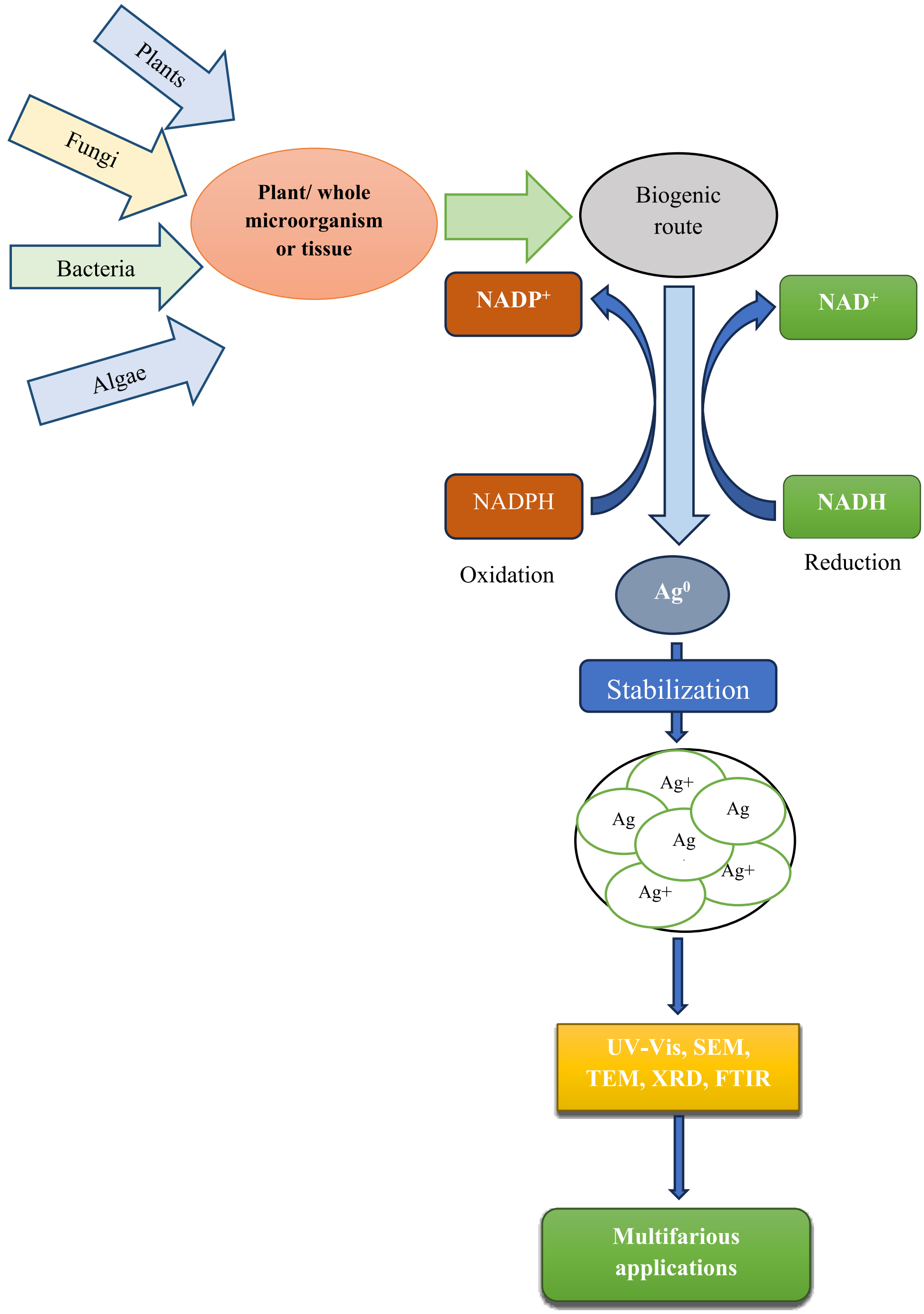
Green Synthesis of Silver Nanoparticles

In addition to small molecules like primary and secondary metabolites and natural products, living organisms also produce large macromolecules like proteins, lipids, polysaccharides, and nucleic acids. Each of these molecules serves a specific purpose for the growth, development, and maintenance of the organism within its environment [32]. The biogenic formation of AgNPs synthesized from these biomolecules has received a lot of attention recently. They have potential roles in different fields due to their nontoxic nature. The process of the biogenic synthesis of AgNPs is given in Fig. 1. They are produced by the reduction of Ag^+ to Ag^0 by various biomolecules such as flavonoids, polyphenols, ketones, aldehydes, carboxylic acids, tannins, and proteins/enzymes, which are present in the plant/microbial extract [33]. Thus, such a bioinspired synthesis appeared as a green and sustainable approach. This green approach is eco-friendly, cost-effective, has a simple route, and can also be employed to fabricate substantial amounts of nanoparticles free of contamination [10]. There are two basic steps followed for green synthesis: biosorption and bioreduction. Bioreduction refers to the reduction of metal ions into their stable forms, and biosorption is the process in which metal ions bind to the surface of organisms, like cell walls or peptides, to form more stabilized complexes [34]. Different plant parts like leaves, bark, roots, and stems have been employed for the green synthesis of AgNPs. Recent

Table 1 Comparison of different methods used for the synthesis of silver nanoparticles

Factors	Physical methods	Chemical methods	Biological methods
Energy	Energy inefficient	Efficient or inefficient	Energy efficient
Cost of production	High	Depending on the method employed	Low cost
Solvent used	Solvent-free	Solvents are used	Solvent-free
Ease of controlling the characteristics of NPs	Difficult	Possible	Possible
Waste generated	Low	High	Low
Eco-friendly nature	Less	No	Yes (High)

Fig. 1 Mechanism of synthesis of silver nanoparticles by different biological routes



studies have investigated the potential and therapeutic applications of plants, including *Aloe vera*, *Boerhaavia diffusa*, *Tinospora cordofolia*, *Terminalia chebula*, *Ocimum tenuiflorum*, *Azadirachta indica*, *Catharanthus roseus*, *Cosos nucifera*, and *Cinnmon zeylancium* [35]. Microbes can produce AgNPs either intra or extracellularly. Trapping, reduction, and stabilization are the fundamental processes for AgNP synthesis. They primarily rely on the metal ions present in the bacterial cell wall. The hazardous metals are then converted by the enzymes of the cell wall to nontoxic NPs, which later permeate through the cell wall. The metal ions are reduced to metallic NPs by nitrate reductase or hydroquinone-mediated redox processes [36]. Therefore, it is necessary to understand their sources, interactions with the environment, and risks to provide for the safe use of NPs with no or limited hazardous impact on the environment [37]. Moreover, AgNPs synthesized by biological approaches have excellent applications in the fields of nonlinear optics, intercalation materials for electrical batteries, antimicrobials, and biolabeling [8–11]. The biological methods of AgNP synthesis are possibly safer, nontoxic, and economical and thus biocompatible as compared to physical and chemical procedures [8].

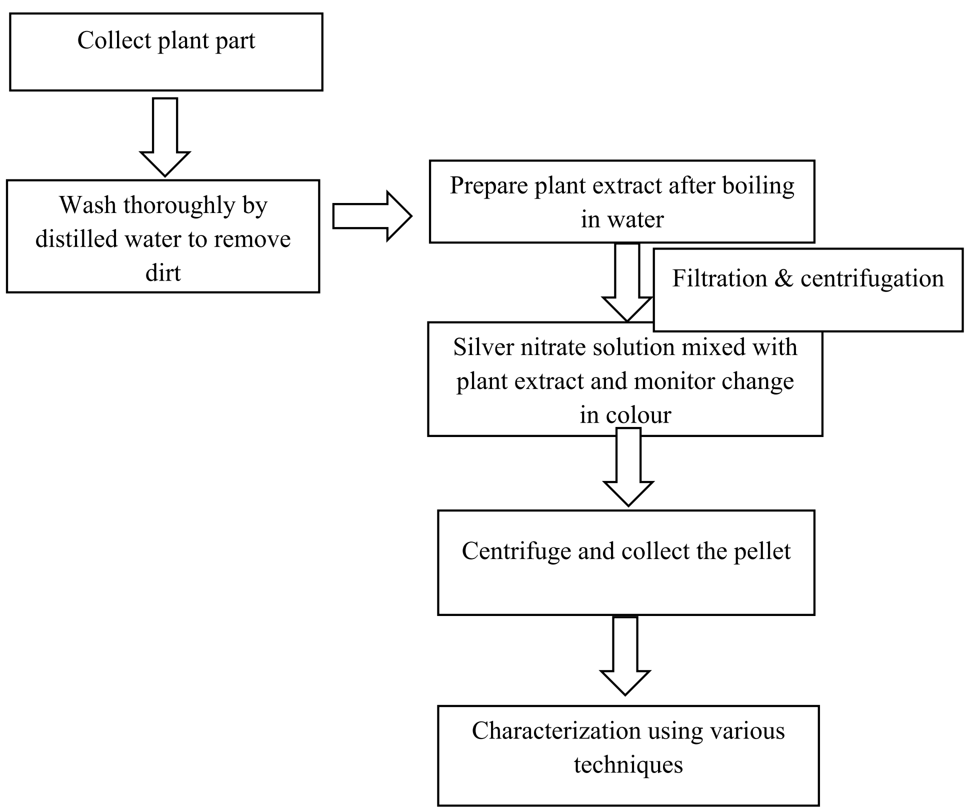
Green Synthesis Using Plants

Of all the bioentities, plants or their extracts appear to be the best agents due to their ease of availability, mass production of silver NPs, and environmentally friendly waste products [38]. In recent years, green synthesis using plant extracts gained more attention over physical or chemical approaches and even than the use of microbes as there is no need to maintain aseptic conditions. In comparison with microorganisms, plant extracts reduce metal ions more quickly. NP production is a matter of minutes or hours, depending on the type of plant employed and the concentration of phytochemicals present [39].

Bioinspired synthesis utilizes different plant parts like leaves, flowers, roots, petals, seed husks, or even the whole plant (Fig. 2) because they are rich in a variety of biomolecules like saponins, terpenoids, amino acids, carbohydrates, proteins, and flavonoids that act as reducing, capping, and stabilizing agents [34]. In addition to the ideal parameters, the principal issue is the selection of the plant from which the extract could be used. Using plants as a biological source has several benefits, such as they are safe to handle, easily accessible, and have a wide variety of active compounds that can enhance the reduction of Ag^{+}. Mainly, the parts like leaves, stems, roots, and latex are used. Biologically synthesized AgNPs from peanut shells were spherical and oval, with an average diameter of 10–50 nm [40]. *Ficus benghalensis* leaf extracts were used to synthesize stable and spherical NPs of size 10–50 nm [41].

AgNPs were synthesized using *Euphorbia wallichii* extract as a stabilizing and reducing agent; the NPs were characterized by UV–visible (UV–Vis) spectroscopy, Fourier transform infrared spectroscopy (FTIR), field emission scanning electron microscopy (FE-SEM), X-Ray diffraction (XRD), and energy-dispersive X-ray and had an average size of 63 nm [42]. The color of the AgNPs synthesized using *Acacia cyanophylla* changed to yellowish brown. Various techniques such as UV–Vis spectroscopy, dynamic light scattering (DLS), and SEM were used to study the characteristics of NPs; their average diameter was 88.1 nm. Different conditions were also optimized for the maximum synthesis of AgNPs. They were effective as an antibacterial agent [43]. FTIR, XRD, and SEM were employed to characterize the AgNPs synthesized using *Acer oblongifolium*. The rod-like AgNPs had antibacterial and antiproliferative activities [44]. Those synthesized from *Cassia tora* seeds possess antibacterial activity [45]. Those obtained using *Conocarpus lancifolius* fruits had a size of 21–173 nm and possessed antibacterial activity against *Streptococcus pneumoniae* and *S. aureus* [46].

Fig. 2 Schematic of the green synthesis of AgNPs using plant extracts



The main advantages of utilizing plants in the synthesis of AgNPs are their easy availability and a substantial amount of bioactive agents like phenolics, terpenoids, amino acids, polysaccharides, alkaloids, flavonoids, and proteins, which are responsible for the reduction of Ag^+ [47]. However, the identification of phytochemicals and their exact mechanism of action involved in the production of AgNPs is still not clear. Therefore, it is necessary to understand the relationship between the synthesis, morphological characteristics, and compounds present in plant extracts which is a very difficult task due to the lack of suitable extract characterization techniques per common phytochemicals. The amounts of toxic substances replaced by nontoxic alternatives during biosynthesis, the levels of energy conserved, and the ecological and economic effects play a major role in the claim of environmental friendliness. Commercially, AgNPs are synthesized employing predetermined procedures to ensure the quality in terms of homogeneity in NP morphology and surface properties. Additionally, because the size and shape of a majority of the green synthesized AgNPs cannot be controlled accurately, it affects the physicochemical characteristics of the NPs. Some studies used anionic and cationic reagents, cetyltrimethylammonium bromide, detergents, and amphiphilic compounds for the production of shape-controlled AgNPs. The impact of phytoconstituents on shape formation in green synthesized AgNPs was not demonstrated empirically or supported by any scientific evidence [48]. Some other plant extracts used for the synthesis of AgNPs are given in Table 2.

Green Synthesis Using Fungi

Among all the microorganisms considered for AgNP synthesis, fungi are an excellent source that may produce AgNPs both intracellularly and extracellularly [111] (Table 3). The precursor metal is introduced to the mycelial culture and co-opted in the fungal biomass during intracellular synthesis. Thus, for nanoparticle extraction, the disruption of biomass requires chemical treatment, centrifugation, and filtration. Alternatively, the metal precursor is introduced to the aqueous filtrate, which contains the biomolecules from fungal biomass in the case of the extracellular approach; therefore, no treatment is needed to release the NPs from the cells [47]. The NPs synthesized utilizing fungi as a biological source possess acceptable dimensions, excellent stability, and good polydispersity. Other advantages include high metal tolerance and ease in the scaling process. Additionally, during the synthesis of NPs, proteins obtained from fungi are coated on them to boost their stability and perhaps impart biological activity [112]. The extracellular synthesis of AgNPs by utilizing the biomass filtrate of *Aspergillus niger* and their anticancer activity was studied [113]. The average size of the spherical NPs was observed to be 21 nm, as ascertained by SEM. The green synthesis of AgNPs using the extract of the white rot fungus *Trametes trogii* after an incubation period of 72 h was reported [114]. The extracellular synthesis of polydispersed AgNPs having a size of 10–12 nm using *Penicillium verrucosum* was observed [115]. AgNPs produced by *Talaromyces funiculosus* were examined using spectroscopic techniques; they were discovered to have an antibacterial effect against the foodborne pathogens *Staphylococcus aureus*, *Enterococcus faecalis*, as well as certain strains of *Pseudomonas aeruginosa*, *Bacillus subtilis*, and *Escherichia coli* [116]. As a sustainable and renewable source of reductase enzymes and metabolites, the fungal biomass of *Trichoderma reesei* was employed to synthesize AgNPs with bactericidal properties [117].

Green Synthesis Using Bacteria

Bacteria are mostly preferred for the synthesis of AgNPs because of their high growth rate, ease of handling, and convenient genetic modification, though they own various properties [137]. Different bacterial strains have been reported for the biological synthesis of various metal NPs. The supernatants from a variety of bacterial species, including *Arthrobacter gangotriensis*, *Pseudomonas proteolytic*, *Pseudomonas meridiana*, *Phyllophora antarctica*, and *Promachocrinus kerguelensis*, function as environmentally friendly nanofactories and are used as reductants in AgNP synthesis [138]. The antimicrobial activity of AgNPs synthesized using *Aeromonas* spp. THG-FG1.2 was observed to be significant; the average size of the spherical NPs was 8–16 nm, as observed by TEM [139]. The AgNPs fabricated employing *Lactobacillus bulgaricus* had an average size between 30.65 and 100 nm [140]. AgNPs formed via reduction using the three bacterial species, i.e., *Rhodococcus*, *Brevundimonas*, and *Bacillus*, obtained within 24 h, were spherical or rod shaped with a size of 20–50 nm as detected by TEM; it is necessary to consider the disadvantages of using bacteria for the synthesis of AgNPs, the main being: (1) their continuous growth even after the formation of AgNPs and (2) the limited size and shape of NPs obtained as compared to traditional methods [141]. The other bacteria used are summarized in Table 4.

Green Synthesis Using Algae

Algae are autotrophic organisms that exhibit significant ecological and economic value. They are found in freshwater, seawater, or moist rocks and can be either single-celled or multicellular. Microalgae and macroalgae are the two different groups of algae. They are crucial in diverse fields, including pharmacy, cosmetics, medicines, forestry, and aquaculture. They are a significant supplier of several industrial goods, biodiesel, and natural dyes. A field of

Table 2 Synthesis of silver nanoparticles using different plant extracts

Serial No	Biological source	Part used	Size (nm) and shape	Applications	Refs
1	*Vitex negundo L*	Plant extract	18.2 nm	Antimicrobial activity against Gram-positive and Gram-negative bacteria	[49]
2	*Alternanthera sessilis*	Leaf extract	< 100 nm with a crystalline nature	Rapid silver ion reduction agent with considerable antiproliferative effects on prostate cancer cells	[50]
3	*Morinda citrifolia*	Root extract	30–55 nm, spherical shape	Cytotoxic effect on HeLa cell	[51]
4	*Delphinium denudatu*	Root	< 85 nm, spherical shape	Larvicidal against *Aedes aegypti* and antibacterial against *Staphylococcus aureus*, *Bacillus cereus*, *Escherichia coli,* and *Pseudomonas aeruginosa*	[52]
5	Orange	Plant extract	91 nm, spherical	–	[53]
6	*Justica adhatoda*	Plant extract	11–20 nm, spherical	–	[54]
7	*Chrysanthemum indicum*	Plant extract	37.71–71.99 nm, spherical	–	[55]
8	*Alstonia scholaris*	Plant extract	50 nm, spherical	–	[56]
9	*Piper nigrum*	Plant extract	7–50 nm and 9–30 nm, spherical	–	[57]
10	*Achillea bieberstennii*	Plant extract	12 ± 2 nm, hexagonal, pentagonal, and spherical	–	[58]
11	*Ocimum tenuiforum, Azadirachta indica* and *Musa balbisiana*	Plant extract	Up to 200 nm, cubical, spherical, and triangular	–	[59]
12	*Vitex negundo*	Plant extract	60 nm, spherical	–	[60]
13	Grape	Seeds	25–35 nm, polygonal and spherical	Antibacterial activity against *Vibrio alginolyticus*, *V. anguillarum*, *V. parahaemolyticus*, *Escherichia coli, Shigellae dysenteriae*, *Pseudomonas aeruginosa*, *Staphylococcus aureus*	[61]
14	*Abutilon indicum* L	Leaf extract	10–30 nm, spherical	Antitumor and scavenging activities in the MCF-7 breast cancer cell line	[62]
15	*Withania somnifera*	Leaf powder	5–30 nm, spherical	Antimicrobial activity against *Staphylococcus aureus*, *Escherichia coli*, *Aspergillus niger*, *A. flavus*, and *Candida albicans*	[63]
16	Banana	Plant extract	23.7 nm, spherical	–	[64]
17	*Eucalyptus globulus*	Plant extract	1.9–4.3 and 5–25 nm, spherical	–	[65]
18	Cranberry	Plant extract	2.8 ± 2.1, 1.4 ± 0.8, 8.6 ± 2.5 nm, Spherical	–	[66]
19	*Phyllanthus niruri*	Plant extract	30–60 nm, spherical	–	[67]
20	*Zingiber officinale*	Plant extract	3.1 nm, spherical	–	[68]
21	Oak	Plant extract	40 nm, spherical	–	[69]
22	*Averrhoa carambola*	Fruit	10–40 nm, spherical	Antibacterial activity against *Escherichia coli* and *Pseudomonas aeruginosa*	[70]
23	*Solanum trilobatum*	Fruit	12.5–41.9 nm, spherical	Antibacterial activity against *Streptococcus mutans*, *Escherichia coli, Enterococcus faecalis*, and *Klebsiella pneumonia*	[71]
24	Marigold (*Tagetes erecta*)	Flower	46.11 nm, spherical	Antibacterial activity against *Staphylococcus aureus*, *Bacillus cereus*, *Escherichia coli*, *Pseudomonas aeruginosa*, *Candida glabrata*, *Candida albicans*, *Cryptococcus neoformans*	[72]

Table 2 (continued)

Serial No	Biological source	Part used	Size (nm) and shape	Applications	Refs
25	*Nyctanthes arbortristis*	Flower	5–20 nm, spherical and oval	Antibacterial activity against *Escherichia coli*	[73]
26	*Petiveria alliacea*	Leaf	16–33 nm, crystalline	Effective against MDR bacterial strains; strong antifungal effects	[74]
27	*Sinapis arvensis*	Seeds	1–35 nm, spherical	Antibacterial activity against *Neofusicoccum parvum*	[75]
28	*Emblica officinalis*	Fruit	15 nm, spherical	Antibacterial activity against *Staphylococcus aureus*, *Bacillus subtilis*, *Escherichia coli*, and *Klebsiella pneumonia*	[76]
29	*Coffea arabica*	Seed extract	20–30 nm	Antibacterial activity of silver nanoparticles against *Escherichia coli* and *Staphylococcus aureus*	[77]
30	*Terminalia cuneata*	Bark extract	25–50 nm, distorted spherical	Reduction of direct yellow dye-12 dye by catalytic action	[78]
31	*Rheum palmatum*	–	121 ± 2 nm, cubic, spherical, and hexagonal	–	[79]
32	*Excoecaria agallocha*	–	20 nm, hexagonal and spherical	–	[80]
33	*Styrax benzoin*	Gum	12–38 nm, spherical	Antibacterial activity against *Pseudomonas aeruginosa*, *Staphylococcus aureus*, *Escherichia coli*, and *Candida tropicalis*	[81]
34	*Sesbania grandiflora*	Leaf	20 nm, spherical	Antibacterial and antifungal activities were ascertained using the disk diffusion technique	[82]
35	*Solanum nigrum* and *Clitoria ternatea*	–	23 nm, spherical	–	[83]
36	*Azadirachta Indica*	Leaf	34 nm, spherical	Effective against Gram-positive and Gram-negative bacteria	[84]
37	*Diospyros paniculata*	Root	14–28 nm, spherical	Antifungal activity against *Penicillium notatum*, *Aspergillus flavus*, *Aspergillus niger*, *Candida albicans*, *Saccharomyces cerevisiae*	[85]
38	*Caesalpinia pulcherrima*	Flower	12 nm, spherical	Antibacterial and antifungal activities against *Staphylococcus* aureus, *Bacillus cereus*, *Escherichia coli*, *Salmonella typhimurium*, *Cryptococcus neoformans*, *Bacillus subtilis*, *Corallium rubrum*, *Pseudomonas aeruginosa*, *Klebsiella pneumonia Candida glabrata*, and *C. albicans*	[86]
39	*Alcea rosea*	Flower	7.2 nm, spherical	Antibacterial activity against *Escherichia coli* and *Staphylococcus aureus*	[87]

Table 2 (continued)

Serial No	Biological source	Part used	Size (nm) and shape	Applications	Refs
40	*Diospyros sylvatica*	Root	8 nm, spherical	Antibacterial and antifungal activities against *Bacillus pumilis*, *Pseudomonas aeruginosa*, *Bacillus subtilis*, *Staphylococcus aureus*, *Klebsiella pneumoniae*, *Escherichia coli*, *Streptococcus pyogenes*, *Proteus vulgaris*, *Aspergillus niger*, *A. flavus*, *Penicillium notatum*, *Saccharomyces cerevisiae*, *Candida albicans*	[88]
41	*Annona muricata*	Root	15.08–33.11 nm, spherical	Antibacterial activity against *Klebsiella pneumonia* and *Staphylococcus aureus*	[89]
42	*Moringa oleifera*	Stem	3–70 nm, spherical	Antibacterial activity against *Escherichia coli* and *Staphylococcus epidermidis*	[90]
43	*Cornus officinalis*	Fruit	11.7 nm, quasi-spherical	Encouraging antitumor efficacy against liver and prostate cancer	[91]
44	*Waste grass*	Stem	4–34 nm, spherical oblate	Antibacterial activity against *Pseudomonas aeruginosa*, *Acinetobacter baumannii*, *Fusarium solani*, and *Rhizoctonia solani*	[92]
45	*Swertia paniculate*	Stem	31–44 nm, spherical	Antibacterial activity against *Pseudomonas aeruginosa*, *Klebsiella pneumoniae*, and *Staphylococcus aureus*	[93]
46	*Anacardium occidentale* L	Gum	51.9 nm, spherical	Antibacterial activity against *Staphylococcus aureus*, and *Escherichia coli*	[94]
47	*Araucaria heterophylla*	Gum	<50 nm, spherical	Antibacterial activity against *Escherichia coli* and *Streptococcus* spp.	[95]
48	*Cocos nucifera*	Mesocarp	24 nm, spherical	Larvicidal nature	[96]
49	*Carum copticum*		21.48 nm, spheroidal	Biofilm inhibition against Gram-negative bacteria	[97]
50	*Aesculus hippocastanum*	Leaf extract	50 nm, spherical	Antibacterial activity against *Staphylococcus aureus*, *S. epidermidis*, *Listeria monocytogenes*, *Corynebacterium renale*, *Micrococcus luteus*, *Bacillus subtilis*, *B. cereus*, *Enterococcus faecalis*, *Pseudomonas aeruginosa*, *P. fluorescens*, *Escherichia coli*, *Enterobacter aerogenes*, *Klebsiella pneumonia*, *Proteus mirabilis*, *Candida albicans*, *C. tropicalis*, and *C. krusei*	[98]
51	*Carya illinoinensis*	Leaf extract	12–30 nm, spherical	Antibacterial activity against *Escherichia coli*, *Pseudomonas aeruginosa*, *Staphylococcus aureus*, and *Listeria monocytogenes*	[99]
52	*Acacia cyanophylla*	Aqueous extract	88.1 nm	Robust antibacterial activity	[100]
53	*Olea europaea*	Leaf extract	8 nm	Applications for bacterial, antioxidant, cytotoxic, and biocompatibility	[101]

Table 2 (continued)

Serial No	Biological source	Part used	Size (nm) and shape	Applications	Refs
54	*Melaleuca alternifolia*	leaf extract	11.56 nm, spherical	Antibacterial activity against *Staphylococcus aureus*, methicillin-resistant *S.* aureus, *S. epidermidis*, *Streptococcus pyogenes*, *Klebsiella pneumoniae*, *Pseudomonas aeruginosa*, *Trichophyton mentagrophytes*, and *Candida albicans*	[102]
55	*Chloroxylon swietenia*	Leaf extract	6.9 nm, rod-shaped	Dye degrading and antibacterial agents against food dyes and pathogens	[103]
56	*Ginger*	Root extract	15 nm, spherical	Use as antibacterial agents with improved activity and sufficient potential	[104]
57	*Euphorbia wallichii*	Leaf	24 nm, crystalline	Antibacterial action against the causal agent of *Citrus Canker* and antioxidant potential	[105]
58	*Ribes rubrum* L		8–59 nm, roughly spherical	Inhibiting the growth of *Alternaria alternata*, *Colletotrichum musae*, and *Trichoderma harzianum*	[106]
59	*Pteris vittata*	Leaf extract	17 nm	Antivirulence and antibacterial efficacy against *Pseudomonas aeruginosa*	[107]
60	*Eugenia roxburghii* DC	Leaf	35 nm, crystalline	Prevention of the development of biofilms and the bacterial colonies that produce them	[108]
61	*Acer oblongifolium*	Leaf extract	5 nm, rod-shaped	AgNPs are used as antioxidant, antibacterial, and anticancer agents	[44]
62	*Cassia tora*	Seed extract	55–64 nm	Potent antibacterial properties	[45]
63	*Jasminum officinale* L	Leaf extract	9.2 nm, spherical	Strong cytotoxic effects against the MCF-7 and 5637 cell lines and can be an option as a novel cytotoxic drug	[109]
64	*Tridax procumbens*	Leaf extract	11.1–45.4 nm, spherical shape	Possible antibacterial efficacy against human lung cancer cells and MDR clinical isolates	[110]

study known as "phyconanotechnology" focuses on the manufacturing of nanoparticles using algae [166]. Numerous physical factors, including pH, temperature, precursor concentration, exposure, and reaction time, affect the nucleation, growth, and stability of nanoparticles. These factors decide the size and shape of the cell. Furthermore, cell aggregation can also be prevented by modulating these physical factors. Depending on the type of algal species, their extracts contain varying concentrations of different bioactive components such as antioxidants; pigments like chlorophylls, phycobilins, carotenoids, phycocyanin, and phycoerythrin in varying concentrations; carbohydrates; fats; nutrient oils; and vitamins [167]. Table 5 depicts the antimicrobial applications of AgNPs synthesized from different algae.

Characterization of Silver Nanoparticles

AgNPs possess unique properties that determine their potential applications. Researchers have used distinct characterizing techniques for a better understanding of their properties (Table 6). For example, AgNPs can be categorized based on their structural, optical, or electrical characteristics. Additionally, other techniques, such as thermal or magnetic properties, may be incorporated. By understanding the unique properties of AgNPs, researchers can better utilize their potential and application. Additional subdivisions of the structural characterization of silver nanoparticles include morphology, crystal structure, and composition [176]. Such characterization is crucial

Table 3 Synthesis of silver nanoparticles employing various fungi

Serial No	Biological source	Production site	Size (nm)	Application/activity	Refs
1	*Aspergillus clavatus*	Extracellular	550–650 nm	Activity against methicillin-resistant *Staphylococcus aureus* (MRSA) and methicillin-resistant *Staphylococcus epidermidis* (MRSE)	[118]
2	*A. niger*	Extracellular	20 nm	Activity against Gram-negative and Gram-positive bacteria	[119]
3	*A. niger*	Extracellular	3–30 nm	Antimicrobial action against *Staphylococcus* spp., *Bacillus* spp., *Escherichia coli*, and *Aspergillus niger*	[120]
4	*Fusarium semitectum*	Extracellular	10–60 nm	Potential biomedical applications	[121]
5	*Phoma glomerata*	Extracellular	70–80 nm	Bactericidal efficacy against a majority of Gram-negative bacteria	[122]
6	*Humicola* spp.	Extracellular	5–25 nm	Cytotoxicity of AgNPs on the MDA-MB-231 human breast cancer and NIH3T3 mouse embryonic fibroblast cell lines	[123]
7	*Schizophyllum commune*	Intracellular & Extracellular	51–93 nm	Antimicrobial activity against *Pseudomonas fluorescens*, *Escherichia coli*, *Bacillus subtilis*, and *Klebsiella pneumoniae*	[124]
8	*Fusarium acuminatum*	Extracellular	13 nm	Bactericidal action against extremely pathogenic and multidrug-resistant *Salmonella typhi, Staphylococcus epidermidis*, *Staphylococcus aureus*, and *Escherichia coli*	[125]
9	*Alternaria alternata*	Extracellular	32.5 nm	Fluconazole and AgNPs together demonstrated the greatest suppression of *Candida albicans*	[126]
10	*Trichoderma viride*	Extracellular	5–40 nm	Ampicillin, kanamycin, erythromycin, and chloramphenicol showed enhanced antibacterial activity in the presence of AgNPs	[127]
11	*Macrophomina phaseolina*	Cell-free filtrate	5–40 nm	Antimicrobial action against the human-infective bacterium *Escherichia coli* and the microorganisms that cause plant diseases *Agrobacterium tumefaciens*	[128]
12	*Pleurotus ostreatus*		< 40 nm	*Bacillus subtilis*, *B. cereus*, *Staphylococcus aureus*, *Escherichia coli* and *Pseudomonas aeruginosa* were inhibited	[129]
13	*Aspergillus Terrerus*		2 nm	Better inhibition of Gram-positive bacteria than Gram-negative bacteria	[130]
14	*Arthroderma Fulvum*		15.5 nm	Displayed good antifungal properties	[131]
15	*Penicillium oxalicum*		10–40 nm, spherical	Antibacterial action against common foodborne infections such as *Salmonella typhimurium*, *Escherichia coli*, and *Staphylococcus aureus*	[132]
16	*Aspergillus terreus*	Extracellular	60–100 nm, spherical	*Escherichia coli*, *Staphylococcus epidermidis*, *Enterococcus faecalis*, *Proteus mirabilis*, *Bacillus subtilis*, *Klebsiella pneumoniae*, *Staphylococcus aureus, Salmonella typhi*, and *Pseudomonas aeruginosa*	[133]
17	*Penicillium chrysogenum*	Extracellular	18–60 nm, spherical	*Candida albicans*, *C. krusei*, *C. tropicalis*, *C. parapsilosis*, and *C. glabrata*	[134]
18	*Penicillium oxalicum*	Extracellular	60–80 nm, spherical	*Staphylococcus aureus*, *Shigellae dysenteriae*, and *Salmonella typhi*	[135]

Table 3 (continued)

Serial No	Biological source	Production site	Size (nm)	Application/activity	Refs
19	*Sporotrichum thermophile*	Extracellular	40–70 nm	*Escherichia coli*, *Bacillus subtilis*, and *Micrococcus luteus*	[136]

for assessing the functional characteristics of the nanoparticles produced. Therefore, numerous analytical techniques are employed to characterize nanoparticles, including UV–Vis spectroscopy, DLS, TEM, SEM, FTIR, and atomic force microscopy (AFM) [177].

Multifaceted Applications of Silver Nanoparticles

AgNPs have numerous unique properties that make them useful in biology and material science. Dimensionally, AgNPs are typically < 100 nm in diameter and contain 20–15,000 silver atoms [217]. Magnetic, optical, and electrical characteristics affect the size and formation of AgNPs; they also can be incorporated into biosensors, antimicrobial activity, cosmetic products, cryogenic superconducting materials, electric components, and composite fibers [218]. Additionally, they have a wide range of therapeutic applications, including dentistry, catheters, orthopedic implants, nano-biosensing, and tumor hyperthermia [11] (Fig. 3). A detailed description of the number of applications is provided.

Biomedical Applications

Antimicrobial Activity of Silver Nanoparticles

On average, using 5 nm AgNPs was more effective than vancomycin or ampicillin against certain bacteria, suggesting their effectiveness in treating infectious diseases [219]. AgNPs demonstrated robust antibacterial activity against *E. coli* O157: H7, which causes severe food poisoning, and also against *Salmonella enterica, Streptococcus pyogenes*, *Staphylococcus aureus*, and *Enterococcus faecalis*. Although AgNPs have strong microbicidal effects against prokaryotes, particularly Gram-negative bacteria, they are weakly effective against Gram-positive bacteria [220–222].

Food, agriculture, and human health face massive problems due to the infectious diseases caused by clinical pathogens including multidrug-resistant organisms, several strains of whom have become resistant to many antibiotics [36]. The sudden outbreak of such strains demands the introduction of a global-scale alternative to antibiotics. Due to the toxicity of antiviral compounds and the development of resistance, managing viral infections is even more problematic. Among various nanoparticles, silver nanoparticles can be produced in less time and also exhibit wide-ranging antimicrobial activity due to their toxic nature. AgNPs have long been used to prevent and cure a variety of illnesses due to their highly powerful biocidal effects on bacteria [48], though their characterization and quantification have started only recently [223]. Studies have proved that AgNPs show broad-spectrum antimicrobial effects against various pathogens like bacteria, fungi, and viruses. The antibacterial properties of AgNPs are affected by a variety of key factors, including shape and size, stabilizer, and dose [224]. AgNPs have been developed as antibacterial agents against MDR bacteria because of their unique physicochemical characteristics and high surface area-to-volume ratio, which is inversely proportional to the particle size. Smaller AgNPs have a better binding surface and stronger bactericidal effect when compared to larger AgNPs [48]. Silver nanoparticles are more effective against Gram-negative bacteria as compared to Gram-positive bacteria due to the thick layer of peptidoglycan present in the latter, making it more challenging for the silver nanoparticles to weaken and kill them [23]. The exact mechanism behind the antimicrobial capabilities of silver nanoparticles is yet unknown. The constant discharge of silver ions from nanoparticles, which may be the medium for killing microorganisms, has long been known to researchers. They also can destroy germs directly [217]. AgNPs can exhibit antibacterial activity through three possible mechanisms, which can occur together or separately. AgNPs can cross the bacterial membrane, by binding to and subsequently rupturing it, thereby releasing their contents (Fig. 4). AgNPs can also stop cell division, interfere with DNA replication, and target the respiratory chain, all of which impact the intracellular activities. AgNPs also show a strong microbicidal effect on drug-resistant fungi by influencing the cellular targets implicated in drug resistance and pathogenicity. In addition, it induces cell toxicity by generating reactive oxygen species [224]. Recently, extreme fungal infections have contributed significantly to both the increased occurrence of certain illnesses and the death of people with weaker immune systems [225].

Nanoparticles synthesized from *Viridibacillus* spp. with an average size of 5–30 nm and spherical shape showed antimicrobial activity against *Escherichia coli* and *Pseudomonas aeruginosa* [226]. AgNPs synthesized from *Aloe vera* possess antimicrobial activity against *Pseudomonas aeruginosa* and *Staphylococcus aureus* [227]. AgNPs fabricated employing *Paenibacillus polymyxa* showed antibacterial activity against *Pseudomonas aeruginosa*,

Table 4 Green synthesis of silver nanoparticles using different bacteria

Serial No	Biological source	Production site	Size and shape	Application	Refs
1	*Aeromonas* sp. THG-FG1.2	Extracellular	8–16 nm	Antibacterial activity was the highest against *Candida albicans*, followed by *Pseudomonas aeruginosa*, *Vibrio parahaemolyticus*, *Staphylococcus aureus*, *Candida tropicalis*, *Bacillus cereus*, *B. subtulis*, *Escherichia coli*, and *Salmonella enterica*	[139]
2	*Nocardiopsis sp*. MBRC-1		45 nm	Significant activity against fungi and bacteria. In the human cervical cancer cell line (HeLa), the in vitro cytotoxicity of the. biosynthesized AgNPs showed a dose-dependent response	[142]
3	*Lactobacillus bulgaricus*		30.65–100 nm	*Lactobacillus bulgaricus* had excellent potential for producing AgNPs with more antibacterial activity in comparison to the antibiotics studied	[140]
4	*Bacillus licheniformis* (MN900686)	Extracellular	38 nm	Antibacterial activity against the human pathogens *Bacillus subtilis* and *Pseudomonas aeruginosa*	[143]
5	*Pseudomonas fluorescens* CA 417		5–50 nm, polydispersed	Kanamycin and AgNPs had a synergistic activity against *Klebsiella pneumoniae*, which was boosted by ≤ 58.3%	[123]
6	*Bacillus brevis* (NCIM 2533)		41–68 nm, spherical	Bactericidal ability against multidrug-resistant pathogens, such as *Salmonella typhi* and *Staphylococcus aureus*	[144]
7	*Pseudomonas aeruginosa*		27.5 nm, polydispersed and elongated	Antibacterial activity against gram-positive and gram-negative bacteria, more effectively against the latter	[145]
8	*Pseudomonas veronii* AS41G	Extracellular	5–50nm	Antimicrobial activity against environmental contaminants and human pathogens, such as MRSA	[146]
9	*Ochrobactrum anhtropi*		38–85 nm, spherical	Bactericidal potential against pathogens such as *Staphylococcus aureus*, *Vibrio cholerae*, *Salmonella typhi*, and *Salmonella paratyphi*	[147]
10	*Paenibacillus polymyxa*		2–40 nm, oval, spherical, or triangular	*Escherichia coli* K-12, *Pseudomonas aeruginosa* 50.3, *Bacillus subtilis* 26-D, and *Fusarium oxysporum* were affected by the antibacterial and antifungal activities. Nanoparticles were effective at killing human melanoma cells SK-MEL-2	[148]
11	*Raoultella planticola* and *Pantoea agglomerans*		10–50 nm, centered cubic crystals	Significant antibacterial activity against *Staphylococcus aureus*, *Streptococcus pyogenes*, *Salmonella*, and *Bacillus amyloliquefaciens*	[149]
12	*Massilia* sp. MAHUQ-52	Extracellular	15–5 nm, spherical	Antibacterial activity against *Klebsiella pneumoniae* and *Salmonella enteritidis*	[150]

Table 4 (continued)

Serial No	Biological source	Production site	Size and shape	Application	Refs
13	*Streptomyces* strains	Intracellular	1.17–13.3 nm, spherical	Activity against *Pseudomonas aeruginosa*, *Klebsiella pneumoniae*, *Salmonella typhi*, *Bacillus cereus*, *Enterococcus faecalis*, *Staphylococcus aureus*, *Escherichia coli*, and *Enterococcus faecalis*	[151]
14	*Cedecea* spp.	Extracellular	10–40 nm, spherical	Bactericidal effects against *Escherichia coli*, *Pseudomonas aeruginosa*, *Staphylococcus aureus*, and *S. epidermis*	[152]
15	*Arthrobacter bangladeshi*	Extracellular	12–50 nm, spherical	Activity against *Salmonella typhimurium* and *Yersinia enterocolitica*	[137]
16	*Paenibacillus* spp.	Extracellular	17.4–52.8 nm, spherical	Antibacterial activity against *Escherichia coli*, *Streptococcus pneumoniae*, *Staphylococcus aureus*, and *Enterococcus faecalis*	[153]
17	*Lysinibacillus xylanilyticus*	Extracellular	8–30 nm, spherical	Growth inhibition of *Vibrio parahaemolyticus* and *Salmonella typhimurium*	[154]
18	*Cyanobacteria desertifilum*	Intracellular	4.5–26 nm, spherical	Antibacterial activity against *Pseudomonas aeruginosa*, *Bacillus subtilis, Bacillus cercus*, *Shigella flexneri*, and *Salmonella enterica*	[155]
19	*Citrobacter* spp. MS5	Extracellular	5–15 nm, spherical	Growth inhibition of *Enterobacter hormaechei* and *Klebsiella pneumoniae*	[156]
20	*Sphingobium* sp.	Extracellular	7–22 nm, spherical	Effective against *Escherichia coli* and *Staphylococcus aureus*	[157]
21	*Lactobacillus plantarum*	Intracellular	14 nm, spherical	Antimicrobial activity against *Salmonella* spp., *Escherichia coli*, *Staphylococcus epidermidis*, *Staphylococcus aureus*, etc	[158]
22	*Escherichia coli*	Extracellular	5–50 nm, spherical	Growth inhibition of *S. typhi*, *E. vermicularis*, *Pseudomonas aeruginosa*, *Klebsiella pneumoniae*, *Bacillus subtilis*, *Staphylococcus aureus*, and *Bacillus cereus*	[159]
23	*Pseudoduganella eburnea* MAHUQ-39	Extracellular	8–24 nm, spherical	Inhibit *Staphylococcus aureus* and *Pseudomonas aeruginosa*	[160]
24	*Acinetobacter baumannii*	Extracellular	37–168 nm, spherical	Effective against *Escherichia coli*, *Pseudomonas aeruginosa*, and *Klebsiella pneumoniae*	[161]
25	*Pseudomonas* spp. THG-LS1.4	Extracellular	10–40 nm, irregular	Inhibit *Escherichia coli*, *Pseudomonas aeruginosa*, *Vibrio parahaemolyticus*, *Bacillus cereus*, *Staphylococcus aureus*, and *Candida tropicalis*	[162]
26	*Novosphingobium* spp. THG-C3	Extracellular	8–25 nm, spherical	Antimicrobial potency against *Staphylococcus aureus*, *Candida tropicalis*, *Pseudomonas aeruginosa*, *Escherichia coli*, *Vibrio parahaemolyticus*, *Candida albicans*, *Salmonella enterica*, *Bacillus subtilis*, and *Bacillus cereus*	[163]

Table 4 (continued)

Serial No	Biological source	Production site	Size and shape	Application	Refs
27	*Sporosarcina koreensis* DC4	Extracellular	30–50 nm, spherical	Bactericidal activity against *Vibrio parahaemolyticus*, *Escherichia coli*, *Salmonella enterica*, *Bacillus anthracis*, *Bacillus cereus*, and *Staphylococcus aureus*	[164]
28	*Kinneretia* THG-SQI4	Extracellular	15–20 nm, spherical	Inhibit *S. aureus*, *Salmonella enterica*, *Pseudomonas aeruginosa*, *Vibrio parahaemolyticus*, *Escherichia coli*, *Candida albicans*, *C. tropicalis*, *Bacillus cereus*, and *B. subtilis*	[139]
29	*Bacillus safensis*	Extracellular	5–30 nm, spherical	Growth inhibition in *Escherichia coli*	[74]
30	*Weissella oryzae*	Extracellular	10–30 nm, spherical	Inhibit *Candida albicans*, *Staphylococcus aureus*, *Escherichia coli*, *Bacillus cereus*, *B. anthracis*, and *Vibrio parahaemolyticus*	[165]

Table 5 Synthesis of silver nanoparticles using different algae

No	Biological source	Size and shape	Biological activity	Ref
1	*Sargassum longifolium*	Spherical	Antifungal defenses against harmful fungus *Fusarium* sp., *Candida albicans*, and *Aspergillus fumigatus*	[168]
2	*Portieria hornemannii*	70–75 nm, spherical	Active against *Vibrio harveyii, Vibrio parahaemolyticus, Vibrio alginolyticus,* and *Vibrio anguillarum* fish pathogens	[169]
3	*Caulerpa racemose*	5–25 nm, spherical and triangle	AgNPs showed antibacterial action against *Salmonella typhi, Escherichia coli, Shigella sp., Pseudomonas aeruginosa* and *Staphylococcus aureus*	[170]
4	*Cyanobacterium Oscillatoria limnetica*	3.30–17.97 nm, quasi-spherical	AgNPs demonstrated potent antibacterial action against *Escherichia coli* and *Bacillus cereus*, which are resistant to many antibiotics, as well as cytotoxic effects on human breast (MCF-7) and colon cancer (HCT-116) cell lines	[171]
5	*Caulerpa racemosa*	5-–25 nm, face-centered cubic	Antimicrobial action against human infections including *Proteus mirabilis* and *Staphylococcus aureus*	[172]
6	*Sargassum coreanum*	19 nm, distorted spherical shape	Outstanding catalytic activity	[173]
7	*Ulva rigida*	12 nm, spherical	Effective substitute anti-dermatophytes for skin infections and cancer-fighting MCF-7 cell line agents	[174]
8	Chlorella ellipsoidea	220 nm, spherical, cubic, rod, triangular	Antimicrobial activity against *Escherichia coli, Klebsiellapneumoniae, Staphylococcus aureus* and *Pseudomonas aeruginosa*	[175]

Escherichia coli, *Bacillus subtilis*, and *Fusarium oxysporum* [148]. Other findings demonstrated the antibiofilm action of AgNPs at sub-MIC levels (1/2, 1/4, and 1/8), which was concentration dependent [228]. AgNPs produced from the aerial parts of *Anthemis pseudocotula* showed antibacterial activity against *Staphylococcus aureus*, MRSA, and *Candida albicans* [229]. The antifungal activity of green synthesized silver nanoparticles from *Bacillus thuringiensis* was identified against *Aspergillus terrus*, *A. niger*, *A. fumigatus*, and *A. flavus* [230]. Silver nanoparticles synthesized from *Nigrospore oryzae* were investigated for antifungal activity against eight *Fusaria* spp., and fungal growth was inhibited by different concentrations of AgNPs [231]. The silver nanoparticles biosynthesized from *Aloe vera* effectively inhibited the growth of *Candida albicans*, thus acting as a potent antifungal agent [232]. The green AgNPs synthesized from Pomegranates had an average size of 33 nm and inhibited the Tobacco Mosaic Virus, which infects tomato plants [233]. Another study on the synthesis of green AgNPs using medicinal plants such as *Andrographis paniculate*, *Tinospora cordifolia*, and *Phyllanthus niruri* demonstrated them to be a potential therapeutic alternative against the chikungunya virus [234]. Several other examples of the antimicrobial activities of AgNPs synthesized using different biological sources are listed in Table 7.

Table 6 Different techniques used to characterize silver nanoparticles

Technique of characterization	Property measured	Findings	Refs
UV–visible spectroscopy	Absorbance of the particle in the visible region	Characterize the particle size, shape and other physical properties	[178–182]
Fourier transform infrared spectroscopy (FTIR)	Vibrational stretch frequency	measure the chemical composition or functional groups of nanoparticles	[183–188]
Scanning electron microscopy (SEM)	It helps in measuring the repulsion and attraction of electrons between beams that are driven through a sample and atoms at different depths	This technique helps to create the image and analyze the surface morphology of the NPs as well as their interactions with other systems	[171, 189–193]
Dynamic light scattering (DLS)	This technique quantify the Brownian motion of NPs	Particle size and size distributions can be evaluated by this technique	[103, 194–196]
Transmission electron microscopy (TEM)	Scattering of electrons	It creates data about molecule size and shape	[197–201]
X-ray diffraction	Constructive interference of X-rays	This technique helps in determination of crystallographic structure of a material	[186, 202–205]
Atomic force microscopy	Atomic forces exerted by the samples	Nanostructure study of NPs surface	[206–210]
Energy dispersive X-ray (EDX)	Electromagnetic radiation and matter interactions	Characterizing a sample chemically or by elemental analysis	[211–216]

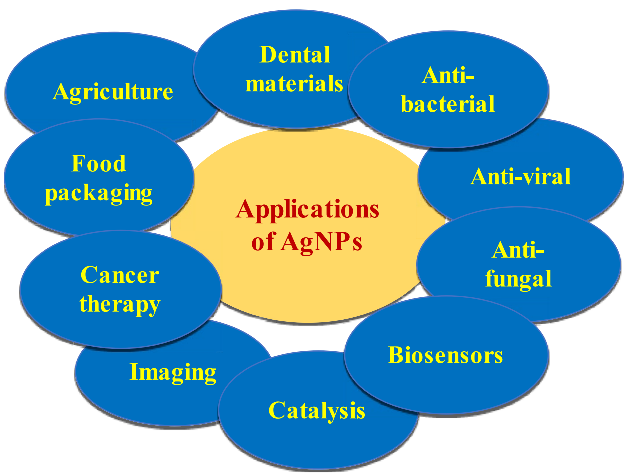


Fig. 3 Multifarious potential applications of silver nanoparticles

Antimalarial Activity

Malaria, which is one of the most prevalent infectious illnesses, is quickly becoming a global public health issue. Traditional antimalarial medicines include quinine-based compounds, such as artesunate and chloroquinine. Such treatments are highly effective but have severe adverse effects, such as medication resistance [271]. The wide-ranging uses of nanoparticles, particularly in medicine, have led to advancements in the formation of nanomaterials for enhancing therapeutic efficacy and delivery, the sustained release of nanomaterials, and lowering chemical toxicity [272]. The antimalarial efficacy of AgNPs against *Plasmodium falciparum* synthesized using *Aloe arborescens* was greater than those using *Artemisia arbrotanum*, as the growth of the parasite was blocked and the maturation cycle was hindered [271]. AgNPs in the diameter range of 31–43 nm, biosynthesized using *Azadirachta indica* extract, are effective against two strains of *P. falciparum*, W2 (chloroquine resistant) and 3D7 (chloroquine sensitive), showing great potential for malaria therapy [273]. A green method for the biosynthesis of AgNPs using either α-amylase or leaf extracts of *A. indica* (Neem) and *Saraca asoca* (Ashoka) was developed; the IC_{50} of amylase (3.75 µg/mL), neem (30 µg/mL), Ashoka (8 µg/mL) obtained in the antiplasmodial assays revealed that the extracts or enzymes alone did not show antimalarial activity [274]. In another study, the antimalarial activity of green synthesized AgNPs using the marine seaweed *Sargassum tenerrimum* was reported against *P. berghei* and *P. falciparum*, with respective IC_{50} values of 23 and 7.71 µg/mL, confirmed the excellent antimalarial efficacy [275]. A novel method for the biosynthesis of silver nanoparticles using *Anisomeles indica* and effective against the malarial vector was proposed; an LC50 value of 31.65 µg/mL *Anopheles subpictus* confirmed their significant insecticidal activity [276]. The potential larvicidal activity against *A. stephensi* by the AgNPs fabricated using *Aristolochia indica* leaf extracts was ascertained [277].

Drug Delivery

In medicine, the inherent therapeutic impact of a drug is not as significant as its pharmacokinetics and pharmacodynamics. Nanoparticles have garnered a great deal of attention in the design and development of new and better drug delivery systems because precise and selective administration and activity of therapeutic agents to improve health care have become one of the most explored areas [278]. AgNP-based

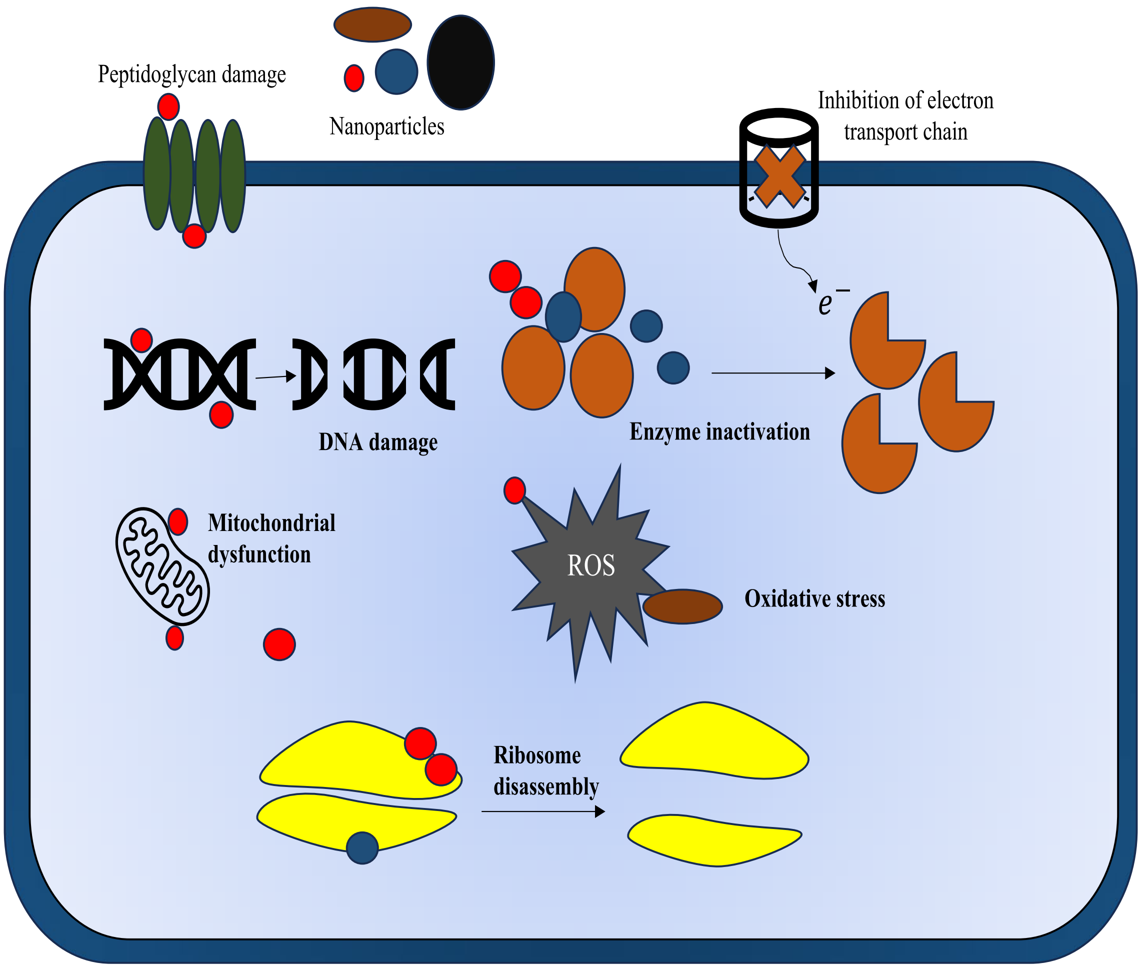


Fig. 4 Various mechanisms of the antimicrobial activity of silver nanoparticles

nanosystems have been investigated as potential molecular therapeutic carriers for anti-inflammatory, antioxidant, antibacterial, and anticancer effects. Additionally, such a specialized drug delivery platform should permit the maximum therapeutic effectiveness at concentrations lower than that of the single bioactive agent with the fewest adverse effects, as well as provide adequate and adaptable drug loading and releasing profiles [279]. AgNPs have proved to be extremely successful at delivering anticancer medication to tumor tissues. They are small enough to easily permeate tissues, ensuring effective medication delivery. Scientists are highly interested in the use of AgNPs for the delivery of anticancer medications since traditional techniques have harmful consequences for both malignant and healthy/normal cells [166]. The growth of *Candida albicans*, *Aspergillus niger*, and Gram-negative bacteria was inhibited by the silver nanoparticles made from 10 mmol/L $AgNO_3$ solution. In an *in vitro* antibacterial experiment, drug-loaded silver nanoparticles (Ciprofloxacin + 10 mmol/L AgNPs) had a greater ability to inhibit the growth of *Escherichia coli* and *Enterobacter aerogenes* than either synthetic silver nanoparticles or ciprofloxacin alone [280]. The size of NPs affects the efficiency of the endocytosis of drugs. Spherical AgNPs were obtained from the *Aerva javanica* plant and loaded with the anticancer medication gefitinib; gefitinib-AgNPs or gefitinib alone was tested for apoptotic potential; remarkably lesser breast cancer cell viability was observed after treatment with conjugated gefitinib-AgNPs; gefitinib delivered using AgNPs maximized its efficacy and minimized the negative effects [281]. Doxorubicin (DOX) and daunorubicin (DNR), two hydrophilic anticancer medications, were loaded onto the AgNPs produced by employing different amounts of *Setaria verticillata* seed extract; the DOX- and DNR-AgNPs were found to possess enhanced efficiency potential due to their high loading capacities of 80.50% and 40.25%, respectively [282]. Haq et al. [283] reported that green synthesized silver nanoparticles fabricated using *Taverniera couneifolia* considerably improved drug delivery; diabetic rats, when treated with these AgNPs, showed an improvement in the dyslipidemia status indicated by an enhancement in body weight

Table 7 Synthesis of AgNPs from different biological sources and their antimicrobial activity

Biological source	Target pathogens	Refs
Debregeasia salicifolia	*Escherichia coli* and *Staphylococcus aureus*	[186]
Moringa oleifera	*Staphylococcus aureus*	[235]
Conocarpus Lancifolius	*Streptococcus pneumonia* and *Staphylococcus aureus*	[46]
Pteris vittata	*Pseudomonas aeruginosa*	[107]
Cullen tomentosum	*Staphylococcus aureus* and Bacillus *cereus*	[236]
Coleus forskohlii	*Staphylococcus aureus*	[237]
Penicillum verrucosum	*Aspergillus flavus* and *Fusarium chlamydomonas*	[115]
Bauhinia tomentosa	*Aspergillus flavus and Candida albicans*	[238]
Portulaca oleracea	*Curvularia spicifera, Bipolaris* sp. and *Macrophomina phaseolina*	[239]
Lampranthus coccineus and *Malephora lutea*	HAV-10, HSV-1 and CoxB4	[240]
Cinnamomum cassia	H7N3 influenza A virus	[241]
Cyperus rotundus	Effective against infectious bronchitis virus and laryngotracheitis virus	[242]
Skimmia laureola	*Escherichia coli, Klebsiella pneumoniae, Pseudomonas aeruginosa, Proteus vulgaris, Staphylococcus aureus*	[243]
Prosopis farcta	*Staphylococcus aureus, Bacillus subtilis, Escherichia coli, Pseudomonas aeruginosa*	[244]
Aloe vera	*Aspergillus* sp., *Rhizopus* sp.	[245]
Eclipta alba	*Escherichia coli, Staphylococcus aureus, Pseudomonas aeruginosa*	[246]
Momordica charantia	*Bacillus* spp., *Staphylococcus* spp., *Pseudomonas* spp., *Escherichia coli, Aspergillus niger, Aspergillus flavus*	[247]
Leptadenia reticulate	*Streptococcus pneumonia, Klebsiella pneumonia*	[248]
Tea leaf	*Staphylococcus aureus, Escherichia coli*	[249]
Raphanus sativus	*Aspergillus fumigatus, Fusarium Solani*	[65]
Mukia maderaspatana	*Bacillus subtilis, Klebsiella pneumonia, Salmonella typhi, Staphylococcus aureus*	[250]
Clitoria ternatea	*Bacillus subtilis, Staphylococcus aureus, Streptococcus pyogenes, Escherichia coli, Pseudomonas aeruginosa, Klebsiella aerogenes*	[251]
Croton sparsiflorus morong	*Staphylococcus aureus, Escherichia coli, Bacillus subtilis*	[172]
Grewia flaviscences	*Bacillus, Pseudomonas aeruginosa*	[252]
Terminalia arjuna	*Staphylococcus aureus, Escherichia coli*	[253]
Prunus yedoensis	*Propionibacterium acnes, Staphylococcus epidermidis* (skin bacteria)	[40]
Justicia adhatoda L	*Pseudomonas aeruginosa*	[254]
Withania somnifera	*Staphylococcus aureus, Pseudomonas aeruginosa, Candida albicans, Proteus vulgaris, Escherichia coli, Agrobacterium tumefaciens*	[63]
Thymbra spicata	*Bacillus cereus, Staphylococcus aureus, Escherichia coli, Salmonella typhimurium*	[255]
Indigofera tinctoria	*Bacillus pumilis, Staphylococcus aureus, Pseudomonas* sp., *Escherichia coli, Aspergillus fumigatus, Aspergillus niger*	[256]
Tecoma stans	*Bacillus subtilis, Staphylococcus aureus, Klebsiella pneumonia*	[257]
Salvia leriifolia	*Pseudomonas aeruginosa, Escherichia coli, Staphylococcus coagulase, Citrobacter freundii, Enterobacter aerogenes, Acinetobacter baumannii, Serratia marcescens, Klebsiella pneumonia, Streptococcus pneumonia*	[258]
Leucaena leucocephala L	*Pseudomonas aeruginosa, Streptococcus pyogenes, Staphylococcus aureus, Escherichia coli, Salmonella typhi, Bacillus subtilis*	[259]
Selaginella bryopteris	*Staphylococcus aureus, Escherichia coli, Aspergillus niger*	[257]
Galega officinalis	*Escherichia coli, Pseudomonas syringae, Staphylococcus aureus*	[260]
Camellia sinensis	*Staphylococcus aureus, Klebsiella pneumonia*	[261]
Justicia spicigera	*Bacillus cereus, Klebsiella pneumoniae, and Enterobacter aerogenes, Macrophomina phaseolina, Alternaria alternata, Colletotrichum* sp., *Fusarium solani*	[262]
Kleinia grandiflora	*Pseudomonas aeruginosa, Candida albicans*	[263]
Eucalyptus citriodora	*Candida albicans, Acinetobacter baumannii, Escherichia coli, Klebsiella pneumoniae, Pseudomonas aeruginosa*	[264]
Juniperus procera	*Micrococcus luteus, Bacillus subtilis, Proteus mirabilis, Klebsiella pneumoniae, Candida albicans*	[265]

Table 7 (continued)

Biological source	Target pathogens	Refs
Capparis zeylanica	*Staphylococcus epidermis, Enterococcus faecalis, Salmonella paratyphi, Shigella dysenteriae, Candida albicans, Aspergillus niger*	[266]
Phyllanthus amarus	*Escherichia coli, Pseudomonas* spp., *Bacillus* spp., *Staphylococcus* spp., *Aspergillus niger, Aspergillus flavus, Penicillium* spp.	[267]
Rice	*Rhizoctonia solani*	[268]
Cestrum nocturnum	*Citrobacter*, *Enterococcus faecalis, Salmonella typhi, Escherichia coli, Proteus vulgaris* and *Vibrio cholera*	[269]
Ziziphus jujuba	*Escherichia coli*	[270]

as well as liver, lipid, and renal profiles [283]. Rauf et al. [284] analyzed the inhibitory and amyloidogenic effects of green synthesized AgNPs on the aggregation of human serum albumin and concluded that protein aggregation was inhibited; biologically synthesized AgNPs could be applied to develop more effective drugs against aggregation-related disorders [284]. In another study, *Padina tetrastromatica* was employed to develop AgNPs, which were used as drug delivery agents [285].

Imaging

Over the past 20 years, AgNP uses have advanced steadily. Nanoparticles have been extensively employed in the imaging of DNA, proteins, cells, tissues, and *in vivo* tumors, using a contrast agent due to their sharper and robust surface plasmon resonance and various other crucial optical features. Several detection methods, such as calorimetry, scattering, surface-enhanced Raman spectroscopy (SERS), and metal-enhanced fluorescence, are available. They are based on the phenomenon of light scattering by metallic nanoparticles; their extinction spectrum integrates both scattering and absorption. In limited surface plasmon resonance, metal conduction electrons oscillate coherently with the positive lattice of these metal nanoparticles at a specific frequency due to their interaction with the light oscillating electromagnetic field [286]. For example, NIR-sensitive SERS nanoprobes employed for *in vivo* aromatic chemical identification using multiplex molecular imaging were identified. The plasmonic extinction band in the 700–900 nm NIR optical window red-shifted because of the placement of plasmonic Au/Ag hollow-shelled NIR-SERS probes on silica nanospheres. The signals of the NIR-SERS nanoprobe could be applied for single particle detection in 8-mm-deep animal tissues. M-SERS dot, an Ag-embedded SERS nanoprobe with powerful magnetic capabilities for identifying the desired cells and a Raman signature for imaging target cancer cells, was fabricated by Jun et al. [287]. The synthesized AgNPs demonstrated an enhanced green fluorescence signal used in the imaging of human lung fibroblasts when compared to fluorescein [288].

Catheters

Catheters are easily infected by pathogenic microorganisms, leading to severe nosocomial complications. Catheters coated with AgNPs dramatically suppressed the colonization of antibiotic-resistant clinical Gram-positive (*Staphylococcus epidermidis* and *Staphylococcus aureus*) and Gram-negative (*Escherichia coli*, *Proteus mirabilis*, and *Pseudomonas aeruginosa*) bacteria. AgNPs were more effective against Gram-negative than Gram-positive bacteria. Coated catheters had a considerable inhibitory effect on both types that persisted for 72 h. Catheters coated with AgNPs inhibited bacterial colonization and subsequent infections [289]. Moreover, AgNP-coated catheters demonstrated potential antibacterial and antibiofilm activity. The synergistic impact of AgNPs and antibiotics indicates that they can boost the activity of antibiotics [48]. Sengodan et al. [290] reported that intravascular catheters coated with AgNPs synthesized using plant extracts demonstrated antibacterial effects against *Staphylococcus aureus*, *Klebsiella pneumoniae*, *Pseudomonas aeruginosa*, *Staphylococcus epidermidis*, and *Escherichia coli*. Urinary catheters coated with AgNPs were applied to prevent bacterial colonization; they effectively inhibited the growth of *Proteus mirabilis* and *Escherichia coli*, proving that AgNPs may help prevent bacterial colonization [291].

Bone Cement

Bone cement is a biomaterial frequently utilized during orthopedic procedures to anchor the bone to an orthopedic device. Any surgery has a significant risk of microbial infection. This predicament is further worsened due to these antibiotics becoming less effective as a result of the increasing resistance of germs to them. In an investigation, bone cement samples made up of poly(methyl methacrylate) were mixed in varying ratios with oleic acid-capped AgNPs. AgNPs at 0.05% demonstrated antimicrobial activity against *Staphylococcus aureus*, *Staphylococcus epidermidis*, and *Acinetobacter baumannii*. To ensure that the bone cement containing these NPs is safe to use in orthopedic surgical procedures, its mechanical characteristics and cytotoxicity were also evaluated [292].

Dental Materials

Since some researchers have embraced the method of including antimicrobials in dental biomaterials, AgNPs have emerged as a viable ingredient in dentistry. Several MDR bacteria have shown susceptibility to AgNPs. Therefore, their direct application in dentistry would clean the oral cavity and guard it against harmful bacteria [293]. Depending on the kind of dental material used, several methods are utilized to introduce AgNPs. The most typical method for composite resin and adhesive systems involves adding a monomer, often 2-(tert-butylamino) ethyl methacrylate, to enhance the solubility of Ag salt. A completely different procedure is followed for dental implants; titanium samples are exposed to UV light emitted by a high-pressure Hg lamp after being dried and submerged in $AgNO_3$ solution, depending on the concentration of which samples with varying Ag contents can be produced [294]. An evaluation revealed that metal ion incorporated RelyX luting cement had an effective antibacterial activity, as evidenced by inhibition zones that were bigger than those created by traditional antibiotics and a sevenfold decrease in bacterial counts following a 24-h incubation [295].

Cancer Therapy

The ability of AgNPs to disrupt the mitochondrial respiratory chain, leading to ROS production, ATP generation, and ultimately DNA damage, makes them useful in cancer treatment. The MCF-7 cancer cells were susceptible to AgNPs fabricated employing *Sesbania grandiflora*, which enhanced the generation of ROS, causing oxidative stress and caspase-mediated apoptosis. This effect led to morphological alterations such as cytoplasmic condensation, loss in cell development, disturbance of cell membrane integrity, and more. These findings indicate that mitochondria play a crucial role in the mechanism of cell death. Thus, these AgNPs may represent a promising therapeutic approach for the management of cancer cells. AgNPs synthesized using the alcohol extracts of *Nyctanthes arbor-tristis* flowers are efficient for molecular imaging and medication administration. Even at a maximum dose of 250 mg/mL, these AgNPs demonstrated modest in vitro toxicity in L929 cells. Furthermore, Bcl-2 expression declined, and Bax expression was elevated in MCF-7 cells after treatment with either these AgNPs or cisplatin [296]. Another study revealed that treatment with a combination of gemcitabine and AgNPs had a considerably stronger cytotoxic impact in ovarian cancer cells compared to that caused by either of these agents alone. Increased ROS production and antioxidant depletion appear to be related to this synergistic cytotoxicity and apoptotic effect. Undoubtedly, a combination of camptothecin and AgNPs might be more effective than monotherapy in treating cervical cancer [297]. The death of HeLA cells caused by AgNPs biosynthesized using *Nepeta deflersiana* may indicate anticancer properties [298]. AgNPs synthesized employing *Padina tetrastromatica* served as anticancer agents against melanoma tumor growth [285]. *Gracilaria edulis*, a marine seaweed, was employed to fabricate AgNPs, the anticancerous effects of which were studied in MDA-MB-231 breast carcinoma cells; they inhibited the growth of various pathogenic bacterial strains [299].

Biotechnological Applications

Catalysis

The release of harmful organic dye pollutants, which are widely employed in a variety of industries, including textiles, plastics, cosmetic leather, paper, medicines, food, and clothing, is disastrous for the environment. They critically endanger both biotic and abiotic systems when released into open sewage systems at an estimated range of 5%–15%. Moreover, these dyes are usually resistant to destruction or cleanup by conventional means and are occasionally highly hazardous, carcinogenic, teratogenic, and genotoxic. Additionally, it is difficult to remove such dyes from the environment by conventional treatment methods. Currently, a variety of approaches are used for this, including precipitation, biodegradation, photo-degradation, filtering, adsorption, and ion exchange. However, these techniques are considered laborious, time-consuming, hard to apply, and require expensive equipment. The effective breakdown of several organic dyes has been achieved by utilizing nanoparticles created using environmentally friendly and green biosynthetic approaches [300]. Photocatalytic treatment is the chief method applied for the treatment of hazardous organic dyes [301]. It converts the contaminants into harmless products like CO_2 and water. The breakdown of several pollutants involves the illumination of semiconductor particles. An electron (e) and hole (h^+) pair are produced when AgNPs are exposed to radiation, and the electron gets excited from the valence to the conduction bands. The hydroxyl radical formed when water is converted into h^+ causes the oxidative destruction of the dye. In contrast, a free electron combines with an O_2 molecule to produce a superoxide radical. Additionally, the hydroxyl radical is created from the superoxide radical. It is a potent oxidizing agent that nonselectively breaks down organic molecules into harmless byproducts [302]. The photocatalytic activity of the silver nanoparticles created was evaluated using methylene blue degradation. Green silver nanoparticles successfully reduced the color by ~ 95% after 72 h of exposure [57]. Water containing methylene blue dye was mixed separately with nanoparticles ranging from 2 to 10 mg (10 mg/1000 mL). Controls excluded the AgNPs. Aliquots of the sample, 2–3 mL, were filtered, and OD_{660} was measured at predetermined intervals, based on which the percentage of dye degradation was estimated. It increased as the day lengthened. A dye solution containing 10 mg of AgNPs at different concentrations demonstrated 75% dye degradation after 5 d of incubation at room temperature [303]. Hence, it can be suggested that silver nanoparticles find good applications in catalysis. The photocatalytic activity of silver nanoparticles fabricated employing *Citrus reticulata* under sunlight was reported in which malachite green dye was completely destructed after 5 d of incubation [304]. Silver nanoparticles made from cyanobacteria degraded methylene blue by 18% at 4 h [305]. Additionally, the decolorization of additional dyes such as reactive yellow dye (82%–100%) [306], methylene blue (71.3%) [307], and Rhodamine B (85%) [308] was observed in the presence of biosynthesized AgNPs.

Protein and Enzyme Immobilization

Enzymes are biocatalysts of a variety of biological processes found in microbes, plants, and animals. Enzymes are employed extensively in the food, dairy, medical, pharmaceutical, leather, and detergent sectors. However, the lack of shelf life, reusability, and long-term operating stability prevents the reliable employment of enzymes despite their all-positive traits and vast industrial uses. One method to solve this issue was enzyme immobilization on the proper matrices [309]. The technique of enzyme immobilization was devised in 1961; using charcoal and aluminum hydroxide as adsorbent materials did not interfere with the enzyme's (invertase) function. This characteristic led to the creation of the currently used immobilization methods [310]. Immobilized enzymes are more stable and convenient to handle because the functioning of enzymes and the rates of the reactions catalyzed by them are determined by the structure of the free enzymes. Interaction with a matrix, binding stereochemistry, and the chemical and physical features of the carriers, as well as the immobilization conditions, are only a few examples of the factors that contribute to stabilization [309]. The choice of matrix material for immobilization is largely dependent on many factors, such as the size of the nanoparticles required, surface characteristics, degree of biocompatibility, biodegradability, and toxicity [311]. Due to their perfect properties, which include a large specific surface area, resistance to mass transfer, and a higher enzyme loading capacity, nanoparticles are excellent support materials for enzyme immobilization. There are four methods for immobilizing an enzyme onto nanoparticles: (i) adsorption via electrostatic forces, (ii) covalent bonding to the surface-modified nanoparticles, (iii) protein-specific conjugation; (iv) direct conjugation of proteins to the nanoparticle surface [310]. For example, an immobilized enzyme displayed its peak activity of 1,006 U throughout 18 h of incubation with AgNPs. Under ideal circumstances, the reusability of the enzyme immobilized on AgNPs fabricated using avocados was evaluated; the enzyme activity declined after five iterations; the enzyme was released from the AgNPs by an anionic detergent [309].

Biosensors

AgNPs are currently used as biosensors in several industries, including food, pharma, and healthcare, as well as environmental research. Among them, the food industry is primarily involved in investigating the applications of AgNP-based biosensors. For example, a procedure has been established for the calorimetric estimation of caffeine in beverages utilizing AgNP biosensors combined with microspheres. In humans, excessive coffee use seriously harms the nervous system and these biosensors might be helpful in precisely determining the amount of caffeine in the beverages consumed. A method for measuring Hg ions using biologically synthesized Ag nanosensors has been reported by another study. Such biosensors are crucial in the dairy industry for identifying microbial infections that affect production and storage times, as well as detecting chemical impurities that lower the quality of dairy products. In addition to these applications, such biosensors can be employed in a wide variety of biological analyses. AgNPs have higher sensitivity as biosensors despite being less chemically stable than AuNPs because of their localized surface plasmon resonance, which acts as a supportive property [312]. *Legionella pneumophila*, which causes Pontiac fever, was detected using silver nanoparticles and graphene quantum dots by ascertaining the concentration of pathogen DNA [313]. Another study on biosensing technology employed silver nanoparticles silk fibroin for the detection of Hg ions and concluded them to be rapid to use and cheap [314].

Tissue Engineering (TE)

TE has employed nanoparticles for several uses, including enhancing biological, electrical, and mechanical qualities; transmitting viruses; delivering genes; transfecting DNA; patterning cells into various tissues; and detecting and sensing chemicals. Depending on the application, the inclusion of a suitable type of nanoparticle in TE can considerably improve the biological, mechanical, and electrical properties of scaffolds as well as perform a variety of other tasks [315]. AgNPs enhance the biocompatibility and structural stability of decellularized pig liver through crosslinking [316]. Notably, AgNPs can kill cancer cells; a study discovered that a porous chitosan-alginate-containing biosynthesized AgNP was lethal to breast cancer cells [317].

Environmental Remediation

To stop the environmental pollution brought on by burning coal and gasoline, nanomaterials can be utilized as catalysts to react with deadly gases, such as CO and NO, in power-generating equipment and automotive catalytic converters (Fig. 5). AgNPs are of great value to biological systems and wastewater treatment facilities [286].

Air Disinfection

The extent and variety of human activities during various stages of civilization have had a detrimental effect on modern-day air quality. The issue at hand is maintaining a clean atmosphere devoid of harmful particles, gases, and volatile organic compounds, as well as airborne infectious viruses, bacteria, and fungi. Among the many difficulties posed by air-related infections, the latter has drawn a lot of attention since these germs cause chronic diseases. It heightens the awareness of the purification of air in a medical facility. Air purification is necessary to inhibit the growth of airborne viruses, bacteria, fungi, and other organisms. Asthma, SARS (severe acute respiratory syndrome), and anthrax are among the disorders that they are mostly to blame for. These bioaerosols are excessively deposited on filters and air conditioning systems, where they grow as a result of the elevated moisture levels. There are a few engineering methods for the elimination of bioaerosols that make use of air ozonolysis, photocatalytic oxidation, and UV irradiation. AgNPs demonstrate effective antibacterial activities for engineering nanomaterials to regulate air quality [318]. Silver nanoparticles have demonstrated their potent antibacterial capabilities. The tested isolates required a minimum inhibitory concentration of 30 g/mL; six recognized *Staphylococcus* species had different levels of sensitivity. The size distribution of bacterial growth inhibition zones reveals

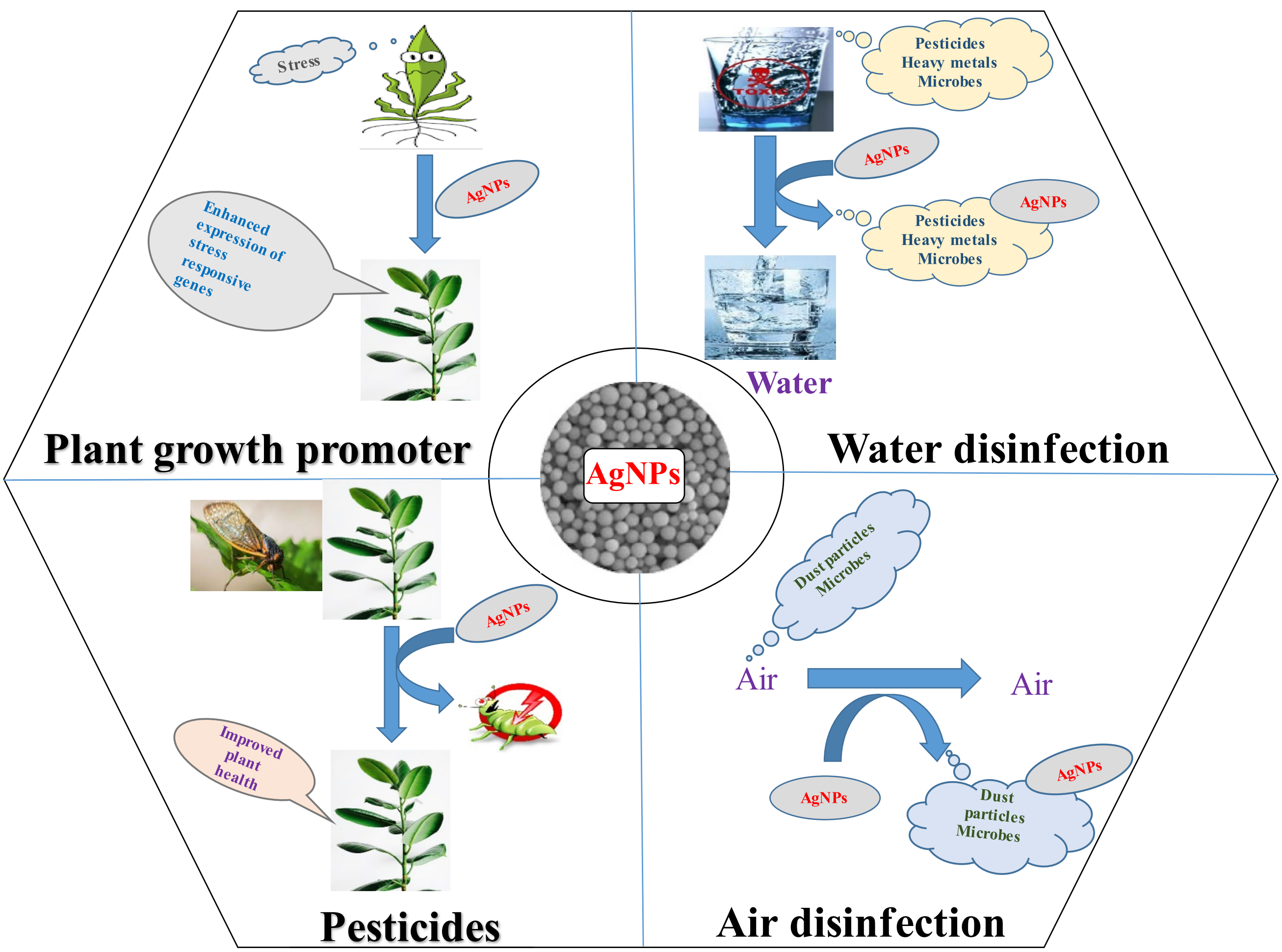


Fig. 5 Multifarious applications of biogenic silver nanoparticles in environmental remediation and agriculture

that resistance to varying nanosilver concentrations is a trait unique to each strain [319]. Ko et al. [320] demonstrated a simple method to produce monodispersed AgNP decorated silica particles for synergistic action against Gram + ve and Gram -ve bacteria in the air filter unit; the AgNP@SiO_2 solution showed an antibacterial efficacy of 99.99% against both bacterial types and was stable for up to six months. Thus, these hybrid materials can be used as a coating for appliances and air purification systems in the future [320]. The effectiveness of AgNPs as an antiviral agent when coated on medium air filters was investigated against the MS2 bacteriophage [321].

Water Disinfection

Recent years have seen a significant increase in the creation and use of AgNPs in the treatment of wastewater. Pesticides, heavy metals, and microbes are the three main pollutants that are mostly removed with AgNPs [322]. The effectiveness of silver-based disinfection depends on several factors, including temperature, pH, exposure period, and concentration. The other components of the water, like Cl, Ca, and sulfur dioxide, also contribute significantly to the disinfection process. Silver's bactericidal activity is influenced markedly by Ca and sulfide in water, but chloride has a lesser impact. Therefore, silver in a nanocrystalline form would be more effective in disinfecting water. Silver nanocrystals incorporated in ceramic water filters can serve as a disinfectant more efficiently than a conventional filter [318]. The Ag/wood filter can degrade > 98.5% of methylene blue through catalytic breakdown. It is composed of biomass and is easy to handle. After the suspensions were passed through the Ag/wood filter, *Escherichia coli* and *Staphylococcus aureus* were inactivated and eliminated. These outcomes demonstrate the potential of the Ag/wood filter developed for application in point-of-use water filtering [323]. Recently, it was shown that Ag-based porous nanocomposites (AgNPs) effectively rendered bacteria and viruses in drinking water inactive to the extent of 99%–100%. Silver-based nanoparticles may destroy MS2 bacteriophages and *E. coli* with a 99.99% success rate [324]. Allam et al. [325] examined the dye degradation capacity of AgNPs synthesized from *Bacillus paralicheniformis*, *Bacillus pumilus*, and *Sphinogomonas paucimobilis* under solar radiation. Romeh et al. [326] fabricated AgNPs using *Brassica*, *Plantago*, *Ipomoea*, and *Camellia* to study the degradation of toxic pesticides; the maximum amount of pesticides was degraded by *Brassica* within 48 h.

Agricultural Applications

Plant Growth Promotion

AgNPs have been considered viable agents to boost plant development and seed germination, hence increasing agricultural production. AgNP concentration has either a positive or negative influence on the growth response of plants [327]. AgNPs promoted plant development, as evidenced by faster blooming and enhanced accumulation of leaf and bulb biomass. In addition, plants exposed to silver nanoparticles displayed increased flower production and a longer flowering period. The leaves developed the highest levels of chlorophyll a, chlorophyll b, and carotenoids at 100 ppm AgNPs, and they were also the richest in K, Ca, and S [328].

By lowering oxidative stress and absorption of Na and Cl in salt-stressed plants, the AgNPs significantly boosted plant growth. Additionally, AgNPs maintained the ionic balance (Na^+, K^+, and Na^+/K^+ ratio) of cells. In plants under salt stress, AgNPs increased catalase and superoxide dismutase activities, decreased peroxidase activity, and lowered H_2O_2 and MDA levels [329]. When seedlings of *Trigonella foenum-graecum* L. (fenugreek) were exposed to AgNPs, root and shoot length, as well as leaf number, were enhanced markedly, along with a 23% rise in diosgenin—the main phytochemical of fenugreek [330]. AgNPs synthesized using *Pisum sativum* improved yield components [327]. Similar findings were made by Razzaq et al. [331] who found that 25–50 ppm AgNPs can significantly improve chlorophyll concentrations, plant height, as well as fresh and dry weights over the control. They also assessed the impact of wheat exposed to 0–150 ppm AgNPs.

Nanofertilizers

AgNPs enable a slow release of agrochemicals and are extremely biodegradable. Thus, they can be utilized in agriculture to create nanocapsules for the optimized and slow delivery of agrochemicals, pesticides, and fertilizers. Nanoencapsulated agrochemicals are designed to have desired qualities, such as effective optimal concentration, time-controlled release, increased activity at the target location, and less hazardous side effects. Through disintegration, biodegradation, dispersal, and osmotic pressure with appropriate pH, they aid in the regulated, slow exposure of agricultural chemicals to the target host. Nanotagged agrochemicals lessen the harm to nontarget plant tissues and lessen the hazard of vague synthetic defilement in the encompassing climate. Inorganic manure mixtures primarily provide three supplements—N, K, and P—to diverse crops at distinct developmental stages. These encapsulated NPK fertilizers are enclosed in nanosilver to enhance nutrient control [332]. According to certain reports, silver nanoparticles might be employed to improve the seed germination ability in many plants. Nanofertilizers assist in the effective and gradual release of nutrients, avoiding losses. They can improve the ability of plants to absorb nutrients from the soil [333]. An efficient nano-biofertilizer for tomato and brinjal plants was synthesized from onion extract. Utilizing

Table 8 Green synthesized AgNPs and their targeted pathogens

Serial No	Green synthesized AgNPs	Effective against	Refs
1	*Syzygium cumin*	*Aedes aegypti*, *Anopheles stephensi*and *Culex quinquefasciatus*	[335]
2	*Annona squamosa* L	*Anopheles stephensi*and *Culex quinquefasciatus*	[336]
3	*Ocimum tenuiflorum*	*Xanthomonas axonopodis*	[337]
4	*Solanum torvum*	*Ralstonia solanacearum* and *Xanthomosa*	[338]
5	Strawberry	*Fusarium oxysporum, nematode, Ralstonia solanacerum, Meloidegyne incognita*	[329]

such nano-biofertilizers can cut down farm management expenses, excessive use of chemical fertilizers, and environmental damage [334].

Application as Pesticides

Pests present a great danger to the agricultural industry, resulting in lower crop yields and, consequently, lesser product quality. Additionally, synthetic pesticides harm the environment. Nanotechnology can be used in pest management. Additionally, the silver nanoparticle-based pesticide delivers a significant amount of insecticide to the target plants, making nanosilver a highly effective, risk-free, and improved pest control agent. The organisms used in the environmentally friendly way of producing silver nanoparticles can be either bacteria or plants; however, the flavonoids found in plants are harmful to them. Therefore, the silver nanoparticle-derived pesticidal action can be very helpful. Additionally, silver nanoparticles have antifungal activity, making them useful in the treatment of fungal diseases of plants. UV-induced AgNPs may be applied in the biocontrol of pests like mosquito larvae [333]. Table 8 depicts the antimicrobial applications of AgNPs synthesized from different medicinal plants.

Conclusions and Future Perspectives

Synthesis of AgNPs using a green approach offers an eco-friendly, cost-effective, and nontoxic route. Different plants and microorganisms like yeast, bacteria, fungi, algae, and actinomycetes can be used for the green synthesis of AgNPs. In summary, the green approach overcomes the limitations of physical and chemical approaches and offers large-scale synthesis. The main focus of the present review was the green methods employed for synthesizing AgNPs, their characterization, and their multifarious applications in different fields. It is now understood that several types of small and large phytoconstituents present in the plant and microbial extracts can act as reducing agents for the green synthesis of AgNPs. Among all the microorganisms used in nanoparticle synthesis, fungi are considered the best option due to their higher metal tolerance and ability to secrete large amounts of enzymes. However, plants are better than other biological sources. It can be concluded that AgNPs own unique properties which make them more useful in medical applications and biotechnology-based processes. AgNPs are used in biomedical applications, dental materials, biosensors, biotechnology, and agriculture. They have excellent activity against both Gram-positive and Gram-negative bacteria as well as *Plasmodium* and fungi. These nanoparticles can disrupt the bacterial cell membrane and interfere with the cellular machinery, which can lead to cell death. The photocatalytic mechanism of AgNPs helps in the removal of toxic dyes in the treatment of wastewater. Additionally, AgNPs are effective for plant growth and in therapeutic and biotechnological applications.

Both *in vitro* and *in vivo* studies have demonstrated the cytotoxicity, accumulation, and toxicity of AgNPs in various organs. These effects vary with their size, shape, dose, and route of exposure. Further, the information related to mechanisms of action of AgNPs in animal models and others is limited. Therefore, the efficiency of AgNPs can be further improved with metallic components and other metabolites. Doping AgNPs with small quantities of a second metal may be used to enhance the efficiency of AgNPs while maintaining biocompatible levels. Gold and platinum are excellent candidates as dopants because they have a greater electrochemical potential than silver and higher biocompatibility.

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Declarations

Conflict of interest The authors declare that there is no conflict of interest.

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