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(Review Article)

A systematic review on green synthesis of silver nanoparticles, characterization and applications

M. Muntasir Alam Muhib #, Mahi Mubassira #, Sanzida Khanam #, S. Abeed-Ul-Haque # and M. Faruk Hasan *

Department of Microbiology, University of Rajshahi, Rajshahi 6205, Bangladesh.
 # Contributed equally to the work.

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Abstract

The increasing demand for environmentally friendly and sustainable synthesis methods has prompted the exploration of green routes for the production of silver nanoparticles (AgNPs). This study focuses on the green synthesis of AgNPs from different plants and microbes. The article indicated successful formation of stable AgNPs with well-defined characteristics. The eco-friendly synthesis approach ensures antimicrobial activities of the green-synthesized AgNPs, including bacteria and fungi. The mode of action of the nanoparticles on microbial cells were also investigated, shedding light on their potential as novel antimicrobial agents. Furthermore, the versatility of these green-synthesized AgNPs was explored in different applications, such as biomedical, agricultural, and environmental sectors. Moreover, the environmental implications of utilizing these eco-friendly nanoparticles were assessed, highlighting their potential in addressing contemporary challenges.

Keywords: Green synthesis; Silver nanoparticles; Characteristics; Applications

1. Introduction

Nanotechnology is a branch of science concerned with the creation, manipulation, and application of materials ranging in nanometers (1). It deals with creating nanomaterials and nanoparticles (NPs) for use in a variety of industries, including food technology, electrochemistry, biomedicines, sensors, chemical manufacturing, etc. (2-4) Among other materials, metal nanoparticles have recently received a lot of attention due to their unique optical and electrical properties, as well as potential biomedical applications (5,6) gained early recognition for their effective biomedical properties, such as anti-inflammatory, antifungal, anticancer, antibacterial, antiviral, and larvicidal effects (7-13) Silver nanoparticles can be synthesized using various methods and approaches, which include chemical (14) electrochemical (15) radiation (16), photochemical methods (17) Langmuir-Blodgett (18,19), and biological techniques (20). However, most of the approaches mentioned involve the use of expensive and toxic chemicals that can create biological risks, and sometimes these processes cause harm to the ecology and the ecosystem. This enhances the increasing need to develop eco-friendly processes through green synthesis and other biological approaches (10,21). In recent times, biological methods have been widely preferred. Green synthesis of AgNPs provides advantages over chemical and physical methods due to its cost-effectiveness, environmental friendliness, ease of scaling up for large-scale synthesis, and lack of need for toxic chemicals and high temperatures (22). The sources of the reducing and stabilizing agents used in the green synthesis of nanoparticles are bacteria, fungi, viruses, algae, and plant extracts (23). In this regard, several plant parts, including the leaf, flower, stem, fruit, seed, shoot, bark, peel, root, and callus, etc., have been studied (24-28), as plants are rich in a variety of proteins and secondary metabolites such as quinones, flavonoids, saponins, and terpenoids, which contribute to the stabilization or reduction of the nanoparticles (29,30). AgNPs show potential antimicrobial effects against infectious microorganisms like *E. coli* and *S. aureus*. AgNPs are also used in biological tags

* Corresponding author: Md. Faruk Hasan

and biosensors in diagnostic applications, footwear, wound dressings, antimicrobial nano-paints, cosmetics, food-related products, and packaging (31,32). The purpose of this study is to thoroughly analyze the body of literature already in existence, offering insights into the characterizations, synthesis methods, and many applications, thus advancing our knowledge of green nanotechnology.

2. Materials and methods

2.1. Plant extracts

More stabilization and decrease are shown in plant phytochemicals (34). AgNPs that revealed the presence of alkaloids, flavonoids, saponins, and sugar compounds were created using *Eugenia jambolana* leaf extract (35). An extract from the bark of *Saraca asoca* revealed the presence of carboxyl and hydroxyl groups (36). After synthesizing AgNPs from *Rhynchotechum ellipticum* leaves, the presence of steroids, polyphenols, flavonoids, alkaloids, and terpenoids was shown (37). When AgNPs measuring between 5 and 60 nm are formed, pepper-leaf extract functions as a reducing and capping agent (38). Malus domestica fruit extracts served as a reducing agent. In a similar vein, *Vitis vinifera*, *Andean blackberry* (39), *Adansonia digitata* (40), *Solanum nigrum* (41), *Nitraria schoberi* (42), or more fruit peels. Polysaccharide (43), soluble starch (44), natural rubber (44), tarmac (45), stem-derived callus of green and red apples (46)(47), egg white (48), lemongrass (49), coffee (50), black tea (51) and *Abelmoschus esculentus* juice (52) are a few more reductants that are employed for AgNO3.

2.2. Microbial extracts

Microorganisms like fungi, bacteria, and yeast are of huge interest for NP synthesis. NPs formed by microorganisms can be classified into distinct categories, depending upon the location. Otari et al synthesized AgNPs intracellular using *Actinobacteria* and *Rhodococcus sp.* Kannan et al. (53) reported biosynthesized AgNPs using Bacillus subtillus extracellular. AgNPs were synthesized using microalgae *Chaetoceros calcitrans, C. salina, Isochrysis galbana*, and *Tetraselmis gracilis* (54). *Cystophora moniliformis* was used as a reducing and stabilizing agent to synthesize AgNPs (55). Some fungal species such as *Fusarium oxysporum* (56) *Verticillium, Aspergillus fumigatus, Fusarium semitectum* (57) *Phanerochaete chrysosporium* and *Alternaria alternata* (58) were used for AgNPs production.

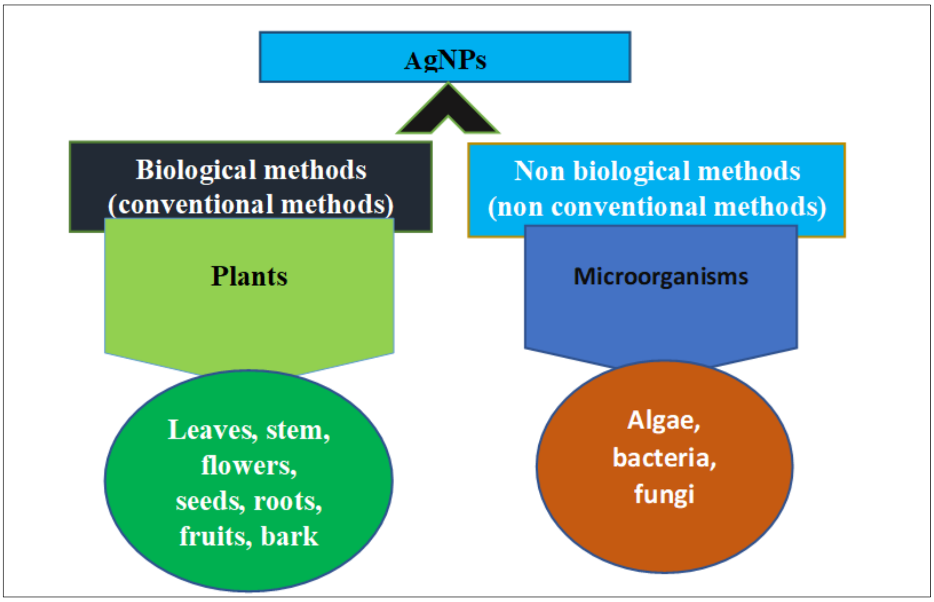

Figure 1 Several techniques for synthesizing silver nanoparticles.

2.3. Extraction and fractionation of plants and microbial extracts

The plants or plant parts are collected from the available sites. Removal of dirt and extra organic waste by washing thoroughly twice or thrice has been made. The fresh and clean plant parts are dried for two weeks in the dark (59). ~10 gm of the fresh and clean plant parts are mixed with 100 ml of sterile distilled water, boiled for 5 minutes, and cooled to room temperature. The boiled mixtures are finely crushed in a kitchen grinder and filtered through Whatman filter paper. The filtrate is utilized for the synthesis of silver nanoparticles (60,61). For extracting the leaf, analytical grade methanol is used twice for soaking the plant material and kept at room temperature for 15 days. The filtrate is concentrated using a rotary evaporator under vacuum at 40°C, to obtain a crude methanolic extract. For the fractionation of the crude methanolic extract, different solvents were utilized (62) and to utilize the wide range of bioactive chemicals generated by microbes, it is crucial to extract and fractionate microbial extracts carefully. This involves extracting specific bioactive compounds through processes like cell destruction, filtering, and centrifugation. Fractionation then separates these constituents based on their characteristics. In the synthesis of AgNP using microorganisms, a solution containing microbial biomass serves as a bio-reducing agent for silver ions, aiding in the creation of stabilized Ag-NPs (63-65).

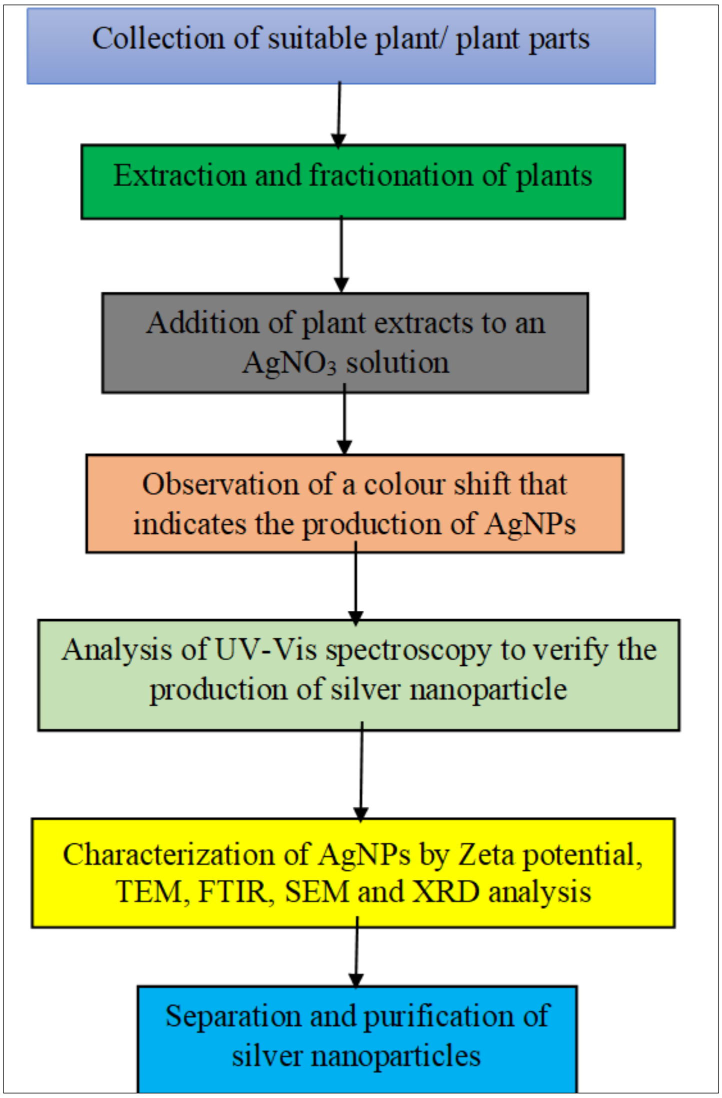

Figure 2 AgNO3 formation steps

2.4. Biosynthesis of AgNPs from different materials

Effective biosynthesis of nanoparticles has been achieved through the utilization of plant-related materials such as leaves, stems, roots, shoots, flowers, barks, seeds, and their metabolites (66,67) to produce AgNPs, plant extracts are added to an AgNO3 solution, which is subsequently transformed into Ag+ ions. The resultant solution undergoes a color change after a while, which indicates the production of AgNPs (68).

Utilizing microbial cells to produce metal nanoparticles sounds like a really smart idea these days.The size of AgNPs generated utilizing *Escherichia coli*, *Klebsiella pneumoniae*, *Enterobacter cloacae*, and other bacteria that efficiently produced silver nanoparticles is controlled by parameters such as pH, temperature, and AgNO3 concentration (69).

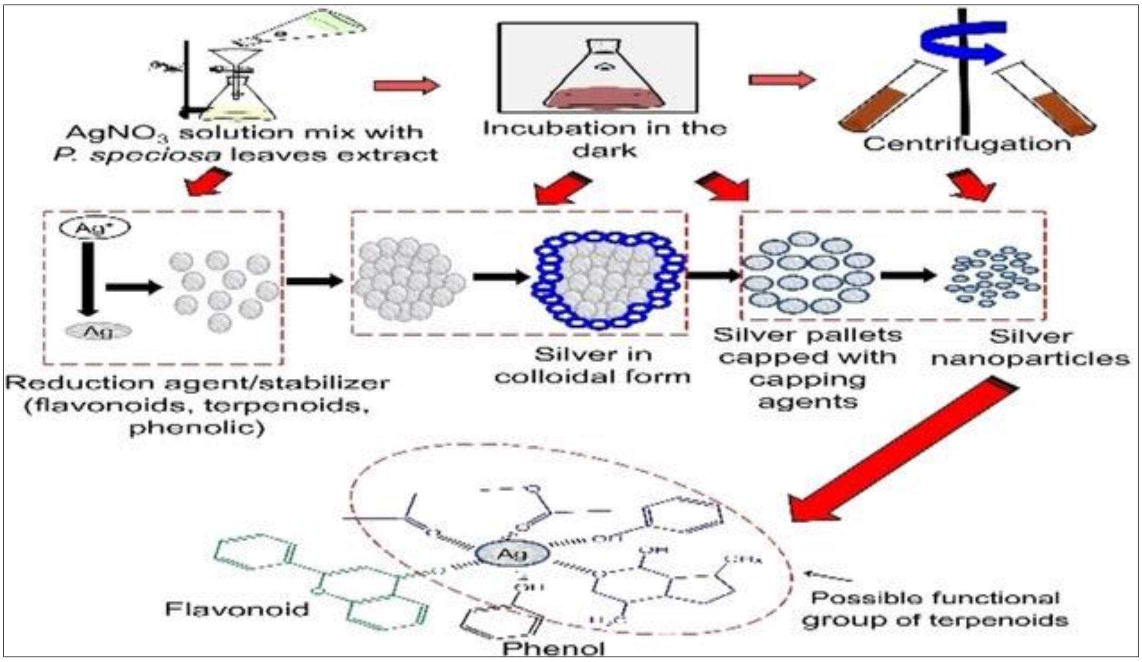

Figure 3 Systematically green synthetic approaches of nanoparticles (70).

3. Characterization of AgNPs

3.1. TEM analysis

Using picture magnifying software, which can enlarge particles smaller than 10 nm and provide distinct morphological information, one can ascertain the size of the silver nanoparticles (71). At the EM National Research Centre, University, transmission electron microscopy (TEM) was used to visualize the morphology and form of the green Nanosilver. One ethanol-negatively stained drop of the emulsion was placed on a copper grid. A tungsten-source transmission electron microscope (JEOL JEM-1400Plus) running at 80 kV was used to capture the TEM micrographs (72). The scale shown in the micrograph can be used to determine the particle's size (73).

3.2. Zeta potential

Zeta potential measurement can be used to determine the surface electric charge of the nanoparticle, which aids in estimating the suspension stability of the silver nanoparticle (74). Using laser Doppler electrophoresis at room temperature, the surface charge of green Nanosilver was determined using the Malvern Zeta sizer ZS (Malvern Instruments, Worcestershire, UK). Before measurement, the samples were diluted using deionized water. To quantify charge, the samples were subsequently put into a capillary cell. The repellent forces among the particles in the emulsion system are shown by zeta potential values (75). The high negative value increases the formulation's stability by confirming the particles' repulsion to one another (76).

3.3. Fourier transform infrared (FTIR) analysis of silver nanoparticles

One method that can be used for checking the surface chemistry of metal nanoparticles and the contribution of biomolecules to the creation of nanoparticles is FTIR spectroscopy (77).

3.4. UV-Visible Spectroscopy Analysis

Using a UV-visible spectrophotometer (CECIL CE 2041 2000 SERIES), the production of AgNPs was verified. To get the UV-visible spectra of the sample, precisely 4 mL of the diluted supernatant of the WMRE-AgNPs sample was put in a quartz cuvette with a 1 cm path length and inserted in a UV-Vis spectrophotometer in the wavelength range of 300–700 nm (78). Using distilled water as a reference, green-produced silver nanoparticles were exposed to UV-visible spectrophotometry at wavelengths between 200 and 800 nm. This method yields data on the stability and concentration of the nanoparticles in addition to their size and shape (79).

3.5. Scanning Electron Microscopy (SEM)

After 48 hours, the surface morphology of the nanoparticles was examined using SEM at a 30 kV accelerating voltage. The precipitate was allowed to dry following the AgNPs solution's centrifugation. A coater applied a gold coating to the dried nanoparticles to stop the accumulation of electrical charges (80). Ag-NPs are also characterized by a suspension of particles.

3.6. X-Ray Diffraction (XRD) Analysis

An X-ray-dx was used to study the crystal structure of Ag-NPs. X-rays were used to penetrate the powdered Ag-NPs and scan a region of 2θ, ranging from 0° to 80° (81).

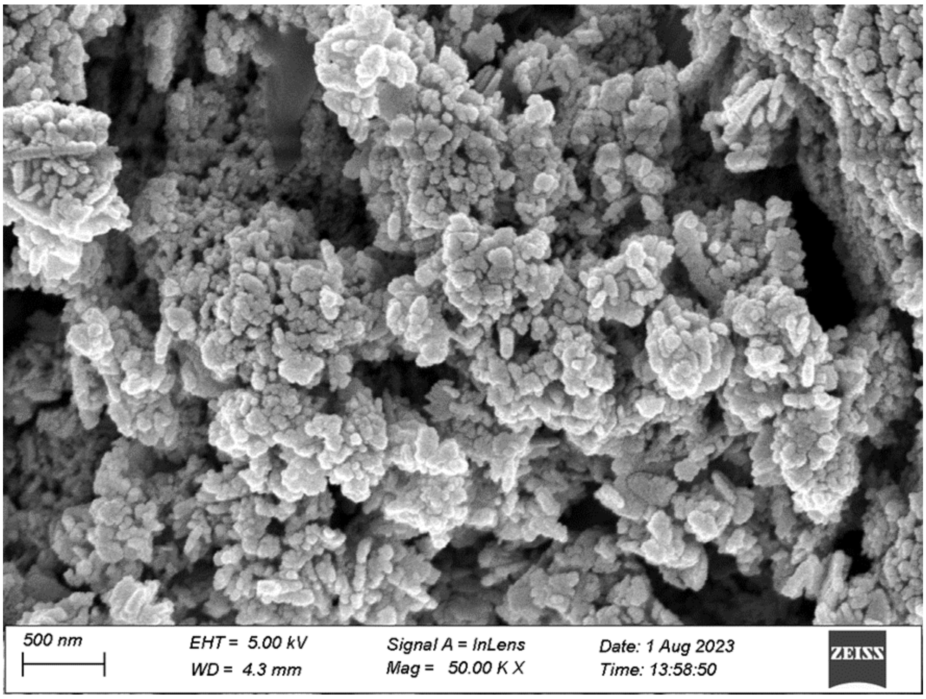

Figure 4 SEM image of silver nanoparticle synthesized from neem leaf extract

3.7. Applications of Silver Nanoparticles

Silver-coated dressings are currently widely used in wound care, especially for burns, diabetic wounds, leg ulcers that don't go away, and injuries from trauma. Furthermore, it has been proposed that metallic biomaterials, catheters, vascular grafts, burn therapy, arthroplasty, and biomaterial-mediated infections in prosthesis can all be prevented with the use of materials containing silver (82).

The addition of silver nanoparticles (about 225 nm) dramatically enhanced the antibacterial activity of penicillin G, amoxicillin, erythromycin, clindamycin, and vancomycin against *S. aureus* and *E. coli*. The strongest synergistic effect against *S. aureus* was identified with erythromycin, while the biggest fold increase in area from the disk diffusion experiment was obtained for vancomycin, amoxicillin, and penicillin G (83).

Not only does nanocrystalline silver offer outstanding antibacterial qualities, but it also has demonstrated beneficial effects in reducing inflammation at the wound site and promoting wound healing. At the contaminated wound site in a pig model, nanocrystalline silver increased cellular death and decreased local matrix metalloproteinase levels (84).

The antifungal power of silver nanoparticles with amphotericin B and fluconazole, two of the strongest fungicides, have been compared against several different fungi (85). The results show that the antifungal power of silver nanoparticles is similar to one of the strongest fungicides and is much stronger than fluconazole (33). Antifungal agent was assessed the effectiveness of silver nanoparticles using yeast (86).

AgNPs from plants have anticancer properties, and neither humans nor other living things are harmed by them. AgNPs dramatically reduced lung cancer cells' ability to proliferate. Specifically, NCI-H460 cells treated with green AgNPs at

240 ppm demonstrated 2% cell viability (87,88). and many AgNPs were shown to be harmful or to have stunted the growth of the MCF-7 breast cancer cell line (89).

The treatment involving biosynthesized silver nanoparticles showed promise in modulating the expression of key cytokines, reducing pro-inflammatory signals, and promoting an anti-inflammatory environment, which could be beneficial for the wound healing process after burn injuries (90,91).

The unique properties of the green-synthesized silver nitrate nanoparticles demonstrated their successful production on mice for heat damage, diabetic wounds, and chronic wounds to study the impact of silver nanoparticles on scar tissue formation and wound healing (92).

By using Ag-NPs instead of traditional Ag Sulfadiazine and gauze dressing, wound dressings significantly shortened the healing period or injuries by an average of 3.35 days while increasing bacterial clearance from contaminated wounds without having any negative effects (93).

Harvests and trees provide nanosized lignocellulosic materials, which have created a new market for valuable and inventive nanosized products and materials. These can be applied to the development of food items and other packaging as well as the body structures of vehicles. As part of agribusiness, nano fertilizers, nano pesticides that incorporate nano herbicides, nanocoating, and innovative plant nutrition delivery systems are widely used. These products contain 100–250 nm Ag-NPs, which are more soluble in water and therefore more active (94).

Prosthetic silicone heart valves were the first cardiovascular devices coated with Ag elements to reduce endocarditic occurrences (95). To prevent bacterial contamination of the silicone valve and lessen the heart's inflammatory response, the use of Ag was suggested (96). In addition, Ag-NPs are utilized in several consumer byproducts that are part of the broader field of nanotechnology, including room sprays, deodorants, socks, soaps, water filters, and sanitization systems (97-100).

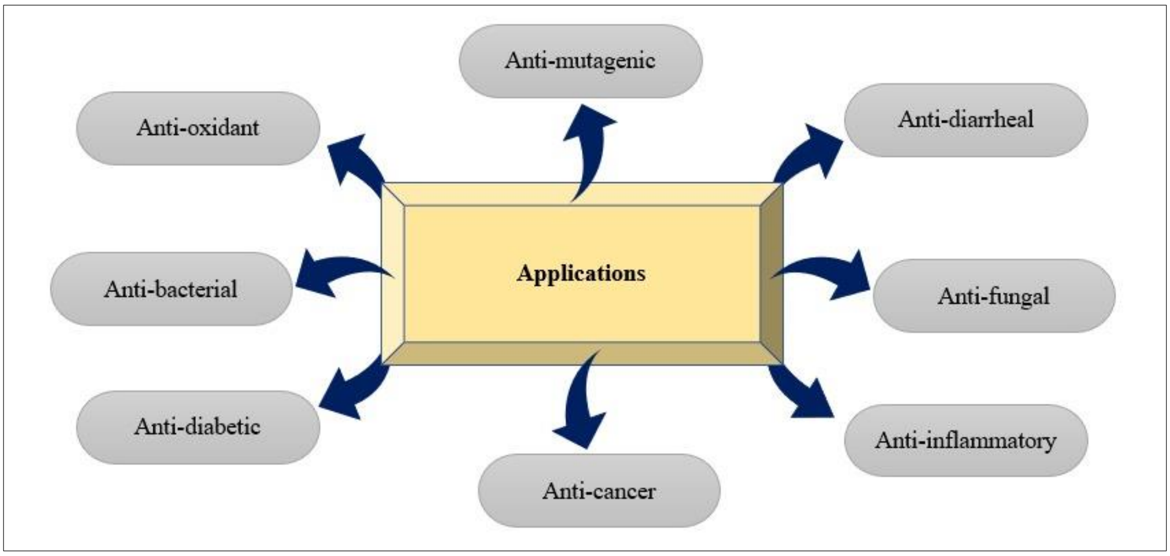

Figure 5 Applications of silver nanoparticle

3.8. Various plants used for the green synthesis of AgNPs

A new era in quick and safe nanoparticle production techniques has been brought about by current research on the biosynthesis of nanometals from plant extracts. Numerous researchers have documented the production of metal nanoparticles using extracts from different parts of plants and their possible uses (101-105).

Table 1 Green synthesis of AgNPs from different plants extracts and their applications

SI No.	Plants name	Applications	References
1	*Coffea arabica*	Antimicrobial activity	(106)
2	*Artocarpus hirsutus*	Antibacterial activity	(107)
3	*Salvia hispanica*	Antibacterial activity against *E. coli* and *S. aureus*	(108)
4	*Annona squamosa*	Antibacterial activity against *S. aureus*	(109)
5	*Vigna sp.*	Antimicrobial activity	(110)
6	*Alpinia katsumadai*	Antioxidant, cytotoxicity, and antibacterial activities	(111)
7	*Persea americana*	Antimicrobial activity against *E. coli*	(112)
8	*Phoenix dactylifera*	Antibacterial activity against *S. aureus*	(113)
9	*Jatropha curcas*	Antimicrobial, antioxidant, antidiarrheal, and antidiabetic activity	(114)
10	*Calendula officinalis*	Antimicrobial properties	(115)
11	*Syzygium cumini*	Antioxidant activity	(116)
12	*Pistacia atlantica*	Antibacterial activity against *S. aureus*	(117)
13	*Acacia leucophloea*	Antibacterial activity	(118)
14	*Boswellia ovalifoliolata*	Antibacterial and antifungal activity	(119)
15	*Moringa oleifera*	Anti-inflammatory and antibiotic	(120)
16	*Cinnamon zeylanicum*	Antibacterial activity	(121)
17	*Azadirachta indica*	Antibacterial Activity	(122)
18	*Prosopis juliflora*	Antimicrobial Activity	(123)
19	*Citrus sinensis*	Antioxidant, anticancer and antimicrobial activities	(124)
20	*Citrus limon*	Effective against gram-negative bacteria	(125)
21	*Piper longum*	Antibacterial activity	(126)
22	*Piper retrofractum*	Antibacterial activity	(127)
23	*Emblica officinalis*	Antimicrobial activity against *E. coli, K. pneumonia*, *S. aureus* and *B. subtilis.*	(128)
24	*Averrhoa carambola*	Antibacterial activity	(129)
25	*Capsicum frutescence*	Antibacterial activity against *E. coli* and *B. substilis*	(130)
26	*Cassia fistula*	Antibacterial activity	(131)
27	*Fructus amomi*	Activity against *S. aureus* and *E. coli*	(132)
28	*Vitis vinifera*	Antimicrobial activity, antioxidant and anti-inflammatory properties	(133)
29	*Camellia sinensis*	Reduce cancer, inflammation and antimicrobial properties.	(134)
30	*Carica papaya* L.	Antimicrobial activity against multi-drug resistant human pathogen	(135)
31	*Acalypha indica*	Antibacterial activity against *E. coli* and *V. cholera*	(136)
32	*Morinda tinctoria*	Potocatalytic activity	(137)

33	*Datura stramonium*	Activity against *S. aureus* and *E. coli*	(138)
34	*Paederia foetida*	Antimicrobial reactivity	(139)
35	*Viburnum lantana*	Antibacterial Activity	(140)
36	*Mukia maderaspatana*	Antibacterial, antimalarial, and anticancer agents	(141)
37	*Origanum vulgare*	Antimicrobial activity against human pathogenic bacterial strains	(142)
38	*Vitex negundo*	Antibacterial Activity (*E. coli* and *S. aureus*)	(143)
38	*Sapindus mukorossi*	Activity against *Mycobacterium tuberculosis*	(144)
40	*Abies webbiana*	Antibacterial activity against *S. aureus, E. coli* and *P. aeruginosa*	(145)
41	*Coccinia grandis*	Photocatalytic activity	(146)
42	*Coleus aromaticus*	Antibacterial effect against *S. aureus, B. subtilis, E. coli* and *K. pneumonia*	(147)
43	*Asiatic Pennywort*	Antimicrobial activities against *Staphylococcus epidermidis*	(148)
44	*Bryophyllum*	Antimicrobial activities against *Pseudomonas fluorescens*	(149)
45	*Berberis vulgaris*	Antibacterial Activity	(150)
46	*Calotropis gigantean*	Antibacterial activity on *V. alginolyticus*	(151)
47	*Coriandrum sativum*	Antimicrobial activity	(152)
48	*Ceratonia siliqua*	Antibacterial activity against *E. coli*	(153)
49	*Dodonaea viscosa*	Antibacterial and anticancer activity	(154)
50	*Eriobotrya japonica*	Antibacterial activity against *Shigella* and *Listeria*	(155)
51	*Citrullus colocynthis*	Remedy for indigestion, gastroenteritis, and intestinal parasites	(156)
52	*Pterocarpus santalinus*	Antipyretic, anti-inflammatory, anthelmintic, anti-hyperglycemic and diaphoretic.	(157)
53	*Melia dubia*	Anti-diabetic, anti-inflammatory, antioxidant, antibacterial, antiviral, and fungicidal treatment	(158)
54	*Lantana camara*	Respiratory infections, dysentery and gastropathy	(159)
55	*Alternanthera dentate*	Antimicrobial effects against clinical bacteria and fungi strains	(160)
56	*Nelumbo nucifera*	Antioxidant, immunomodulatory, antipyretic, anticancer, antiischemic	(161)
57	*Azhadirachta indica*	Antibacterial and antioxidant activity	(162)
58	*Euphrasia officinalis*	Anticancer, antibacterial and biofilm inhibition activity	(163)
59	*Melia azedarach*	Antimicrobial activity	(164)
60	*Melissa officinalis*	Antibacterial activity	(165)
61	*Petroselinum crispum*	Anti- *E. coli, K. pneumonia, S. aureus*	(166)
62	*Rubus glaucus benth*	Hepatic Cancer	(167)
63	*Alternanthera tenella*	Breast Cancer	(168)
64	*Acacia nilotica*	Antibacterial, anticholesterol activity and maintain blood sugar level	(169)
65	*Acacia rigidula*	Skin infections	(170)
66	*Dioscorea bulbifera*	Synergic antibacterial activity with broad spectrum antibiotic	(171)

67	*Eulophia herbacea*	Antibacterial and antifungal activity	(172)
68	*Jasminum auriculatum*	Antibacterial activity	(173)

3.9. Green synthesis of AgNPs using various microorganisms

Antimicrobial substance might potentially overcome antibiotic resistance. They are efficient against bacteria that are gram-positive and negative. AgNP is said to bind with and penetrate the bacterial cell wall, causing a major disruption in the cell's ability to function that ultimately results in cell death (174-176). The antibacterial properties of AgNPs are influenced by various physicochemical characteristics, such as their size, shape, concentration, surface charge, and colloidal state (177). The production process for the nanoparticle has a major influence on these physicochemical qualities. Table 1 enumerates the antibacterial activity of AgNPs produced by various algae. Sondi et al. demonstrated that AgNP adheres to the *Escherichia coli* cell wall and creates holes in the membrane, which ultimately results in cell death (178). AgNPs exhibit anti-biofilm-forming properties through both bactericidal and bacteriostatic action. AgNP's bactericidal efficacy against *E. coli* has been demonstrated at the concentrations of 60μg/ml or higher (179).

Table 2 Green synthesis of AgNPs from different plants extracts and their applications

SI No.	Species name	Applications	References
1	*Gelidiella acerosa*	Antifungal	(180)
2	*Sargassum tenerrimum*	Antibacterial	(181)
3	*Ulva fasciata*	Antimicrobial	(182)
4	*Gracilaria corticata*	Antifungal	(183)
5	Microalgae	Antibacterial	(184)
6	*Enteromorpha flexuosa*	Antibacterial	(185)
7	*Spirulina platensis*	Anti-bacterial	(186)

4. Conclusion

This review article demonstrated the importance of the environmentally friendly production of silver nanoparticles, including the use of waste grass extract, natural rubber latex (NRL) solutions, marine algae *Ecklonia cava*, *Abelmoschus esculentus* flowers, and *F. macrocarpa*. These nanoparticles exhibit unique properties, positioning them for varied applications, including antibacterial, antioxidant, and anticancer activities. The exploration of plant extracts, encompassing different plant parts, highlights the versatility of green synthesis. Notably, its scalability, sustainability, cost-effectiveness, simplicity, and eco-friendliness make it a promising alternative to chemical and physical methods. The biocompatibility of the resulting products and minimal environmental impact further accentuate the advantages of green synthesis, emphasizing its potential for widespread adoption in large-scale production.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare that the research was possessed no relevant financial or non-financial interests.

Author Contributions

The authors have made a substantial direct and intellectual contribution to the work and approved it for publication. Each author contributed equally to all sections of the manuscript.

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