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REVIEW

Green nanotechnology: a review on green synthesis of silver nanoparticles — an ecofriendly approach

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Background: Nanotechnology explores a variety of promising approaches in the area of material sciences on a molecular level, and silver nanoparticles (AgNPs) are of leading interest in the present scenario. This review is a comprehensive contribution in the field of green synthesis, characterization, and biological activities of AgNPs using different biological sources.

Methods: Biosynthesis of AgNPs can be accomplished by physical, chemical, and green synthesis; however, synthesis via biological precursors has shown remarkable outcomes. In available reported data, these entities are used as reducing agents where the synthesized NPs are characterized by ultraviolet-visible and Fourier-transform infrared spectra and X-ray diffraction, scanning electron microscopy, and transmission electron microscopy.

Results: Modulation of metals to a nanoscale drastically changes their chemical, physical, and optical properties, and is exploited further via antibacterial, antifungal, anticancer, antioxidant, and cardioprotective activities. Results showed excellent growth inhibition of the microorganism.

Conclusion: Novel outcomes of green synthesis in the field of nanotechnology are appreciable where the synthesis and design of NPs have proven potential outcomes in diverse fields. The study of green synthesis can be extended to conduct the in silco and in vitro research to confirm these findings.

Keywords: green synthesis, plant mediated synthesis, silver bioactivity, microorganism

Introduction

Nanotechnology offers fields with effective applications, ranging from traditional chemical techniques to medicinal and environmental technologies. AgNPs have emerged with leading contributions in diverse applications, such as drug delivery,[31] ointments, nanomedicine,[37] chemical sensing,[41] data storage,[47] cell biology,[54] agriculture, cosmetics,[60] textiles,[17] the food industry, photocatalytic organic dye–degradation activity,[64] antioxidants,[66] and antimicrobial agents.[68]

Despite the contradictions reported on the toxicity of AgNPs,[69] its role as a disinfectant and antimicrobial agent has been given considerable appreciation. The available documented data[73,74] and the interest of the community in this field prompted us to work on plant-mediated green synthesis and biological activities of AgNPs.

Different types of nanoparticles

Some distinctive reported forms of nanoparticles (NPs) are core–shell NPs,[76] photochromic polymer NPs,[78] polymer-coated magnetite NPs,[80] inorganic NPs, AgNPs,

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CuNPs,[82] AuNPs,[85] PtNPs,[86] PdNPs,[88] SiNPs,[89] and NiNPs,[91] while others are metal oxide and metal dioxide NPs, such as ZnONPs,[94] CuO NPs,[95] FeO,[97] MgONPs,[100] TiO_2 NPs,[102] CeO_2 NPs,[103] and ZrO_2 NPs.[104] Each of these has an exclusive set of characteristics and applications, and can be synthesized by either conventional or unconventional methods. An extensive classification of NPs is provided in Figure 1.[105–111]

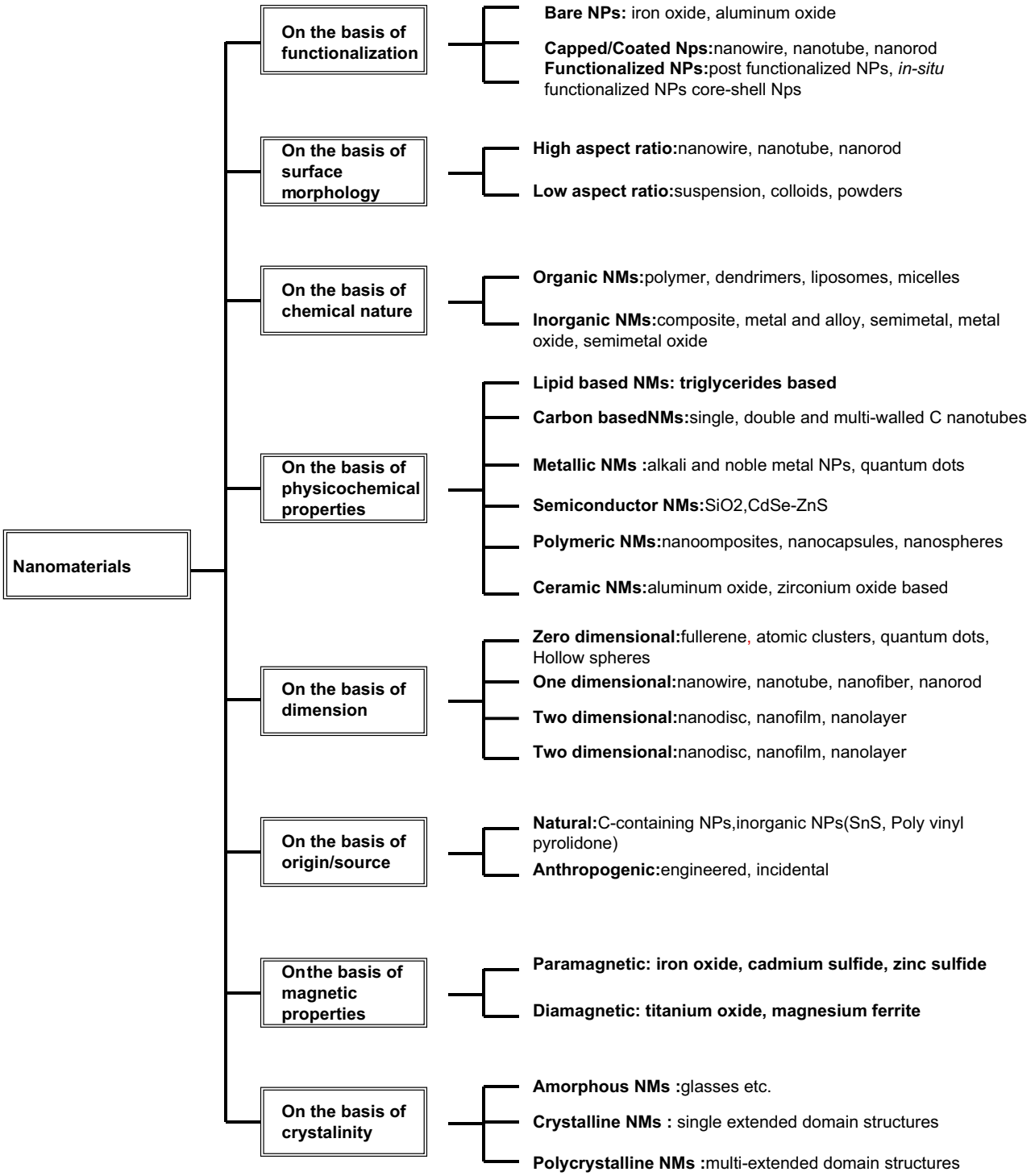

Figure 1 Different approaches to nanomaterial (NM) classification.
Abbreviation: NPs, nanoparticles.

Table 1 Chemical and physical synthesis of AgNPs

Type	Reducing agent	Characterization	Biological activities	Reference
Chitosan-loaded AgNPs	Polysaccharide chitosan	TEM, FTIR, XRD, DSC, TGA	Antibacterial	114
PVP-coated AgNPs	Sodium borohydrine	UV-vis, TEM, EDS, DLS, Fl-FFF	NANA	115
AgNPs	Ascorbic acid	UV-vis, EFTEM	Antibacterial	116
AgNPs	Hydrazine, D-glucose	UV-vis, TEM	Antibacterial	117
Polydiallyldimethylammonium chloride_ and poly-methacrylic acid–caped AgNPs	Methacrylic acid polymers	UV-vis, reflectance spectrophotometery	Antimicrobial	118

Abbreviations: NPs, nanoparticles; TEM, transmission electron microscopy; FTIR, Fourier-transform infrared; XRD, X-ray diffraction; DSC, differential scanning calorimetry; TGA, thermogravimetric analysis; UV-vis, ultraviolet-visible (spectroscopy); EDS, energy-dispersive spectroscopy; DLS, dynamic light scattering; Fl-FFF, flow field-flow fractionation; EFTEM, energy-filtered TEM; NA, not applicable.

Nanoparticle synthesis

Comprehensive approaches available for NP synthesis are bottom-up and top-down.[112] The latter approach is immoderate and steady, whereas the former involves self-assembly of atomicsize particles to grow nanosize particles. This can be achieved by physical and chemical means,[113] as summarized in Table 1. However, ecofriendly green syntheses are economical, and proliferate and trigger stable NP formation, as shown in Figure 2.

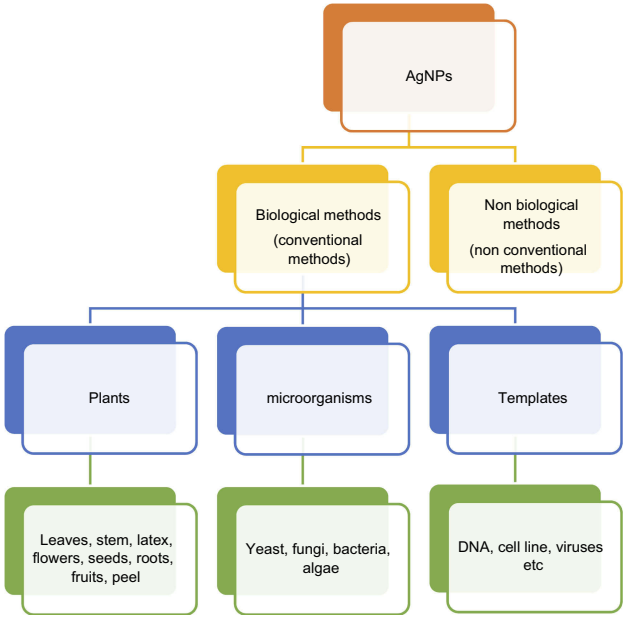

Figure 2 Various approaches to the synthesis of Ag nanoparticles (NPs).

Green approach (biological/ conventional methods)

The surging popularity of green methods has triggered synthesis of AgNPs using different sources, like bacteria, fungi, algae, and plants, resulting in large-scale production with less contamination. Green synthesis is an ecofriendly and biocompatible process,[119] generally accomplished by using a capping agent/stabilizer (to control size and prevent agglomeration),[120] plant extracts, yeast, or bacteria.[121]

Green synthesis using plant extracts

In contrast to microorganisms, plants have been exhaustively used,as apparent from Table 2. This is because plant phytochemicals show greater reduction and stabilization.[122] *Eugenia jambolana* leaf extract was used to synthesize AgNPs that indicated the presence of alkaloids, flavonoids, saponins, and sugar compounds.[123] Bark extract of *Saraca asoca* indicated the presence of hydroxylamine and carboxyl groups.[124] AgNPs using leaves of *Rhynchotechum ellipticum* were synthesized, and the results indicated the presence of polyphenols, flavonoids, alkaloids, terpenoids, carbohydrates, and steroids.[125] *Hesperidin*was used to form AgNPs of 20–40 nm.[126] Phenolic compounds of pyrogallol and oleic acid were reported to be essential for the reduction of silver salt to form NPs.[127] Pepper-leaf extract acts as a reducing and capping agent in the formation of AgNPs of 5–60 nm.[128] Fruit extracts of *Malus domestica* acted as a reducing agent. Similarly, *Vitis vinifera*,[39] Andean blackberry,[129] *Adansonia digitata*,[130] *Solanum nigrum*,[131] *Nitraria schoberi*132 or multiple fruit peels have also been reported for AgNP synthesis.[133] Combinations of plant extracts have also been reported.[134] Some other reductants used for $AgNO_3$ are polysaccharide,[135] soluble starch,[136] natural rubber,[137] tarmac,[138] cinnamon,[25] stem-derived callus of green apple,[25] red apple,[139] egg white,[140] lemon grass,[141] coffee,[142] black

Table 2 Plant-mediated synthesis of AgNPs

Plant (Family)-Local Name	Part	Characterization	Phytoconstituents Present in plant	Size of AgNPs	Shape of AgNPs	Reference
Acacia nilotica (Fabaceae) — babul	Pod	UV-vis, HRTEM, FTIR, DLS, EDS, XRD, ζ-potential	Gallic acid, ellagic acid, epicatechin, rutin	HRTEM (20–30 nm)	Distorted spherical	151
Ocimum sanctum (Lamiaceae) — tulsi	Fresh leaf	UV-vis, TEM, XRD, FTIR	Alkaloids, glycosides, tannins, saponins, aromatic compounds	TEM (3–20 nm, average 9.5 nm)	Spherical	152
Citrullus colocynthis (Cucurbitaceae) — bitter apple	Fresh leaf	UV-vis, FTIR, AFM	NA	AFM (31 nm)	Spherical	153
Coccinia grandis (Cucurbitaceae) — ivy gourd	Fresh leaf	UV-vis, HRTEM, SEM, XRD, FTIR, TGA, EDS	Triterpenoids, alkaloids, tannin	TEM (20–30 nm)	Spherical	154
Pterocarpus santalinus (Fabaceae) — sandalwood	Fresh leaf	UV-vis, SEM, XRD, FTIR, AFM, EDX	NA	SEM (20–50 nm, average 20 nm), AFM (41 nm)	Spherical	155
Coleus aromaticus (Lamiaceae) — borage	Fresh leaf	UV-vis, XRD, FTIR, EDAX	Carvacrol, caryophyllene, patchoulene, flavonoids	SEM (40–50 nm)	Spherical	156
Jatropha curcas (Euphorbiaceae) — physic nut	Seed	UV-vis, HRTEM, XRD	NA	HRTEM (1,550 nm) at 10^{-3} M and 30–50 nm at 10^{-2} M	Spherical (at 10^{-3} M), unevenly shaped (at 10^{-2} M)	157
Melia dubia (Meliaceae) — malai vembu	Fresh leaf	UV-vis, TEM, SEM–EDS, XRD	Alkaloids, carbohydrates, glycosides, phenolic compounds, tannins, gums, mucilages	XRD (average 7.3 nm)	Irregular, but mostly spherical	158
Capsicum annuum (Solanaceae) — peppers	Fresh leaf	UV-vis, TEM, FTIR, SAED, XRD, XPS, CV, DPV	Proteins/enzymes, polysaccharides, amino acids, vitamins	TEM (10±2 nm at 5 hours)	Spherical	159
Annona squamosa (Annonaceae) — sweetsops	Young leaf	UV-vis, XRD, TEM, FTIR, EDS, ζ-potential	Glycoside, alkaloids, saponins, flavonoids, tannins phenolic compounds, phytosterols	TEM (20–100 nm)	Spherical	160
Camellia sinensis (Theaceae) —tea	Dried leaf	XRD, TEM, FTIR	NA	Debye–Scherrer equation (3.42 nm), TEM (2–10 nm, average 4.06 nm)	Spherical	161

(*Continued*)

Table 2 (Continued).

Plant (Family)-Local Name	Part	Characterization	Phytoconstituents Present in plant	Size of AgNPs	Shape of AgNPs	Reference
Citrus sinensis (Rutaceae) — orange	Peel extract	UV-vis, TEM, FESEM, FTIR, XRD, EDAX	Vitamin C, flavonoids, acids, volatile oils	XDS (33±3 nm at 25°C, 8±2 nm at 60° C,), HRTEM (35±2 nm)	Spherical	38
Lantana camara (Verbenaceae) — wild/red sage	Fresh leaf	UV-vis, TEM, FESEM, FTIR, XRD, XPS, AFM, SAED	Phenolics, flavonoids, terpenoids, alkaloids, lipids, proteins, carbohydrates	FESEM (34 nm), AFM (17–31 nm), TEM (14–27 nm), XRD (11–24 nm), SAED (~14 nm)	Spherical	162
Coriandrum sativum (Apiaceae) — coriander	Fresh leaf	UV-vis, TEM, FTIR, XRD, Z-scan techniques	Carotene, thiamine, riboflavin, niacin, oxalic acid, sodium	TEM (8–75 nm, average 26 nm)	Spherical	163
Aloe vera (Asphodelaceae) — first-aid plant	Fresh leaf	UV-vis, TEM, FTIR, AFM, NIR absorption spectroscopy	NA	TEM (15.2±4.2 nm)	Spherical	164
Memecylon edule (Melastomataceae) — delek bangas	Shade-dried leaf	UV-vis, TEM, SEM, FTIR, EDAX	Triterpenes, tannins, flavonoids, saponin	TEM (50–90 nm)	Square	165
Hibiscus rosa-sinensis (Malvaceae) — rose mallow	Leaf	UV-vis, TEM, FTIR, XRD, SAED	Proteins, vitamin C, organic acids (essentially malic acid), flavonoids, anthocyanins	TEM (average size 13 nm), Scherrer equation (13 nm)	Spherical	166
Cinnamomum camphora (Lauraceae) — camphorwood	Fresh leaf	UV-vis, TEM, SEM, XRD, AFM	NA	TEM (55–80 nm, average diameter 64.8 nm)	Quasispherical	55
Piper longum (Piperaceae) — pipli	Dried fruit powder	UV-vis, SEM, FTIR, DLS	Piperidine, alkaloids, tannins, dihydrostigmasterol, sesamim, terpenines	DLS (15–200 nm, average 46 nm)	Spherical	167
Sesbania grandiflora (Fabaceae) — hummingbird tree	Fresh leaf	UV-vis, FE-TEM, FTIR, XRD, SAED	Carboxylic compounds, flavonoids, terpenoids, polyphenols	TEM (10–50 nm, average 24.1 nm), XRD (18.52 nm)	Spherical	168
Moringa oleifera (Moringaceae) — drumstick tree	Fresh stem bark	UV-vis, TEM, HRSEM, FTIR, DLS, AFM	Phenols, β-sitosterol, caffeoylquinic acid, quercetin, kaempferol	HRTEM (average size 40 nm), DLS (38 nm), SEM (40 nm)	Spherical and pentagonal	169
Origanum vulgare (Lamiaceae) — oregano	Leaves	UV-vis, FESEM, FTIR, XRD, DLS, ζ-potential	NA	FESEM (63–85 nm), Scherrer formula (65 nm), DLS (136±10.09 nm)	Spherical	170

(*Continued*)

Table 2 (Continued).

Plant (Family)-Local Name	Part	Characterization	Phytoconstituents Present in plant	Size of AgNPs	Shape of AgNPs	Reference
Vitex negundo (Lamiaceae) — Chinese chaste tree	Fresh leaf	UV-vis, TEM, FESEM, FTIR, XRD, EDX	Alkaloids, glycosides, flavonoids, phenolic compounds, reducing sugars, resin tannins	TEM (5–47 nm)	Spherical	171
Tephrosia tinctoria (Fabaceae) — alu pila	Shade dried stem extract	UV-vis, TEM, SEM, FTIR	Phenol, flavonoids	TEM (73 nm)	Spherical	172
Mimusops elengi (Sapotaceae) — Spanish cherry	Seed	UV-vis, TEM, FTIR, XRD, HPLC	Ascorbic acid, gallic acid, pyrogallol, resorcinol	TEM (12.8–30.48 nm)	Spherical	173
Alternanthera dentate (Amaranthaceae) — Joseph's coat	Leaf	FTIR, TEM, SEM, XRD	NA	SEM (50–100 nm)	Spherical	174
Sesuvium portulacastrum (Aizoaceae) — salt marsh	Leaf	UV-vis, TEM, FTIR, XRD	NA	TEM (5–20 nm)	Spherical	175
Dalbergia spinosa (Faboideae) — liana	Shade-dried leaf	UV-vis, TEM, FTIR, DLS	Flavonoids, isoflavonoids, neoflavonoids, steroids, terpenoids	TEM (18±4 nm)	Spherical	176
Sambucus nigra (Adoxaceae) — European black elderberry	Frozen fruit	UV-vis, FTIR, XRD, ζ-potential	Polyphenol anthocyanins	TEM (20–80 nm)	Spherical	177
Millingtonia hortensis (Bignoniaceae) — neem	Dried leaf	NA	NA	2–8 nm	NA	178
Syzygium cumini (Myrtaceae) — jamun	Air-dried seed	UV-vis, SEM, XRD, FTIR, DLS, ζ-potential, HPLC	Gallic acid, *p*-coumaric acid, quercetin, 3,4-dihyroxybenzoic acid	SEM (40–100 nm), average 43.02 nm, Z-average 43±1.25	Irregular spherical contour	179
Mukia maderaspatana (Cucurbitaceae) — Madras pea pumpkin	Fresh leaf	UV-vis, FESEM, FTIR, XRD, ART	NA	FESEM (13–34 nm), Debye–Scherrer formula (64 nm)	Spherical	180
Nelumbo nucifera (Nelumbonaceae) — sacred lotus	Fresh leaf	UV-vis, TEM, SEM, FTIR, XRD	Betulinic acid, steroidal pentacyclic triterpenoid, procyanidins	TEM (25–80 nm, average 45 nm), SEM (25–80 nm)	Spherical (TEM), triangular (SEM)	181

(*Continued*)

Table 2 (Continued).

Plant (Family)-Local Name	Part	Characterization	Phytoconstituents Present in plant	Size of AgNPs	Shape of AgNPs	Reference
Rhizophora mucronata (Rhizophoraceae) — mangrove	Leaf	UV-vis, FTIR, XRD, AFM	Alkaloids, flavonoids, polyphenols, terpenoids	AFM (60–95 nm)	Spherical	182

Abbreviations: CV, Cyclic voltammograms; ART, total reflectance technique; NPs, nanoparticles; UV-vis, ultraviolet-visible spectroscopy; TEM, transmission electron microscopy; SEM, scanning electron microscopy; FESEM, field-emission SEM; HREM, high-resolution transmission electron microscopy; XRD, X-ray diffraction; FTIR, Fourier-transform infrared spectroscopy; AFM, atomic force microscopy; HPLC, high-performance liquid chromatography; DLS, dynamic light scattering; EDX, energy-dispersive X-ray (spectroscopy); EDAX, ED X-ray analysis; SAED, selected-area electron diffraction; TGA, thermogravimetric analysis; NA, not available; CV, ; ART, .

tea,[143] and *Abelmoschus esculentus* juice.[144] Besides these, an extensive diagram representing different parts of different plant leaves, eg, peel, seed, fruit, bark, flower, stem, and root, also used in nanoformulations, is given in Figure 3. Green synthesis is economical and innocuous.[30,38,150]

Biosynthesis using microorganisms

Bacteria-mediated synthesis of AgNPs

Microorganisms like fungi, bacteria, and yeast are of huge interest for NP synthesis; however, the process is threatened by culture contamination, lengthy procedures, and less control over NP size. NPs formed by microorganisms can be classified into distinct categories, depending upon the location where they are synthesized.[183] Otari et al synthesized AgNPs intracellularly using Actinobacteria *Rhodococcus*sp. NCIM 2891.[184] Kannan et al biosynthesized AgNPs using *Bacillus subtillus* extracellularly.[185] Table 3 provides some illustrative examples of the synthesis of AgNPs using different bacterial strains.

Alga-mediated synthesis of AgNPs

A diverse group of aquatic microorganisms, algae have been usedsubstantiallyand reported to synthesize AgNPs. They vary in size, from microscopic (picoplankton) to macroscopic (Rhodophyta). AgNPs were synthesized using microalgae *Chaetoceros calcitrans*, *C. salina*, *Isochrysis galbana*, and *Tetraselmis gracilis*[199] *Cystophora moniliformis* marine algae were used by Prasad et al as a reducing and stabilizing agent to synthesize AgNPs.[200] Table 4 illustrates some examples of the micro and macro-algae used for AgNPs synthesis.

Fungus-mediated synthesis of AgNPs

Extracellular synthesis of AgNPs using fungi is also a viable alternative, because of their economical large-scale production. Fungal strains are chosen over bacterial species, because of their better tolerance and metal-bioaccumulation property. Table 5 gives some of the fungal strains used for AgNP synthesis.

Synthesis from miscellaneous sources

Nanotechnology has placed DNA on a recent drive to be used as a reducing agent.[215] Strong affinity of DNA bases for silver make it a template stabalizer[216] AgNPs were synthesized on DNA strands and found to bepossiblylocated at N^7 guanine and phosphate.[217] Another attempt

Figure 3 Plant mediated synthesis of AgNPs.

Table 3 Bacteria-mediated synthesis of AgNPs

Reducing agent: bacterial strain	Characterization	Size	Shape	Gram$^+$/ Gram$^-$	Reference
Serratia nematodiphila	UV-vis, SEM, EDS	SEM (65–70 nm)	Spherical	Gram$^+$	186
Bacillus stearothermophilus	UV-vis, TEM, FTIR, DLS	TEM (9.96–22.7 nm, average 14±4 nm)	Spherical	Gram$^+$	187
Bacillus strain CS11	UV-vis, TEM	TEM (42–92 nm)	NA	Gram$^+$	188
Exopolysaccharide-producing strain *Leuconostoc lactis*	UV-vis, TEM, SEM, AFM, XRD, TGA-DTA, Raman spectroscopy	TEM (30–200 nm, average 35 nm), AFM (average 30 nm)	Spherical	Gram$^+$	189
Escherichia coli	NA	NA	NA	Gram$^-$	190
Streptomyces hygroscopicus	UV-vis, TEM. EDXA, FE XRD, BioAFM	TEM (20–30 nm)	More or less spherical	Gram$^+$	191
Pediococcus pentosaceus, Enterococcus faecium, Lactococcus garvieae	NA	NA	NA	NA	192
Bacillus cereus, B. subtilis, Escherichia coli, Enterobacter cloacae, Klebsiella pneumonia, Lactobacillus acidophilus, Staphylococcus aereus, Pseudomonas aeroginosa	UV, TEM, EDS	TEM (28.2−122 nm, average 52.5 nm)	NA	Gram$^+$ and Gram$^-$	193
Morganella morganii RP42	UV, TEM, XRD, SAED	TEM (10–50 nm)	Quasispherical	Gram$^-$	194
Escherichia coli	UV, FTIR, XRD	TEM (average 50 nm)	Spherical	Gram$^-$	195
Pseudomonas antarctica, P. proteolytica, P. meridiana, Arthrobacter kerguelensis, A. gangotriensis, Bacillus indicus, B. cecembensis	UV, TEM, AFM	TEM (6.1±2.8 nm), AFM (4.6–13.3 nm)	Spherical	Gram$^+$ and Gram$^-$	196
Staphylococcus aureus	UV, AFM	AFM (160–180 nm)	Irregular	Gram$^+$	197
Bacillus brevis (NCIM 2533)	UV-vis, SEM, FTIR, AFM, TLC	SEM (22–60 nm, average 41 nm), AFM (average 68 nm)	Spherical	Gram$^+$	198

Abbreviations: NPs, nanoparticles; UV-vis, ultraviolet-visible (spectroscopy); TEM, transmission electron microscopy; SEM, scanning electron microscopy; FESEM, field-emission SEM; HRSEM, high-resolution TEM; XRD, X-ray diffraction; FTIR, Fourier-transform infrared (spectroscopy); AFM, atomic force microscopy; HPLC, high-performance liquid chromatography; DLS, dynamic light scattering; EDX, energy-dispersive X-ray (spectroscopy); EDAX, ED X-ray analysis; SAED, selected-area electron diffraction; TGA, thermogravimetric analysis; NA, not available; TLC, thin-layer chromatography.

Table 4 Alga-mediated synthesis of AgNPs

Reducing agent: alga strain	Characterization	Size	Shape	Algae type	Macro/ microalgae	Reference
Sargassum wightii Greville	UV, TEM, XRD, FTIR	TEM (8–27 nm)	Spherical	Brown	Macroalgae	201
Caulerpa racemosa	UV, TEM, FTIR, XRD	TEM (10 nm)	Spherical and triangular	Green	Macroalgae	202
Polysaccharide extracted from algae: *Pterocladia capillacae*, *Jania rubins*, *Ulva fasciata*, *Colpmenia sinusa*	UV, TEM, FTIR	TEM (7, 7, 12, and 20 nm for *U. fasciata*, *P. capillacae*, *J. rubins*, and *C. sinusa*, respectively)	Spherical	Red and green	Macroalgae	203
Chaetomorpha linum	UV-vis, SEM, FTIR	SEM (3–44 nm, average ~30 nm)	Varied	Green	Macroalgae	204
Chaetoceros calcitran, *Chlorella salina*, *Isochrysis galbana*, *Tetraselmis gracilis*	UV, SEM	SEM (53.1–73.9 nm)	NA	Green	Microalgae	199
Gelidium amansii	UV-vis, SEM, FTIR	SEM (27–54 nm)	Spherical	Red	Macroalgae	205

Abbreviations: NPs, nanoparticles; UV-vis, ultraviolet-visible (spectroscopy); TEM, transmission electron microscopy; SEM, scanning electron microscopy; XRD, X-ray diffraction; FTIR, Fourier-transform infrared (spectroscopy).

Table 5 Fungus-mediated synthesis of AgNPs

Fungal species used	Characterization	Size	Shape	Reference
Fusarium oxysporum	UV-vis, TEM, FTIR	TEM (5–50 nm)	Spherical and few triangular	206
Verticillium	UV-vis, TEM, SEM, EDX	TEM (25–12 nm)	Spherical	207
Aspergillus fumigatus	UV-vis, TEM, XRD	TEM (5–25 nm)	Spherical and triangular	208
Penicillium fellutanum	UV-vis, TEM	TEM (5–25 nm)	Spherical	209
Aspergillus flavus	UV-vis, TEM, FTIR, XRD	TEM (8.92±1.61 nm)	NA	210
Fusarium semitectum	UV-vis, TEM, FTIR, XRD,	TEM (10–60 nm)	Spherical	211
Alternaria alternata	UV-vis, TEM, SEM, FTIR, EDX	SEM (20–60 nm, average 32.5 nm)	Spherical	212
Rhizopus stolonifer	UV-vis, TEM, SEM, FTIR, AFM	TEM (3 and 20 nm)	Spherical	213
Phanerochaete chrysosporium	UV-vis, TEM, FTIR, AFM, TLC	TEM (34–90 nm)	Spherical and oval	214

Abbreviations: NPs, nanoparticles; UV-vis, ultraviolet-visible (spectroscopy); TEM, transmissionelectron microscopy; SEM, scanning electron microscopy; EDX, energy-dispersiveX-ray (spectroscopy); XRD, X-ray diffraction; FTIR, Fourier-transform infrared (spectroscopy); AFM, atomic force microscopy; TLC, thin-layer chromatography.

was made with calf-thymus DNA to synthesize AgNPs.[218] Similarly, silver-binding peptides were identified and selected using a combinatorial approach for NP synthesis.[219]

Bioactivities

Antibacterial activity of AgNPs

As a broad-spectrum antibiotic, silver is highly toxic to bacteria. It has been of great interest for the past couple of years, due to its wide spectrum of pharmacological activities, with applications in the fields of agriculture, textiles, and especially medicine. Some attributed contributions are given in Table 6.

Antifungal activity of AgNPs

Resistant pathogenic activities of bacteria and fungi have increased invasive infections at an alarming rate. Ultimately, the subsequent need is to find more potent antifungal agents. Table 7 provides some examples from the literature that have reported antifungal properties of green synthesized AgNPs.

Anticancer activity of AgNPs

The paramount need of today is the synthesis of effective anticancer treatment, as cardiovascular at the top most; cancer is the second most leading cause of human dysphoria. Therefore the synthesis of anticancer agents isof theutmost necessity. AgNPs also possess substantial anticancer activities,[239] as shown in Table 8.

Anti-inflammatory activity of AgNPs

AgNPs of 20–80 nm were synthesized using *Sambucus nigra* (blackberry) extract. The NPs were characterized using ultraviolet-visible and Fourier-transforminfrared

Table 6 Antibacterial activities of AgNPs

Biological entity	Testmicroorganism	Method	Reference
Citrullus colocynthis	*Escherichia coli*	Agar diffusion method	153
Pterocarpus santalinus	*E. coli*	NA	154
Madhuca longifolia flower extract	*Bacillus cereus, Staphylococcus saprophyticus, E. coli, Salmonella typhimurium*	Agar well diffusion method	220
Aspergillus clavatus fungus	*E. coli, Pseudomonas aeruginosa*	NA	221
Chenopodium murale leaf extract	*E. coli*	Cup–plate agar-diffusion method	222
Iresine herbstii leaf extract	*Staphylococcus aureus, Enterococcus faecalis, E. coli*	Agar-diffusion method	223
Beetroot	*E. coli, P. aeruginosa, Staphylococcus, Streptococcus*	NA	224
Dioscorea bulbifera plant	*St. aureus, E. faecalis, E. coli*	Diskc diffusion method	225
Rosa indica flower petals	*E. coli, P. aeruginosa, Staphylococcus, Streptococcus*	Agaer well diffusion method	226
Ocimum tenuiflorum plant	NA	Agar well diffusion method	227
Cassia fistula fruit extract	*E. coli, Klebsiella pneumonia*	Disk diffusion method	
Chitosan polymer	*S. aureus*	Parallel-streak method, colony-counting method	114
Chitosan polymer	*E. coli* (ATCC 25922), *S. aureus* (ATCC 6538)	Agar disk diffusion method	228
Oxidized AgNPs	*E. coli*	Cup–plate agar-diffusion method	229
Gallic acid	*E. coli*	Microdilution method	230
AgNPs	*E. coli, Vibrio cholerae, P. aeruginosa, Salmonella typhi*	Agar diffusion method	73

Abbreviations: NPs, nanoparticles; NA, not available.

Table 7 Antifungal properties of AgNPs

Biological entity used for reduction	Fungal speciesused as test organism	Characterization	Reference
Green and black tea leaves	*Aspergillus flavus, A. parasiticus*	UV-vis, SEM, FTIR, EDX	231
Waste dried grass	*Fusarium solani, Rhizoctonia solani*	UV-vis, TEM, XRD	232
*Dodonaea viscosa*and *Hyptis suoveolens* leaf extracts	*Candida albicans*(ATCC 90028), *C. glabrata*(MTCC 3019), *C. tropicalis*(MTCC 184), clinical isolate (MTCC 11,802)	FTIR, SEM, XRD, DLS, ζ-potential	233
Cysteine and maltose	*C. albicans*(ATCC 10231), *C. parapsilosis* (ATCC 22019)	UV-vis, TEM, SEM, DLS	234
Lignin	*A. niger*	UV-vis, TEM, SEM, EDS, XRD	235
Cyanobacterium *Nostoc* strain HKAR2 cell extract	*A. niger, Trichoderma harzianum*	UV-vis, TEM, SAED, SEM, FTIR, XRD, ζ-potential	236
Bergenia ciliate plant extract	*A. fumigatus* (FCBP 66), *F. solani*(FCBP 0291), *A. niger*(FCBP 0198), *A. flavus*(FCBP 0064)	UV-vis, SEM, FTIR	237
Trifolium resupinatum seed extract	*Neofusicoccum parvum, R. solani*	UV-vis, TEM FTIR, XRD	238

Abbreviations: NPs, nanoparticles; UV-vis, ultraviolet-visible (spectroscopy); TEM, transmission electron microscopy; SEM, scanning electron microscopy; XRD, X-ray diffraction; FTIR, Fourier-transform infrared (spectroscopy); DLS, dynamic light scattering; EDX, energy-dispersive X-ray (spectroscopy); EDAX, ED X-ray analysis; SAED, selected-area electron diffraction.

Table 8 Anticancer property of AgNPs

Biological entity used for reduction	Cancer cells under study	Characterization	Reference
Cleome viscosa fruit extract	Lung (A549) and ovarian (PA1) cancer cell lines	UV-vis, TEM, SEM, FESEM, EDAX, FTIR, XRD	240
Annona muricata leaf extract	Human fibroblasts isolated from dermis	UV-vis, TEM, XRD, DLS, ζ-potential	239
N,N,N-trimethyl chitosan chloride and poly-electrolyte complex	Colon cancer cell lines (HCT116) and Mammalian cell lines (African green monkey kidney cell lines (VERO cells)	HRTEM, FESEM, FTIR, EDX, XRD, ^{1}H NMR	241
Rheum Rhabarbarum fresh stem extract	Cervical carcinoma HeLa cell line	UV-vis, SEM, TEM, FTIR, EDX, TGA, XRD, ζ-potential	242
Matricaria chamomilla	A549 lung cancer cells	UV-vis, TEM, FESEM, FTIR, XRD EDS, DLS	243
Zataria multiflora leaf extract	Cervical carcinoma cells (HeLa cell line)	UV-vis, TEM, FTIR, EDS, DLS, ζ-potential	96
Phoenix dactylifera hair-root extract	Human breast cancer (MCF7 cell line)	UV-vis, TEM, FTIR, XRD, FESEM, EDAX, Nanophox spectra analysis, PCCS	244

Abbreviations: NPs, nanoparticles; UV-vis, ultraviolet-visible (spectroscopy); TEM, transmission electron microscopy; SEM, scanning electron microscopy; FESEM, field-emission SEM; HRTEM, high-resolution TEM; XRD, X-ray diffraction; FTIR, Fourier-transform infrared (spectroscopy); AFM, atomic force microscopy; HPLC, high-performance liquid chromatography; DLS, dynamic light scattering; EDX, energy-dispersive X-ray (spectroscopy); EDAX, ED X-ray analysis; TGA, thermogravimetric analysis; PCCS, .

spectroscopy and X-ray diffraction, and further investigations were carried out for anti-inflammatory effects, both in vitro and in vivo, against Wister rats.[177]

Antiviral activity of AgNPs

Multidimensional biological activities of AgNPs provide significant antiviral potentiality. HEPES buffer was used to synthesize NPs of 5–20 nm. Postinfection antiviral activity of AgNPs was evaluated using Hut/CCR5 cells using ELISA. AgNPs inhibited HIV1 retrovirus 17%–187% more than the reverse-transcriptase inhibitor azidothymidine triphosphate[245] Polysulfone-incorporated AgNPs manifested antiviral and antibacterial activity. This was attributed to the release of sufficient silver ions from the membrane, acting as an antiviral agent.[246]

Cardioprotection

Themedicinal herb neem (*Millingtonia hortensis*) has been used to synthesize AgNPs, and showed significant cardioprotective properties in rats.[178]

Wound dressing

anotechnology has contributed significantly in the area of wound healing, as healing is attributed to increased anti-inflammatory and antimicrobial activity. A cotton fabric treated with NPs of size 22 nm exhibited potent healing power.[247] Another advance in this area was made with the impregnation of AgNPs into bacterial cellulose for antimicrobial wound dressing. *Acetobacter xylinum* (strain TISTR 975) was used to produce bacterial cellulose, which was immersed in silver nitrate solution. It was effective against both Gram-positive and Gram-negative bacteria.[248] The performance of a polymer is increased by the introduction of inorganic NPs. In this regard, polyurethane solution containing silver ions was reduced by dimethylformamide using electrospinning. Collagen was introduced to increase its hydrophilicity. This collagen sponge incorporatingd AgNPs had enhanced wound-healing ability in an animal model.[249] Most recently, Jacob et al biosynthesized nanoengineered tissue impregnated with AgNPs, which significantly prevented borne bacterial growth on the surface of tissue and could help in controlling health-associated infections.[250]

Conclusion

Nature has its own coaching manners of synthesizing miniaturized functional materials. Increasing awareness of green chemistry and the benefit of synthesis of AgNPs using plant extracts can be ascribed to the fact that it is ecofriendly, low in cost, and provides maximum protection to human health. Green synthesized AgNPs have unmatched significance in the field of nanotechnology. AgNPs cover a wide spectrum of significant pharmacological activities, and the cost-effectiveness provides an alternative to local drugs. Besides plant-mediated green synthesis, special emphasis has also been placed on the diverse bioassays exhibited by AgNPs. This review will help researchers to develop novel AgNP-based drugs using green technology.

Author contributions

All authors contributed to data analysis, drafting or revising the article, gave final approval of the version to be published, and agree to be accountable for all aspects of the work.

Disclosure

The authors report no conflicts of interest in this work.

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