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Green Synthesis of Silver Nanoparticles from Medicinal Plants and Their Biological Applications: A Review

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Review Article

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ABSTRACT

The manufacture of metal nanoparticles using plant extracts is one of the simplest, most useful, economical and environmentally advantageous approaches to decrease the usage of hazardous substances. Since the earliest days of human history, silver and silver salts have been employed, but silver nanoparticles (Ag NPs) have just recently reached light. Particularly in agriculture and medicine, these have been used as antibacterial, antifungal, and antioxidants. The current research on the environmentally friendly manufacture of silver nanoparticles (AgNPs) utilising various plant extracts and their potential use as antibacterial agents is summarised and explained in this review. The main objective is to provide a comprehensive and systematic review of how various factors affect the synthesis of green Ag NPs with antimicrobial properties. These factors include the type

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and concentration of plant extracts and phytochemicals, the solvent and temperature of extraction, and the temperature, pH, time, and concentration of the reaction. Recent advances in using different plants to yield Ag NPs with different sizes, shapes, and stabilities have been presented. It is currently demonstrated that Ag NPs prevent many bacteria and fungi from growing and multiplying by combining Ag/Ag+ with the biomolecules found inside the microbial cells. Antioxidants and reactive oxygen species that might be produced by Ag NPs, which, by preventing cell replication, cause apoptosis and cell death. SEM and TEM images of the nanoparticle-pathogen solution show that Ag NPs may enter cells and break through the cell wall since they are smaller than microorganisms. It has similarly been established that lesser Nps present additional risks than superior ones. Additionally, Ag NPs are used in packaging to prevent microbial contamination of food products. Ag NPs' toxicity is influenced by the size, concentration, pH of the media, and length of pathogen exposure. Comprehensive details have also been provided on the biogenic AgNPs' shape- and size-dependent antibacterial properties as well as the improved antimicrobial activities caused by the synergistic interaction of AgNPs with well-known commercial antibiotic medicines.

Keywords: Nanoparticles; green synthesis; antimicrobial; antioxidant; medicinal plant; algae.

1. INTRODUCTION

The design, synthesis, characterization and use of constituents at ranges in size from 1 to 100 nanometres, constitute the interdisciplinary area of nanotechnology. Nanotechnology has great promise for a number of industries, including biotechnology, engineering, medicine, and agriculture. Nanotechnology dates back to the earliest civilizations, when people employed nanoparticles without fully understanding their properties. For instance, in India between the sixth and third century BC, carbon nanotubes were utilised to coat pottery shards [1]. Another illustration is the Lycurgus cup, a Roman glass object constructed with gold and silver nanoparticles that changes colour depending on the light source [2]. According to Sarsar et al. [3], the word "nanotechnology" refers to the production, representation, handling and use of constructions by regulating form and size at the nanoscale. Numerous industries, including nanomedicine, nanoelectronics, nanomaterials, nanosensors, nanocatalysis and nanobiotechnology, have embraced nanotechnology. Quantum dots, carbon nanotubes, graphene, nanoparticles, nanowires, nanofibers, nanocomposites, and nanodevices are a few examples of items made with nanotechnology. Additionally, unique functional systems, materials, and electronic devices with improved performance and usefulness may be made using nanotechnology.

There are numerous advantages for society from the constantly evolving and interesting science of nanotechnology. However, it also presents various difficulties and dangers, including ethical conflicts, adverse effects on the environment, health concerns, implications for society and regulatory frameworks. Understanding the basics, advancements, potential applications, and limitations of nanotechnology is therefore essential. Nanotechnology is the maximum active field of investigation in physical knowledge due to the tremendous rise in nanoparticle (NP) manufacturing on a worldwide scale. Nanoparticles interact with bacteria, plants and animals through unique features that rely on their size, shape and morphology [4,5,6,7,8,9]. According to certain qualities, shape and structure, NPs exhibit completely new or improved properties [10,11,12]. In general, NPs may be divided into inorganic and organic NPs. While inorganic tiny particles also include semiconductors, metallic NPs and magnetic NPs, organic NPs include carbon NPs. As they offer outstanding properties with practical flexibility, Gold and Ag NPs are gaining popularity [13]. Because of their tremendous surface zone, Ag-NPs display significant biological responsiveness, catalytic action and atomic behaviours when contrasted with larger components with a comparable chemical structure [14].

With regard to a variety of microbes, silver nanoparticles (Ag NPs) have demonstrated outstanding bactericidal characteristics [15,16,17]. They are produced from a variety of angles, frequently in order to examine their morphology or other physical traits. Though they did so unintentionally, several writers have mistakenly employed chemical technique [18] for green synthesis. Because they are used in electronics, catalysis, pharmaceuticals, and biological processes to control the growth of microbes, Ag NPs are advantageous for the environment [19]. Because of the possibility for usage in catalytic processes [20], the production of Ag-NPs has attracted a lot of interest, in plasmonics [21], optoelectronics[22], biological sensors [23, 24], antimicrobial activities [25,26], DNA sequencing [27], SERS [28], environment adjustment and pollution control [29], clean water technology [30], energy generation [31], information storage [32] and biomedical applications [33]. Owing to the production of NPs, which has revealed the promise of nanotechnology during the previous 10 years, they have seen significant advancements in that sector [34].

Bacteria, fungi, yeast, actinomycetes and plant extracts are all used in the biological production of Ag NPs [19,35,36,37]. In addition to enzymes, a variety of plant components, including the different parts of plants, have recently been employed to create gold and silver nanoparticles [4]. The process of production, nature of the solvent, concentration, potency of the reducing agent, and temperature all have an impact on the size, shape and stability of nanoparticles [4,6].

Ag NPs have a major position among all the nanoparticles created and characterized so far due to their innate ability to operate as an antibacterial agent even in the solid state. Even though its importance was understood much earlier, it was not fully utilised outside of its application in currency and Eastern medicine. An estimated 320 tonnes of Ag NPs are produced annually and employed in food, biosensing, and nanomedical imaging applications [38, 39]. Silver nanoparticles (AgNPs) are the subject of extensive research due to their wide range of applications in medical devices [40], pharmaceuticals [41], clothing [42] and water purification [43]. These applications include the adsorption of metals and pesticides [44,45].

Due to mutation, pollution and shifting conservational circumstances, the quantity of multidrug-resistant bacterial and viral stresses is constantly rising. Scientists are working to create medications for the treatment of such microbial diseases in an effort to get around this problem [46,47]. It has been discovered that certain metal salts and metal nanoparticles are efficient at preventing the development of numerous pathogenic bacteria. In the sequence of such metals that have been utilised as antibacterial agents from the dawn of time, silver and Ag NPs have a significant position [48,49].

The most popular method to generate nanoparticles is chemical reduction, which involves an organic solvent like ethylene glycol [50], and reducing agents like hydrazine [51], sodium borohydride [52], trisodium citrate [53] and ascorbate [54]. Since chemical reduction produces low yields, necessitates costly purifying developments and consumes a lot of power, ensuring the development of cleaner and safer technology was necessary. This led to the development of green synthesis, which uses microorganisms (bacteria [55], fungus [56], yeast [57], actinomycetes [58] and plant extract [58] to reduce silver to silver nanoparticles. Microbes can produce nanoparticles either intracellularly [59] or extracellularly [57]. Because of the need to maintain aseptic conditions, the high expense of isolation, and the need to maintain the microbes in culture media, plants hold great potential as good sources of reducing agents for the synthesis of nanoparticles. Leaf [60], bark [61], seeds [62], roots [63] and other plant parts are employed in the synthesis of AgNPs.

2. GREEN SYNTHESIS OF SILVER NANOPARTICLES

Due to its potential for use in several industries, cost-effectiveness, and advantages for the environment, the synthesis of $AgNo_3$ has received a lot of interest recently. An outline has been made for some of the most recent research on this subject in this review, concentrating on the production processes, characteristics, and potential uses of silver nanoparticles made from plant and algae extracts (Fig. 1.). Plant extracts offer a natural supply of reducing and stabilising agents, such as phenolic chemicals, flavonoids, terpenoids, alkaloids and proteins, which is one of the key benefits of employing them to create silver nanoparticles. According to Rai et al. [26], these phytochemicals may convert silver ions to metallic silver and stop them from aggregating, creating stable and homogenous nanoparticles. In addition, plant extracts offer a plentiful, renewable, biocompatible and biodegradable alternative to traditional chemical processes that use toxic and dangerous materials. Due to their distinct characteristics and wide range of uses in fields including medicine, electronics, catalysis, and environmental remediation, AgNPs have become one of the most researched and

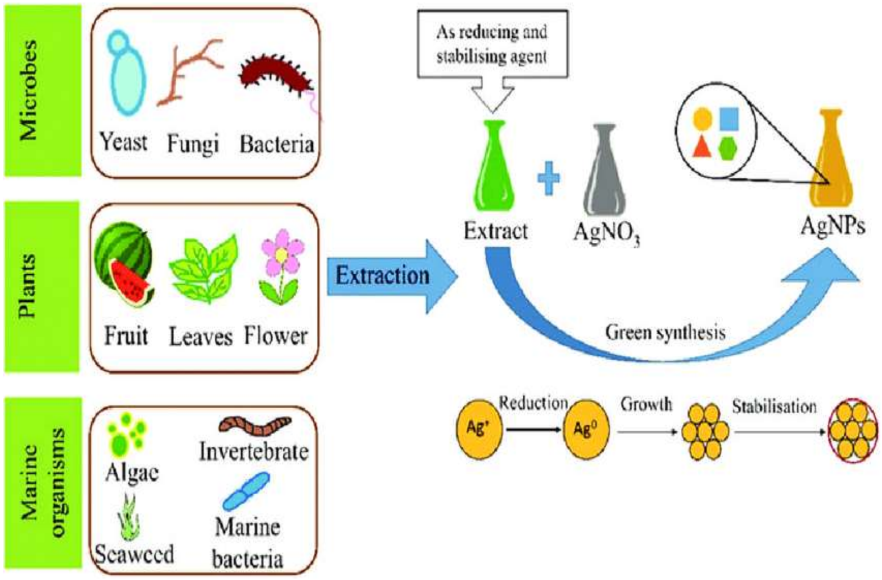

Fig.1. Schematic presentation for Ag-Nps by using different organisms

developed nanomaterials. However, the conventional techniques for making AgNPs sometimes involve dangerous chemicals and energy-intensive procedures, raising difficulties with safety and the environment. In response, green synthesis methods have drawn more attention as viable and environmentally acceptable alternatives [64].

In order to generate silver nanoparticles from plant extracts, an aqueous solution of silver nitrate is typically combined with the extract under a variety of temperature, pH, reaction time, and concentration conditions. Due to the SPR phenomenon, the colour of the solution changes from colourless to brownish-yellow or dark brown, which may be used to monitor the development of silver nanoparticles. A distinctive absorption peak in the visible area is produced by the SPR, which is a shared alternation of electrons on the surface of metal nanoparticles. The size, shape and distribution of the nanoparticles can have an impact on the location and strength of the SPR peak [65].

The type and concentration of the plant extract, the extraction solvent and temperature, the reaction temperature and time, the pH of the solution, and the absorption and ratio of the silver precursor are just some of the factors that might have an impact on the size and form of the silver nanoparticles made using plant extracts. In general, smaller nanoparticles are produced at greater plant extract concentrations, lower reaction temperatures and periods, higher pH levels and lower silver precursor concentrations and ratios. The nanoparticles' shapes might be spherical, triangular, rod-shaped, cubic, hexagonal, or floral. The kind and quantity of phytochemicals in the plant extract, as well as the circumstances surrounding the reaction, might have an impact on the form [66,67].

3. PROTOCOL FOR THE GREEN SYNTHESIS OFAgNO3

3.1 Synthesis of AgNo3from Bacteria

Due to its numerous uses in a variety of industries, such as medicine, electronics, catalysis, and environmental remediation, silver nanoparticles (AgNPs) have attracted a great deal of attention. The utilisation of bacteria as biological agents is one of the most sustainable and ecologically friendly ways to make AgNPs. The mechanics, benefits, difficulties, and possible applications of this green nanotechnology technique are highlighted in this in-depth analysis of the interesting world of bacterial AgNP synthesis [68,69]. Bacteria create inorganic compounds either extracellularly or intracellularly. They can therefore be utilised as prospective biofactories to produce precious metal NPs, such as Gold and Ag.

Ag-NPs are recognised to be biocompatible even if some bacteria are known to be Ag-resistant [11]. Therefore, it is advised to use these bacteria in the commercial recovery of silver from ore sources since they may aggregate silver on their cell walls [70]. At first, Klaus et al., [71] claimed that Pseudomonas stutzeri AG259, an Ag-resistant bacterial strain, was used to create Ag-NPs. Up to 200 nm, these cells assemble a significant number of Ag-NPs. Ag-NPs were synthesised by Shivaji et al., [72] from the culture supernatants of psychrophilic bacteria. Kalimuthu et al., [68] provided evidence that Bacillus licheniformis produces Ag-NPs. After adding an aqueous solution of AgNO3 to the biomass of B. licheniformis, the colour of the biomass changed from whitish-yellow to brown, indicating the formation of Ag-NPs with a size range of 50 nm that were stabilised by the enzyme nitrate. Ag-NPs were also made from Staphylococcus aureus culture supernatants by Nanda and Saravanan [73]. To immediately synthesised Ag-NPs, however, various Enterobacteriaceae bacteria's supernatants from culture may be used.

The study by Samadi et al., [74] it was revealed that employing the Proteus mirabilis PTCC 1710 bacterium to synthesise Ag-NPs produced substantial results. The extracellular and intracellular production of bacteria can be aided by several types of broth used for bacterial incubation. The microorganisms utilised to make green synthesis versatile, logical and a suitable choice for industrial-scale synthesis. Researchers examine the effects of various visible-light radiation exposures on the production of Ag-NPs from Silvernitrate during the photosynthesis process using the culture supernatant of Klebsiella pneumonia. According to research by Lee [75]; Shehata and Marr [76], aqueous Ag ions may also be reduced by a variety of bacteria, including Escherichia coli, Klebsiella pneumonia and Enterobacter cloacae (Enterbacteriaceae).

Within five minutes of the Ag ions entering into contact with the cell filtrate, Ag-NPs formed, demonstrating how much quicker the synthesis rate is Shahverdi et al., [37]. It is crucial to remember that bacteria continued to grow after Ag-NPs were produced in addition to the advantages. In addition to this, the restricted synthesised capacity and the slow progress of the range of sizes and shapes that may be created compared to conventional methods are the major drawbacks of employing bacteria as nano factories. As a result, the production of Ag-NPs was studied using fungi-based nano factories and chemical reactions involving plant and plant extract-based components [77].

3.2 Synthesis of Silver Nanoparticles from Fungi

Fungi, which are simpler to deal with in a research facility than bacteria, have the ability to produce metallic NPs due to their acceptance, high binding capacity, intracellular absorption and capability for metal bioaccumulation [58]. Fungi may be employed in a variety of ways to generate NPs, releasing influential digestive enzymes that are used to dissolve $AgNO_3$ solution [78]. Duran et al., [79] investigated the extracellular production of Ag-NPs using *F. oxysporum* and its antibacterial influence on textile fibres. According to Vigneshwaran et al., [42] *Aspergillus flavus* is a fungus that may be used to synthesise mono-disperse Ag-NPs. TEM measurements show that the regular size of the NPs is in the range of 8.92 ± 1.61. The fungus *Cladosporium cladosporioides* is used in the extracellular production of Ag-NPs and Balaji et al., [80] have observed this process. Using a different strategy, Kathiresan et al. [81] demonstrated *in vitro* generation of Ag-NPs using *Penicillium fellutanum* isolated from coastal mangrove sediment and $AgNO_3$ as a substrate.

According to research Ahmad et al., [82] when uncovered to *Fusarium oxysporum*, aqueous Ag ions are through an enzymatic process, decreased in solution, which causes the production of an extremely stable Ag hydrosol. The NPs are stabilised in solution by a fungus that secretes proteins and ranges in size from 5 to 15 nm. Bhainsa and D'Souza, [83] employed Aspergillus *fumigatus* to extracellularly synthesise mono-dispersed Ag-NPs at a high rate. In a separate method, Li et al.,[84] produced spherical Ag-NPs with an average size of 1–20 nm using *Aspergillus terreus*.

According to Mukherjee et al., [59] they followed the process to produce mono-dispersed Ag-NPs using the fungus *Verticillium*. When the fungal biomass was subjected to an aqueous solution of $AgNO_3$, the metal ions decreased intracellularly; the resultant nanoparticles, or NPs, have a spherical morphology and can range in size from 25 ± 12 nm. In contrast, fungal cells synthesised Ag-NPs with hexagonal, triangular, or spherical geometries below the surface, unlike bacteria. NPs do not form in solution during fungi-based synthesis; instead, they do so on the surface of the mycelia. The Silver nanoparticles were initially coated on the surface of the fungal cells as a result of the electrostatic relationship of charge-negative carboxylate groups in enzymes with positively energised Ag ions. Ag nuclei are formed as a result of the substance being condensed by the enzymes existing in cell membranes. With the help of the fungus *Trichoderma reesei*, Vahabi et al., [85] additionally produced Ag- NPs, which had a size range of 5–50 nm. Benefits like simpler subsequent processing, biomass treatment, and substantially greater production of protein are likely will substantially increase the profitability of this synthetic technique in contrast to bacteria when using fungus instead of bacteria to create standard nano factories. Ahmad et al., [82] used eukaryotic systems, especially fungi, to study the extracellular production of Ag-NPs and showed that released catalysts are accountable for the decrease. Up to this time, all fungi-based colour green reactions have been intracellular. Extracellular synthesis is beneficial since formed NPs cannot bind to biomass [79,80]. When compared to other kinds of microorganisms, fungi are utilised in green synthesis more frequently due to their ecological friendliness and simplicity of maintenance; for instance, white rot fungus are non-pathogenic and encourage the large-scale generation of Ag-NPs [86]. Another point in favours is the response at the top when using this approach. These investigations amply indicate the appropriateness and possibility of employing fungus for the significant synthesis of NPs, in contrast to bacteria. According to Naqvi et al., [87] Ag-NPs were recently discovered to be produced using the *A. flavus*fungus and to be joined with antibiotics to increase the biocidal usefulness against multidrug-resistant bacteria.

3.3 Synthesis of Silver Nanoparticles from Plants and Algae’s

For the effective production of nanoparticles, plant-related components and their metabolites have been employed successfully [4,88] (Table 1.). Beg et al. [89], reported on the current green synthesis of Ag NPs from *Pongamia pinnata* seed extract. An absorption maximum at 439 nm proved that nanoparticles were formed. The zeta potential of the evenly distributed nanoparticles, which had anormal size of 16.4 nm, was 23.7 mV, supporting their stability and dispersion. Investigation into the interaction of Ag NPs with human serum albumin revealed no change in a helix. The green synthesis of Ag NPs from the medicinal plant extract *Pelargonium endlicherianum* has recently been described by Karatoprak et al., [90] Gallic acid, apocyanin and quercetin from the plant function as reducing agents that generate silver nanoparticles. Moldovan et al., [91] reported on the Phyto mediated production of spherical Ag NPs from *Sambucus nigra* fruit extract. They were crystallised, according to an XRD examination. Investigating the *in vivo* antioxidant activity of Wistar rats revealed excellent results. It implies that adding natural phytochemicals to Ag NPs may guard cell proteins from the production of ROS. Additionally, an aqueous leaf extract of *Artocapusaltilis* was used to generate Ag NPs. They have a weak antibacterial and antioxidant effect.

Based on the emergence of a strong peak at 420 nm in the UV-vis region of the spectrum, *Thalictrum foliolosum* root extract mediated Ag NPs generation has been confirmed [92]. The face-cantered cubic shape of the 15–30 nm monodispersed spherical nanoparticle. Logaranjan et al., [93] reported on the regulated production of Ag NPs from *Aloe vera* plant extract and their antibacterial efficacy. The 420 nm UV-vis peak proved that silver nanoparticle production had occurred. Ag NPs with octahedral geometry and a size range of 5 to 50 nm were produced when the sample was microwave-irradiated. Ag NPs were shown to have between two and four times the antibacterial activity of frequently used antibiotics. It has also been possible to biosynthesize Ag NPs from the aqueous *Piper longum* fruit extract [94]. The average particle size of the nanoparticles, as assessed by SEM and a DLS analyser, was 46 nm. The nanoparticles were spherical in form. It is thought that the extract's polyphenol content stabilises silver nanoparticles. *In vitro*, the antioxidant capabilities of the fruit extract and the stabilised nanoparticles were shown. The floral extract of *P. longum* was shown to be less effective against pathogenic bacteria than the nanoparticles. The creation of Ag NPs from *Ceropegia thwaitesii* leaf extract was verified by the absorption of SPR at 430 nm. The crystalline nanoparticles have a diameter of over 100 nm [95].

In order to create Ag NPs of various sizes in colloidal form, plant extract from *Ocimum tenuiflorum, Solanum tricobatum, Syzygiumcumini, Centella asiatica*, and *Citrus sinensis* has been employed [96]. All nanoparticles were found to range in size from 22 to 65 nm. In solution, they were all stable and evenly distributed. In their research on the production of Ag NPs from an aqueous extract of *Alternanthera sessilis*. Niraimathi et al., [97] demonstrated that the extract includes alkaloids, tannins, ascorbic acid, carbohydrates and proteins that purpose as reducing as well as capping agents.

The extract's biomolecules also served to stabilise the silver nanoparticles. *Artocarpus heterophyllus* seed powder extract was used to make Ag NPs [98]. By using SEM, TEM, SAED, EDAX and IR spectroscopy, it was possible to identify the nanoparticles' shape and crystallisation state. They were discovered to be shaped differently. It was discovered that the extract included amino acids, amides and other compounds that served to generate silver nanoparticles. According to Puisoa et al., [99] the number of phytoconstituents in the berry juices was measured and these compounds were in charge of transforming silver ions into Ag NPs. In the UV-vis spectrum, lingonberry and cranberry containing silver nanoparticles both showed an absorbance peak at 486 nm and 520 nm, respectively.

The two absorption peaks cannot be attributed only to Ag NPs because of their differences; rather, they can also be partially attributed to various concentrations of the reducing substances found in the juices. However, the spectra showed that there were silver nanoparticles that were polydisperse. According to Puiso et al., [99], when water is exposed to UV rays, powerful oxidants and reductants are produced as byproducts of photolysis. They convert silver ions to silver oxide or Ag NPs. The oxidant and reductant that are produced by photolysis depend on the radiation dose and exposure duration, which may not be adequate to create enough oxidation-reduction chemicals to reduce Ag+ to Ag NPs or Ag_2O. This claim is false practically because Ag_2O cannot form since it needs a highly potent oxidising agent. On the other hand, whereas $AgNO_3$ alone is slowly reduced in water, the reaction moves forward quickly in the presence of reducing agents. Ag NPs' size, shape and agglomeration which are reflected in the UV-vis spectrahave an impact on the SPR (Surface Plasmon Resonance Study).

In hyperspectral microscopic images, Mock et al., [100] discovered several dispersed colours that are mostly caused by the various sizes and shapes of silver nanoparticles in the colloidal solution. The forms of the sphere, pentagon, round triangle and triangle have been associated with the colours blue, green, yellow and red, respectively. Oxalic acid was used as a reducing agent in Zaheer and Rafiuddin's,[18] paper on the synthesis of Ag NPs, which they misinterpreted for green synthesis. A change in colour of the solution that revealed an absorption peak at 425 nm in the UV-visible band proved the formation of nanoparticles. Additionally, monodispersed spherical Ag NPs were seen to generate a scattered silver coating on the container wall that sparkles and reflects light [101, 102]. The silver sheet is not consistent since the nanoparticles' sizes range from 7 to 19 nm. Because of the unusual form and size of the nanoparticles, it differs from a standard silver mirror. In fact, when $AgNO_3$ is exposed to a reducing agent for a prolonged period of time, extremely small nanoparticles can be produced [103]. According to Zaheer and Rafiuddin, [18] the kinetics and process reported for the generation of Ag NPs by oxalic acid are unsatisfactory since oxalic acid is unable to generate CO_2 without reacting with a carbonate salt or being heated to an extremely high temperature.

The following processes have been suggested by the authors (Zaheer and Rafiuddin, [18]) to demonstrate that the colour of Ag NPs in solution is caused by Ag4 2 + production, which absorbs at 425 nm. Even though the aforementioned reaction is kinetically quite quick, the creation of Ag4 2 + is extremely unlikely. Additionally, Ag4 2 +'s stabilisation is debatable. This idea on the formation of Ag4 2 + is nonsensical and does not include any supporting experimental data. According to the kind of reducing agent employed in their production, the absorbance of Ag NPs in solution ranges between 400 and 445 nm. The SPR band in the UV-vis spectrum is caused by electron oscillation at nanoparticle surfaces. After 60 minutes, there is no additional spectral shift as the reduction process is immediate. a sign that the redox process has been completed. At 70°C, Ag NPs are polydisperse, round, triangular and hexagonal. The XRD and EDAX spectra complement one another.

Microalgae have a roughly 3.4 billion-year history and are distinguished by having a high level of biodiversity. The eukaryotic green microalgae *Chlorella vulgaris* from the genus *Chlorella* is one of several microalgae that have existed on earth since the Precambrian period [117]. With a diameter ranging from 2 to 10 µm, *C. vulgaris* is a ball-shaped atomic form of a cell with a variety of components, including a cell wall, cytoplasm, mitochondrion and chloroplast organelles.Proteins, lipids, carbohydrates, pigments, minerals and vitamins make up the majority of *C. vulgaris*. Half of the dry weight of a fully developed *C. vulgaris* cell's dry weight is made up of proteins, which play a huge role in the structure of the algal cell. In addition to proteins, lipids also contain other components including hydrocarbons and glycolipids. Polysaccharides were present in *C. vulgaris* in the form of carbohydrates such as starch and cellulose [117, 118]. Additionally, due to their capacity to both decrease silver ions and stabilise the resulting AgNPs, polysaccharides derived from algae have a dual effect [119] (Table 1).

Table 1. Synthesis of Silver Nanoparticles of medicinal plants, Algae sample and its biological application

S. No	Plant	Size, shape and antimicrobial activities	Plant components that reduce the amount of silver nitrate	Key references
1	*Aloe vera*	Spherical, 9.4 nm. Antimicrobial activities against *Escherichia coli, Staphylococcus aureus, Pseudomonas aeruginosa* and *Candida albicans*	It contains various phytochemicals such as anthraquinones, aloin, aloesin, aloeresin A and B, barbaloin-emodin-mono-glucoside (BEMG), emodin-anthraquinone (EA), emodin-anthraquinone-mono-glucoside (EAMG), emodin-anthraquinone-diglucoside (EADG), aloenin A (AA), aloenin B (AB), aloenin C (AC), aloe-emodin (AE), rhein-anthraquinone (RA), rhein-anthraquinone-mono-glucoside (RAMG), rhein-anthraquinone-diglucoside (RADG), chrysophanol-anthraquinone (CA), chrysophanol-anthraquinone-mono-glucoside (CAMG), chrysophanol-anthraquinone-diglucoside (CADG), physcion-anthraquinone (PA), physcion-anthraquinone-mono-glucoside (PAMG), physcion-anthraquinone-diglucoside (PADG), aloetic acid (AAc), isoaloeresin D (IAD), 5-hydroxyaloin A (5HAA), 10-hydroxyaloin A (10HAA), 5-hydroxyaloin B (5HAB), 10-hydroxyaloin B (10HAB), and aloesaponarin I and II	104
2	*Azadirachta indica*	Spherical, 20 nm. Antimicrobial activities against *Escherichia coli, Staphylococcus aureus, Bacillus subtilis* and *Aspergillus niger*	It contains various phytochemicals such as azadirachtin, nimbin, nimbidin, salannin, gedunin, mahmoodin, margolone, margolonone, isomargolonone, nimocinol, nimbolide, meldenin, and quercetin	105
3	*Citrus limon*	Spherical, 15 nm. Antimicrobial activities *against Escherichia coli, Staphylococcus aureus, Bacillus subtilis*, and *Candida albicans*	It contains various phytochemicals such as citric acid, ascorbic acid, limonene, citral, neral, geranial, linalool, β-pinene, myrcene, terpinolene, α-terpineol, nerol, geraniol, citronellal, naringenin, hesperidin, eriocitrin, and rutin	106
4	*Curcuma longa*	Spherical, 12 nm. *Escherichia coli, Staphylococcus aureus, Bacillus subtilis* and *Candida albicans*	It contains various phytochemicals such as curcumin, demethoxycurcumin, bisdemethoxycurcumin, turmerones, atlantones, zingiberene, β-sesquiphellandrene, α-curcumene, β-bisabolene, ar-curcumene, α-zingiberene, β-turmerone, ar-turmerone, α-turmerone, curlone, dehydrozingerone, and gingerol	8
5	*Ocimum sanctum*	Spherical, 10 nm. *Escherichia coli, Staphylococcus aureus, Bacillus subtilis* and *Candida albicans*	It contains various phytochemicals such as eugenol, ursolic acid, rosmarinic acid, oleanolic acid, carvacrol, linalool, β-caryophyllene, α-humulene, geraniol, nerol, citronellol, methyl eugenol, myrcene, limonene, terpinen-4-ol, and apigenin	15
6	*Zingiber officinale*	Spherical, 2 nm to 34.6 nm. Antimicrobial activities against	It contains various phytochemicals identified in Zingiber officinale extract	107

S. No	Plant	Size, shape and antimicrobial activities	Plant components that reduce the amount of silver nitrate	Key references
		Escherichia coli, Staphylococcus aureus, Bacillus subtilis, Pseudomonas aeruginosa, Klebsiella pneumoniae, Salmonella typhi, Candida albicans, Aspergillus niger and *Aspergillus flavus*	such as zingerone, gingerenone, zingiberene, gingerol, shogaol, paradol, curcumin, demethoxycurcumin, bisdemethoxycurcumin, turmerones, and gingerdiol.	
7	*Camellia sinensis*	Spherical, 2 nm to 34.6 nm. Antimicrobial activities against*Escherichia coli, Staphylococcus aureus, Bacillus subtilis, Pseudomonas aeruginosa, Klebsiella pneumoniae, Salmonella typhi, Candida albicans, Aspergillus niger* and *Aspergillus flavus*	It contains various phytochemicals identified in Camellia sinensis extract are caffeine, theanine, theaflavins, thearubigins, gallic acid, quercetin, kaempferol, myricetin, and rutin.	108
8	*Emblica officinalis*	Spherical,5 nm to 34.6 nm. Antimicrobial activities against*Escherichia coli, Staphylococcus aureus, Bacillus subtilis, Pseudomonas aeruginosa, Klebsiella pneumoniae, Salmonella typhi, Candida albicans, Aspergillus niger* and *Aspergillus flavus*	It contains various phytochemicals identified in quercetin, rutin, kaempferol, myricetin, and gallic acid.	109
9	*Alhagi graecorum*	Spherical,15 nm to 36 nm. Antimicrobial activities *against Escherichia coli, Staphylococcus aureus, Bacillus subtilis, Pseudomonas aeruginosa, Klebsiella pneumoniae, Salmonella typhi, Candida albicans, Aspergillus niger* and *Aspergillus flavus*	It contains various phytochemicals identified in *Alhagi graecorum* extract are quercetin, rutin, kaempferol, myricetin, and gallic acid	110
10	*Rhodiola rosea*	Spherical,2 nm to 34.6 nm. Antimicrobial activities against *Escherichia coli, Staphylococcus aureus, Bacillus subtilis, Pseudomonas aeruginosa, Klebsiella pneumoniae, Salmonella typhi, Candida albicans, Aspergillus niger* and *Aspergillus flavus*	It contains various phytochemicals identified in Rosavin, rosin, rosarin, and salidroside	111
11	*Boerhaaviadiffusa*	Spherical, 25 nm.	It contains various phytochemicals identified inGallic acid, apocynin and quercetin	112
12	*Calliandra haematocephala*	Spherical in shape with an average size of 70 nm. Antimicrobial activities against *Escherichia coli*.	It contains various phytochemicals identified as flavonoids, Phenols and alkaloids	113
13	*Chlorella vulgaris*	Spherical, 5 nm. Antimicrobial activities *against Escherichia coli, Staphylococcus aureus, Bacillus subtilis, Pseudomonas aeruginosa, Klebsiella pneumoniae, Salmonella typhi, Candida albicans*	It contains various bioactive compounds such as chlorophyll, carotenoids, vitamins, minerals, proteins, and polysaccharides.	114
14	*Padina sp*	Spherical,15 nm. Antimicrobial activities against *Escherichia coli Staphylococcus aureus Bacillus subtilis Pseudomonas aeruginosa Klebsiella pneumoniae Salmonella typhi Candida albicans Aspergillus niger* and *Aspergillus flavus*.	It contains various bioactive compounds such as phenols, flavonoids, terpenes, and polysaccharides	115
15	*Spirulina platensis*	Spherical, 5 nm. Antimicrobial activities against *Escherichia coli, Staphylococcus aureus, Bacillus subtilis, Pseudomonas aeruginosa, Klebsiella pneumoniae, Salmonella typhi, Candida albicans*	It contains various bioactive compounds such as phycocyanin, carotenoids, vitamins, minerals, proteins and polysaccharides.	116

Both forms of bacteria's negatively charged cell walls are attracted to the free positive ions of NPs, which then exert their antibacterial action. Recent research has also demonstrated that Gram-positive bacteria are more resistant to AgNPs than Gram-negative bacteria, which can be explained by the different cell wall structures [120]. The Gram-negative *S. typhimurium*cell is more open to the entry of AgNP ions due to its coating of lipopolysaccharides and peptidoglycans. When compared to Gram-negative bacteria, Gram-positive bacteria like *S. aureus* have a thicker peptidoglycan layer as a protective covering. Another notable factor may be lipopolysaccharide with a negative charge. This chemical, which has a high affinity for NP ions, covers the Gram-negative bacteria. As a result, intracellular damage results from the increasing intake of ions. The results of this study support those of Jo et al., [121] and Singh et al*.,* [122] in that synthesised AgNPs are more harmful to Gram-negative bacteria than to Gram-positive bacteria.

4. MECHANISM OF ANTIBACTERIAL ACTIVITY BY AGNPS

The release of silver ions (Ag+) from the nanoparticles, interactions with bacterial cell components, and interference with crucial cellular processes all play a role in the mechanism of antibacterial suppression by bioinspired silver nanoparticles (AgNPs). This complex process helps explain why AgNPs have such strong antibacterial activity. When in contact with an aqueous environment or bacterial cells, AgNPs release silver ions (Ag+). AgNPs dissolve at different speeds depending on the pH of the environment [123]. A variety of biological components, including proteins, DNA and cell membranes, can attach to silver ions due to their high reactivity [124]. AgNPs can have direct interactions with bacterial cell membranes, resulting in permeability alterations and structural damage. As a result, the bacterial cell's integrity is compromised [125]. Additionally, silver ions have been shown to inhibit membrane-bound enzymes and cause membrane depolarization [126]. According to Nair and Pradeep, [127] the silver ions produced from AgNPs can interact with DNA, causing DNA damage and interrupting the transcription and replication processes. According to Li et al.,*[*128] Ag+ can attach to crucial proteins in bacterial cells, limiting their activities and interfering with cell metabolism. ROS can be produced by bacterial cells as a result of AgNPs. ROS that harm cellular components include hydrogen peroxide and superoxide radicals, which produce oxidative stress [129,130].

A greater interaction with microorganisms is provided by Ag NPs with bigger surface areas[26]. Accordingly, depending on their size, these particles can either stick to the external of the bacterial cell or enter its sheath. Additionally, they remained noted to be extremely contaminated to the bacterial strains, and reducing the particle size increased their antibacterial effectiveness [131]. There are several theories put up to explain how Ag NPs stop microorganisms from growing, but the one that is most compelling is the creation of free radicals, which is also maintained by the presence of a peak at 336.33 in the Ag NPs' ESR spectrum [129]. The production of free radicals is equally visible since, in a biological arrangement, they can harm, dissociate and ultimately prevent the growth of these bacteria by damaging membrane lipids [132].

However, Sondi and Sondi*.,*[133] found that Ag NPs' antibacterial action towards gram-negative bacteria is concentration-dependent. The nanoparticles collect, cause pits in the cell walls of bacteria, and then penetrate inside the bacterial cell, killing it. Ag free radical generation and antibacterial properties have been linked, according to reports [134,135] and this relationship has been validated by ESR [129]. They suggest that equally the definitely and negatively stimulating silver ions and Ag NPs were used in this antibacterial investigation. Spherical nanoparticles may be recognised by their absorption of Ag NPs at 391 nm due to their surface plasmon resonance [136]. Even after diluting the solution of Ag NPs 10 times, the absorption spectra remain unchanged, proving that they are not aggregated. Other inorganic ions, including Ag NPs and silver complexes, have antibacterial capabilities as well [99,137]. In spite of the fact that it is generally identified that Ag ions connect with the proteins of bacteria and avoid them from expanding, microbes also sidestep contact with these particles and procedure the cysts that generate resistance.

Silver ions generated by Ag NPs may infiltrate bacterial cells that contain such as peptidoglycan, DNA, and protein and stop continued bacterial development, according to Chaloupka et al.,[138] and Morones et al., [124]. The issue of Ag+ ions signify the oxidation of elemental silver, requiring the employment of an oxidising agent.

$$\text{Silver nanoparticles} \rightarrow Ag^{+} + e^{-}$$

The formation of Ag+ ions indicate the presence of an oxidising agent, despite the fact that the bacterial cell wall contains organic substances like carbonyl and protein that are electron donors rather than recipients and cannot produce Ag+ ions from Ag atoms [139, 140]. Thus, Ag+ ions are bound to the bacterial proteins and prevent them from performing essential tasks. According to research by Tho et al., [141] spherical Ag NPs made from *Nelumbo nucifera* seed extract are extremely hazardous to Gram-negative bacteria. These NPs range in size from 2.76 to 16.62 nm.

The antibacterial effect of silver nanoparticles (Ag NPs) arises from their interaction with bacterial cell membranes, impeding penetration and cellular respiration. In the case of gram-negative bacteria, these organisms feature an outer layer comprising a lipopolysaccharide coating, while the inner layer consists of a linear polysaccharide chain forming a complex three-dimensional network with peptides.

The assembly of silver nanoparticles occurs due to the attractive forces between the slight positive charge on the polysaccharide and the negative charge on the surface of the silver nanoparticles. This interaction disrupts bacterial cell replication, hindering their ability to reproduce.

5. CONCLUSION AND FUTURE WORKS

The green synthesis of silver nanoparticles (AgNPs) from medicinal plants has emerged as an environmentally friendly and sustainable approach with immense potential for various biological applications. This review has explored the extensive body of research and findings in this field, shedding light on the synthesis methods, properties and diverse biological applications of AgNPs derived from medicinal plants. Green synthesis methods using medicinal plants harness the rich phytochemical content and bioactive compounds present in these natural sources. The reduction and stabilization of AgNPs are achieved through the plant extracts, serving as reducing agents and capping agents simultaneously. The simplicity, cost-effectiveness and eco-friendliness of these methods make them highly attractive for large-scale production. AgNPs synthesized from medicinal plants exhibit unique properties, including size, shape and surface chemistry. These properties can be tailored by adjusting synthesis conditions and the choice of medicinal plant species. The presence of phytoconstituents, such as polyphenols, flavonoids and terpenoids, in plant extracts, contributes to the stabilization of AgNPs and enhances their biocompatibility.

While the green synthesis of AgNPs from medicinal plants offers numerous advantages, there remain challenges related to standardization, scalability and toxicological assessments. Future research should focus on optimizing synthesis protocols, ensuring product consistency and conducting comprehensive safety evaluations to unlock the full potential of these bioinspired nanoparticles. In conclusion, the green synthesis of AgNPs from medicinal plants represents a promising intersection of traditional herbal medicine and cutting-edge nanotechnology. The synergistic properties of these nanoparticles and their diverse biological applications hold great promise for addressing healthcare, environmental and agricultural challenges in a sustainable and eco-friendly manner. As research in this field continues to evolve, it is expected to yield novel solutions that benefit society at large.

COMPETING INTERESTS

Authors has declared that no competing interests exist.

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