ENVIRONMENTALLY FRIENDLY SYNTHESIS OF SILVER NANOPARTICLES

Valeriia Marchenko, Oksana Skrotska*, Rostyslav Koval
National University of Food Technologies, Kyiv, Ukraine
**Corresponding author: skrotskaoi@nuft.edu.ua*

For the biosynthesis of silver nanoparticles, various biological agents are used, including bacteria, cyanobacteria, fungi, yeast, algae and plants. When microorganisms are employed for the biosynthesis of silver nanoparticles, both intracellular and extracellular synthesis pathways are possible. Additionally, the synthesis of nanoparticles using exo- and endogenous cellular metabolites is feasible. Extracts from algae and plant containing polysaccharides, phenolic compounds, proteins, vitamins, carotenoids, astaxanthins, polyols, terpenoids, and sterol are used for the biosynthesis of silver nanoparticles. The mechanisms of nanoparticles biosynthesis using plant are not fully elucidated at present. However, it is known that hydroxyl, methylene, and carboxyl groups of various biological substances participate in the processes of silver ion reduction, nanoparticles formation, and stabilization. Depending on the biological agent and the biosynthesis method, nanoparticles of various shapes (spherical, cubic, icosahedral, triangular, pentagonal, hexagonal) and sizes are formed, affecting their biological properties. Biogenic silver nanoparticles exhibit antibacterial activity against both gram-negative and gram-positive bacteria. The mechanism of their antimicrobial action involves denaturation of bacterial surface proteins and inhibition of cell metabolism and respiration by damaging the electron transport system. Additionally, nanoparticles inhibit bacterial protein translation. Antitumor potential of biogenic nanoparticles has been observed in various cancer cell lines, though their selectivity towards cancer cells over normal cells has not been conclusively demonstrated. The antitumor effect of biosynthesized nanoparticles is associated with inducing cellular and subcellular morphological changes, enhancing oxidative stress and metabolic toxicity, and inducing apoptosis in cancer cells by reducing the expression of anti-apoptotic proteins and increasing the expression of apoptotic proteins.

Keywords: silver nanoparticles, bacteria, fungi, algae, plant

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Introduction

Silver nanoparticles (AgNPs) are used in a variety of industries. In the food industry, the incorporation of nanoparticles into packaging materials can prevent the growth of pathogenic microorganisms in food products. Moreover, metal nanoparticles can be used for water disinfection purposes. There are studies on their use in agriculture as antifungal and antibacterial agents, pesticides, and soil bioremediation agents. In medicine, they can serve as antibacterial, antifungal, antiviral, and antitumor compounds. Furthermore, ongoing investigations are delving into the potential of nanoparticles for diagnosing various diseases (Koul et al., 2021).

Traditional methods of nanoparticles synthesis, namely chemical and physical methods, are lengthy, laborious, and rely on the use of toxic compounds, which subsequently pollute the environment (Joudeh et al., 2022). Considering their environmental impact, biological methods of nanoparticle synthesis serve as an alternative to chemical and physical methods. When choosing a biological method of synthesis, bacteria, fungi, yeast, algae, plants, as well as their metabolites, can be used. Depending on the choice of biological object, its cultivation conditions, and the parameters of biosynthesis, nanoparticles of various sizes and shapes can be formed, affecting their subsequent biological properties and potential applications in various industries (Saravanan, 2021; Vadakkan, 2024).

The aim of this review is to analyze scientific publications regarding the potential use of fungi, yeast, bacteria, cyanobacteria, algae, and plants for environmentally friendly synthesis of silver nanoparticles.

Bacteria

To date, biosynthesis of silver nanoparticles has been investigated using the supernatant of the culture medium of thermophilic bacteria *Ureibacillus thermosphaericus* (Juibari et al., 2011) and probiotic bacteria *Lactobacillus crustorum* F11 (Sharma et al., 2022). Typically, biosynthesis of AgNPs is conducted in darkness, however, when using the supernatant of gram-positive bacteria *Staphylococcus aureus*, the reaction mixture was exposed to bright light for 5 minutes at the beginning of biosynthesis (Nanda, & Saravanan, 2009). Extracellular synthesis of AgNPs has been investigated (Table 1) using biomass of endophytic bacteria *Bacillus cereus* (Sunkar, & Nachiyar, 2012). Additionally, extracellular synthesis of silver nanoparticles has been demonstrated using biomass of soil gram-positive bacteria *Corynebacterium glutamicum* (Gowramma et al., 2015). Furthermore, intracellular synthesis of AgNPs has been investigated using soil gram-positive bacteria *Bacillus cereus* PGN1 (Babu, & Gunasekaran, 2009). Intracellular synthesis of silver nanoparticles has also been demonstrated using biomass of lactic acid bacteria *Lactobacillus casei* subsp. *casei* (Korbekandi et al., 2012).

Table 1. Synthesis of silver nanoparticles using bacteria

Bacteria	Parameters of biosynthesis and characteristics of biogenic nanoparticles	Biological properties of nanoparticles	Reference
Bacillus cereus	22-25 °C (room), 72-120 h; AgNPs: spherical, 11-16 nm	Antibacterial activity	Sunkar, & Nachiyar, 2012
Corynebacterium glutamicum	22-25 °C (room), 24 h; AgNPs: spherical, 15 nm	Antibacterial activity	Gowramma et al., 2015
Lactobacillus crustorum F11	30 °C, 24 h; AgNPs: spherical, 5 nm	Antibacterial and antifungal activity	Sharma et al., 2022
Staphylococcus aureus	22-25 °C (room), 72 h; AgNPs: agglomerated nanostructures, 160-180 nm	Antimicrobial activity against methicillin-resistant bacteria	Nanda, & Saravanan, 2009

While investigating biomolecules that may participate in the biosynthesis of AgNPs, it has been shown that free amino and carbonyl groups present in bacterial proteins can participate in formation and stabilization of silver nanoparticles (Babu, & Gunasekaran, 2009). Additionally, OH-, CH-, and NH-groups of proteins can bind to silver ions and participate in their reduction and nanoparticles formation (Sunkar, & Nachiyar, 2012). Hydroxyl, protein, and carboxyl groups are involved in the biosynthesis of AgNPs using probiotic bacterial strains (Sharma et al., 2022).

Cyanobacteria

The potential for biosynthesis of silver nanoparticles using biomass of *Synechocystis* sp. cyanobacteria has been demonstrated (Table 2). Biosynthesized AgNPs reduced the synthesis of pro-inflammatory cytokines – tumor necrosis factor (TNF-α) and interleukins (IL-1β, IL-6) in diabetic experimental animals (Younis et al., 2022). Synthesis of AgNPs using the culture supernatant of *Cyanothece* sp. was investigated by Mohamed et al. In this study, 56% of Ag^+ ions were reduced to Ag^0 within 72 hours of biosynthesis. The authors examined the effect of phytohormones on the biosynthesis of AgNPs. Addition of indole-3-acetic acid and kinetin to the culture supernatant of *Cyanothece* sp. resulted in bioreduction of Ag^+ at levels of 87% and 55%, respectively, and nanoparticles formation. Gibberellic and abscisic acids did not increase the percentage of reduced silver ions. The highest percentage of silver bioreduction was observed upon addition of methyl jasmonate, but cyanobacteria lost viability at the end of the biosynthesis process (Mohamed et al., 2022).

There are reports of silver nanoparticles biosynthesis using the supernatant of *Desertifilum tharense* AM5E. These cyanobacteria were isolated from soil. The study also demonstrates the potential for AgNPs synthesis using intracellular metabolites of *D. tharense* AM5E (Hanna et al., 2022). Scientific literature includes publications regarding AgNPs synthesis using cyanobacterial pigments. For instance, biosynthesis of silver nanoparticles has been investigated using phycocyanin extracted from *Limnothrix* sp. 37-2-1 (Patel et al., 2015) and soil cyanobacteria *Nostoc linckia* (El-Naggar et al., 2017). Moreover, biosynthesis of silver nanoparticles using photosynthetic pigments of phycobiliproteins, including phycocyanin, phycoerythrin, and allophycocyanin, has been demonstrated. The phycobiliproteins used for AgNPs biosynthesis were extracted from cyanobacteria *Spirulina platensis* and *Nostoc linckia* (Ismail et al., 2021).

Also, silver nanoparticles can be obtained using a cell-free aqueous extract of cyanobacteria, for example, *Leptolyngbya* JSC-1 (Zada et al., 2018), *Trichodesmium erythraeum* (Sathishkumar et al., 2019), *Nostoc Bahar* M (Hamida et al., 2020), and *Anabaena variabilis* (Ahamad et al., 2021). Tomer with co-authors studied the biosynthesis of AgNPs using a cell-free aqueous extract of *Haloleptolyngbya alcalis* KR2005/106. The authors demonstrated the possibility of using the AgNPs solution for rapid determination of water-soluble ammonia. The color of the nanoparticle solution changed from brown to yellow within a few seconds after the addition of ammonia, indicating the formation of a silver-ammonia complex. Simultaneously, a shift in the absorption peak of this solution towards the blue range of the spectrum was observed (Tomer et al., 2019).

Biosynthesis of AgNPs using cell-free aqueous extract of *Plectonema* sp. NCCU 204 has been demonstrated. The biosynthesized nanoparticles exhibited various biological properties. They showed antibacterial activity against both gram-negative and gram-positive bacteria and exhibited synergistic antimicrobial effects with the antibiotic streptomycin and the antifungal drug fluconazole. The non-toxicity of AgNPs towards normal cells has been established, confirming their biocompatibility when using PBMC cell lines (peripheral blood mononuclear cells). Interestingly, removal of the protein shell from the surface of the nanoparticles resulted in a reduction in their biological activity (Zaki et al., 2022).

Table 2. Cyanobacteria for environmentally friendly synthesis of silver nanoparticles

Cyanobacteria	Parameters of biosynthesis and characteristics of biogenic nanoparticles	Biological properties of nanoparticles	Reference
Anabaena variabilis	30 °C, 72 h; AgNPs: spherical, 10-15 nm	Anti-candida, antibacterial, antioxidant activity; synergism of action with antibiotics and antifungal drugs	Ahamad et al., 2021
Desertifilum tharense AM5E	30 °C, 48 h; AgNPs: spherical, 6-11 nm	Antioxidant and antibacterial activity	Hanna et al., 2022
Leptolyngbya sp. WUC 59	70 °C, 15 min; AgNPs: spherical, 20-35 nm	Antibacterial activity; activation of wheat grain germination	Singh et al., 2020
Nostoc sp. PCC7524	121 °C, 5 min; AgNPs: spherical, 6-16 nm	Nematicidal activity; activation of the growth of leguminous plants	Hamed et al., 2019
Nostoc Bahar M	22-25 °C (room), 24 h; AgNPs: spherical, 8.5-26 nm	*Antitumor activity*	Hamida et al., 2020
Plectonema sp. NCCU 204	30 °C, 72 h; AgNPs: spherical, 2-30 nm	Antitumor, antibacterial, anti-candida, antioxidant, anti-inflammatory activity	Zaki et al., 2022
Synechocystis sp.	28 °C, 24 h; AgNPs: spherical, 10-35 nm	Wound healing properties; antibacterial activity against methicillin-resistant bacteria; antioxidant and anti-inflammatory activity	Younis et al., 2022
Spirulina platensis	22-25 °C (room), 24 h; AgNPs: spherical, 15-27 nm	Antibacterial, anti-candidal, anti-tumor, antiviral, antioxidant activity	Ismail et al., 2021

Biosynthesis of silver nanoparticles using a cell-free aqueous extract of soil cyanobacteria *Desertifilum* IPPAS B-1220 has been investigated. The AgNPs exhibited antibacterial activity against both gram-negative and gram-positive bacteria and showed anticancer activity (Hamida et al., 2020). One possible mechanism of the anticancer effect of AgNPs could be that the nanoparticles induce cellular and subcellular morphological changes, increase oxidative stress and metabolic toxicity, and induce apoptosis in cancer cells by reducing the expression of anti-apoptotic proteins such as protein kinase B (Akt), phosphorylated protein kinase B (p-Akt), mammalian target of rapamycin (mTOR), B-cell lymphoma 2 (Bcl-2), and increasing the expression of apoptotic proteins such as tumor suppressor protein (p53) and caspase-3. Under the influence of AgNPs, the number of peroxisomes increases in tumor cells, the activity of glutathione peroxidase increases, and the levels of glutathione decrease. This, in turn, leads to an increase in the levels of reactive oxygen species and oxidative stress. AgNPs also induce metabolic stress in cells by reducing the levels of adenosine triphosphatase (Hamida et al., 2020).

Regarding the mechanisms of biosynthesis of AgNPs using cyanobacteria, it has been shown that aromatic compounds, alkanes, amines, and amides can participate in the reduction of silver ions and the biosynthesis of nanoparticles, as well as contribute to their stabilization (Mohamed, 2022; Younis, 2022). There are reports that enzymes and proteins, particularly their hydroxyl, carbonyl, carboxyl, and amide groups, play an important role in the reduction of silver ions and the formation and stabilization of nanoparticles (Ahamad, 2021; Zaki, 2022). Moreover, in the biosynthesis of AgNPs, polysaccharides (Hamida, 2020; Hanna, 2022), cyanobacterial pigments (El-Naggar, 2017; Ismail, 2021), and phenolic compounds (Tomer et al., 2019) are involved alongside proteins.

Fungi

Cell-free filtrates of fungi are used for the biosynthesis of silver nanoparticles (Birla et al., 2013). However, there are studies where the filtrate of *Aspergillus oryzae* var. *viridis* is used, whose cells have been previously inactivated by autoclaving at 121°C for 15 minutes (Binupriya et al., 2010). It is now known that compared to bacteria, fungi predominantly employ an extracellular mechanism for the biosynthesis of AgNPs (Binupriya, 2010; Birla, 2013). Various proteins play a significant role in these mechanisms (Jain et al., 2011). During the biosynthesis of AgNPs using pathogenic imperfect fungi *Fusarium oxysporum*, authors detected the presence of various functional groups of amino acids and the enzyme reductase in the reaction mixture (Birla et al., 2013). In another study involving *Pleurotus sajor-caju*, researchers found that tryptophan, tyrosine, or phenylalanine are involved in the biosynthesis processes of silver nanoparticles (Nithya, & Ragunathan, 2009).

Yeast

Intracellular biosynthesis of silver nanoparticles has been demonstrated under aerobic and anaerobic conditions using biomass of *Meyerozyma guilliermondii* KX008616. AgNPs were formed as clusters in the cytoplasm or in the inner and outer layers of the cell wall of *M. guilliermondii* KX008616 (Alamri et al., 2018). Biosynthesis of AgNPs has been investigated using the supernatant of *Candida glabrata* culture (Table 3). These yeasts were isolated from the oral cavity of individuals suffering from oral candidiasis (Jalal et al., 2018). The possibility of silver nanoparticles synthesis using the supernatant of *Metschnikowia* sp. HX-YS yeasts, isolated from the surface of hawthorn *Crataegus pinnatifida*, has also been established (Liu et al., 2021). We investigated the biosynthesis of silver nanoparticles using the supernatant of the culture medium and the cell-free extract of *Saccharomyces cerevisiae* M437. In this case, AgNPs obtained using the cell-free aqueous extract were more stable during storage than nanoparticles obtained using the supernatant (Skrotska et al., 2021).

Bolbanabad and colleagues demonstrated the biosynthesis of AgNPs using both cell and cell-free aqueous extracts of *Yarrowia lipolytica* DSM 3286. When using cells, nanoparticles are synthesized inside the cell and then secreted externally. When using the cell-free extract, the biosynthesis of AgNPs occurred five times faster than with biomass, but the nanoparticles were twice as large (Bolbanabad et al., 2020).

When considering the mechanisms of silver nanoparticles biosynthesis using yeast, it is believed that proteins, amino acids, enzymes, vitamins, and polysaccharides act as reducers and stabilizers of AgNPs. When using cell-free aqueous yeast extract, the formation of silver nanoparticles begins with the reduction of Ag^+ ions to Ag^0 by compounds present in the extract, including amino acids, vitamins, and carbohydrates. Subsequently, the formed AgNPs are stabilized

(Shu et al., 2020). However, the most widely accepted mechanism of silver nanoparticles biosynthesis using yeast involves NADH-dependent nitrate reductase. It has been established that the reduction of silver ions occurs through the transfer of electrons from NADH. Subsequently, the stabilization of AgNPs occurs due to the presence of biomolecules in the reaction mixture (Shabbir, & Mohammad, 2018). During intracellular synthesis of silver nanoparticles, various mechanisms of their formation are possible. The first involves the participation of nitrate reductase enzyme systems, which catalyzes the reduction reactions of silver ions in the presence of ATP and NADH. The second mechanism involves the activation of a specific polypeptide that can bind to silver cations, forming a specific complex that is transported into the cellular vacuoles, where the reduction of silver ions occurs. The third mechanism involves the formation of AgNPs on the surface of cells. This may be due to the electrostatic interaction between Ag^{+} ions and negatively charged carboxylate groups of specific enzymes or proteins present on the surface of yeast cells (Alamri et al., 2018).

Table 3. Yeast for ecologically pure synthesis of silver nanoparticles

Yeast	Parameters of biosynthesis and characteristics of biogenic nanoparticles	Biological properties of nanoparticles	Reference
Aureobasidium pullulans RYLF 10	27°C, 120 h; AgNPs: spherical, 2-54 nm	Antibacterial activity	Rahi et al., 2018
Candida glabrata	22-25 °C (room), 24 hours; AgNPs: spherical, oval, 2-15 nm	Antibacterial and anti-candida activity	Jalal et al., 2018
Metschnikowia sp. HX-YS	28 °C, 96 h; AgNPs: spherical, 50-100 nm	Antibacterial and antitumor activity	Liu et al., 2021
Rhodotorula sp. ATL72	22-25 °C (room), 24 hours; AgNPs: spherical, oval, 9-21 nm	Antibacterial and anti-candida activity	Soliman, et al., 2018
Rhodotorula mucilaginosa	25 °C, 168 h; AgNPs: spherical, 11-30	Anti-candidal action; catalytic activity for the degradation of 4-nitrophenol and methylene blue	Cunha et al., 2018
Yarrowia lipolytica DSM 3286	30 °C, 16 h; AgNPs: spherical, 24 nm	Antibacterial activity	Bolbanabad et al., 2020

Algae

The use of green microalgae (Cepoi, 2022; Kumar, 2022; Kumar, 2023), green seaweed (Dogmaz, & Cavas, 2023), brown seaweed (Bhuyar, 2020; Gonzalez-Ballesteros, 2020; Fernandes, 2023), red marine algae (Fatima, 2020; Viswanathan, 2023), as well as freshwater green algae (Rajkumar et al., 2021) to obtain biogenic silver nanoparticles was demonstrated (Table 4).

Regarding the mechanisms of silver nanoparticles biosynthesis, it is known that algae contain various biochemical substances such as carotenoids, amino acids, polysaccharides, starch, polyphenols, vitamins, minerals, astaxanthins, proteins, and enzymes. These components act as reducers and stabilizers during AgNPs biosynthesis (Kumar, 2023; Kumar, 2022). In the identification of potential biomolecules responsible for AgNPs formation, it has been found that the carbonyl groups of amino acid residues and proteins, amino groups of cysteine residues, and sulfate groups of polysaccharides bind with metals. Such binding forms a layer covering the metal within the nanoparticles, thus preventing agglomeration and ensuring their stabilization. Hydroxyl and carboxyl groups of proteins have also been reported to participate in silver nanoparticle biosynthesis (Chokshi et al., 2016). Blocking agents for stabilizing AgNPs may include amines, alkenes, alcohol groups, or polyphenolic compounds (Bhuyar et al., 2020). In some studies, it has been hypothesized that polysaccharides and polyphenolic compounds play an active role in the reduction and stabilization processes during silver nanoparticles biosynthesis (Gonzalez-Ballesteros et al., 2020).

Table 4. Environmentally friendly biosynthesis of silver nanoparticles using algae

Algae	Parameters of biosynthesis and characteristics of biogenic nanoparticles	Biological properties of nanoparticles	Reference
Botryococcus braunii	22-25 °C (room), 3 hours; AgNPs: spherical, 40-90 nm	Catalytic activity for the reduction of 2-nitroaniline	Arya et al., 2019
Cystoseira baccata	100 °C, 30 min; AgNPs: spherical, 15.5-27.9 nm	Antibacterial activity; antioxidant activity against 1,1-diphenyl-2-picrylhydrazyl	Fernandes et al., 2023
Chlorella minutissima	37 °C, 120 h; AgNPs: spherical, 73.13 nm	Antibacterial activity	Kumar et al., 2023
Chlorella sorokiniana	22-25 °C (room), 72 h; AgNPs: spherical, 28.52-40.35 nm	Photocatalytic activity; antibacterial activity	Kumar & Bharadvaja, 2022
Chlorella vulgaris	22-25 °C (room), 72 h; AgNPs: spherical, 45.39-64.73 nm	Photocatalytic activity	Rajkumar et al., 2021
Dunaliella salina	22-25 °C (room), 24 hours; AgNPs: spherical, 15-40 nm	Antioxidant activity	Cepoi et al., 2022
Sargassum muticum	100 °C, 72 h; AgNPs: spherical, 35.3-46.7 nm	Antibacterial activity	Gonzalez-Ballesteros et al., 2020
Padina sp.	60 °C, 48 h; AgNPs: spherical, 25-60 nm	Antibacterial activity	Bhuyar et al., 2020
Portieria hornemannii	22-25 °C (room), 24 hours; AgNPs: spherical, 70-75 nm	Antibacterial activity	Fatima et al., 2020

Marine algae extracts also contain functional groups such as amide, amine, alkane, alkene, carboxylic acid, and methylene groups, which participate in the formation of nanoparticles. For instance, the presence of carboxylic acid groups, alkanes, and amines has been demonstrated, which may be responsible for stabilizing silver nanoparticles. These compounds also prevent their agglomeration (Deepak et al., 2018). Proteins, polysaccharides, amides, and long-chain fatty acids are proven biomolecules responsible for the bioreduction of silver ions and preventing agglomeration (Arya, 2019; Bhuyar, 2020). It has been shown that amino and aliphatic alkyl groups play a key role in the formation of silver nanoparticles. Furthermore, the formation of silver nanoparticles was accompanied by a decrease in the content of proteins, β-carotene, and lipids in the reaction mixture (Cepoi et al., 2022). There is a hypothesis that the functional hydroxyl groups of polyphenols and polysaccharides may participate in the reduction of silver ions. Additionally, proteins and sulfogroups of polysaccharides prevent the agglomeration of nanoparticles. Carbonyl groups also play a role in the reduction and stabilization of AgNPs (Fernandes et al., 2023). Furthermore, the participation of sulfate and hydroxyl groups present in algae extracts in the reduction of silver nanoparticles has also been demonstrated (Madhiyazhagan et al., 2015).

Plant

Plant contain a large number of chemical compounds (flavonoids, alkaloids, terpenoids, phenols, amino acids, steroids, etc.) that can act as reducing and stabilizing agents during the biosynthesis of silver nanoparticles (Jyoti et al., 2016). For the biosynthesis of silver nanoparticles (Table 5), extracts of leaves (Aktepe, 2021b; Baran, 2022), fruits (Bindhu, & Umadevi, 2015), bark (Iravani, & Zolfaghari, 2013), flowers (Sabapathi et al., 2023), and food waste (Aktepe, 2021a; Baran et al., 2021) can be used.

Table 5. Plant components for the biosynthesis of silver nanoparticles

Plant	Parameters of biosynthesis and characteristics of biogenic nanoparticles	Biological properties of nanoparticles	Reference
Ananas comosus	fruit peel extract, 22-25 °C (room), 2 h; AgNPs: spherical, 11.61 nm	Antibacterial and anti-candida activity; antitumor activity	Baran et al., 2021
Cassia auriculate	flower extract, 35 °C, 24 h; AgNPs: spherical, 30-80 nm	Antioxidant activity; antitumor effect; antibacterial activity	Sabapathi et al., 2023
Cicer arietinum L.	leaf extract, 22-25 °C (room), 3 h; AgNPs: spherical, 6.11-9.66 nm	Antitumor effect; antibacterial and anti-candidal activity	Baran et al., 2022
Citrullus lanatus sp.	leaf extract, 22-25 °C (room), 20 min; AgNPs: spherical, 21.27 nm	Antibacterial and anti-candida activity	Aktepe, & Baran, 2021a
Prunus dulcis L.	leaf extract, 22-25 °C (room), 30 min; AgNPs: spherical, 16 nm	Antibacterial and anti-candida activity	Aktepe, & Baran, 2021b

For the biosynthesis of silver nanoparticles, water extracts of watermelon (*Citrullus lanatus* sp.) leaves can be utilized. Therefore, the fruits of *Citrullus lanatus* sp. are used for consumption, while the waste after harvest can be used for the biosynthesis of AgNPs (Aktepe & Baran, 2021a). These same authors investigated the biosynthesis of silver nanoparticles using water extracts of almond tree (*Prunus dulcis* L.) leaves. The synthesized AgNPs exhibited a broad spectrum of antimicrobial activity (Aktepe & Baran, 2021b). In the study of AgNPs obtained using water extracts of chickpea (*Cicer arietinum* L.) leaves, apart from antimicrobial properties, anticancer properties of the nanoparticles were also studied (Baran et al., 2022).

Cassia auriculata is a medicinal plant from the *Fabaceae* family and *Senna* genus, which grows in India. For the biosynthesis of silver nanoparticles, a water extract of *Cassia auriculata* flowers was used, to which silver nitrate was added. Initially, the solution was treated with ultrasound at 37°C, followed by incubation in the dark at 35°C (Sabapathi et al., 2023).

For the synthesis of silver nanoparticles, food waste such as banana peels can be used, which contain pectin, cellulose, and hemicellulose. The functional groups of these polymers can participate in the reduction of Ag^{+} ions to Ag^{0} and the formation of nanoparticles. Biosynthesis of nanoparticles was investigated using a water extract of banana peels at different pH values. No biosynthesis was observed at pH 2-4, which may be attributed to the inactivation of biomolecules at acidic pH values. Highly monodispersed silver nanoparticles were obtained at pH 11 (Ibrahim, 2015). Additionally, a water extract of pineapple peels can be used for the biosynthesis of AgNPs (Baran et al., 2021).

Regarding the mechanism of AgNP biosynthesis, it has been shown that hydroxyl, methylene, and carboxyl groups of biological compounds in plant extracts play a key role (Aktepe & Baran, 2021b). Amides and phenolic compounds participate in the reduction of silver ions and the formation of nanoparticles (Baran et al., 2022). It has been demonstrated that the water extract of *Cassia auriculate* flowers contains polyphenols, steroids, alkaloids, tannins, and triterpenoids, which reduce silver ions, participate in the biosynthesis of nanoparticles, and stabilize them (Sabapathi et al., 2023). In the water extract of *Urtica dioica*, carbohydrates, alkaloids, saponins, proteins, amino acids, phenols, diterpenes, tannins, and phytosterols are present, which may be responsible for the effective stabilization of silver nanoparticles (Jyoti et al., 2016).

Conclusions

Silver nanoparticles can be obtained by biological methods using bacteria, fungi, yeast, algae, and plant. Various biological agents are used for biosynthesis, including biomass, culture supernatant, cell-free extract, and lysate. When using algae and plant for nanoparticle biosynthesis, their extracts are employed. The advantages of using plant for nanoparticles biosynthesis include the ability to prepare plant extracts from dried plant parts, and the extracts themselves can be dried and subsequently dissolved for biosynthesis. However, the disadvantage is that the composition of plant extracts is not constant. It depends on natural conditions, the location, timing of plant sample collection, etc. In addition to plant extracts, plant polyphenols, alkaloids, gum, and juices, as well as essential oils, can be used for silver nanoparticles biosynthesis. Compounds present in the extracts (saponins, terpenoids, steroids, polyols, polyphenols, alkaloids, aldehydes, ketones, proteins, sugars) act as reducers of metal ions and also participate in nanoparticles formation and stabilization. Depending on the biological agent, its cultivation conditions, and the parameters of biogenic synthesis, nanoparticles of different sizes and shapes can be formed, which will affect their further biological properties and potential applications in various fields.

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Conflict of interest

The authors state no conflict of interest.

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