Review

Green-Synthesized Silver Nanoparticle-Based Composites: Sustainable Synthesis, Toxicity Assessment, and Environmental Remediation

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Review

Green-Synthesized Silver Nanoparticle-Based Composites: Sustainable Synthesis, Toxicity Assessment, and Environmental Remediation

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Abstract

Silver nanoparticles (AgNPs) have attracted significant attention due to their remarkable antimicrobial, antibacterial, and catalytic properties, enabling widespread applications in consumer products, biomedical fields, and environmental systems. Conventional chemical and physical synthesis routes, however, often involve toxic reagents and generate hazardous byproducts, raising environmental and health concerns. In response, green synthesis approaches employing biological entities such as plant extracts, bacteria, and fungi have emerged as sustainable and eco-friendly alternatives. These methods utilize natural reducing and stabilizing agents, minimizing toxicity while enhancing biocompatibility. This review comprehensively examines green-mediated synthesis strategies for AgNP-based composites, highlighting their physicochemical properties and functional performance. Additionally, the potential toxicity and environmental implications of AgNPs are critically discussed. Particular emphasis is placed on their applications in environmental remediation, including water purification, pollutant degradation, and antimicrobial treatments. Overall, green-synthesized AgNP composites offer a promising pathway toward sustainable nanotechnology for environmental pollution control.

Keywords: silver nanoparticles (AgNPs); green-mediated; green synthesis; antimicrobial activity; toxicity

1. Introduction

Although one may assume that silver nanoparticles are recent findings, silver nanoparticles as a colloidal form have been in use for more than 100 years [1]. Because of its excellent antimicrobial activity, silver has been used in home appliances and medical devices since medieval times. People in Renaissance Europe started using silver utensils during the outbreak of the Bubonic plague to protect themselves from disease. The 19th and 20th centuries saw a rise in the usage of silver in more sophisticated medical and water purification applications [2]. Silver sulphadiazine is still widely used as a treatment for third-degree burns [3,4]. With the advancement of technology, a new kind of silver has come to the horizon: Nano-silver. Due to their exceptional and to some extent peculiar characteristics nanosilver or silver nanocomposites have been studied to be used in catalysis, biomedical, environmental, and consumer applications. Silver nanoparticles, owing to their exceptional properties, have been used in many applications. Using silver nanoparticles as nano-reinforcements in polymer filler materials have been reported to be used in applications from food packaging to electronics packaging applications [5–10]. Various biomedical and industrial [11] applications of polymer silver nanocomposites have also been reported [12–15].

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As discussed earlier, silver has excellent antimicrobial properties, but due to its cost and inconsistent performance with temperature, an alternate solution has been found, and some claim it is nanosilver. Silver at the nanoscale has a surface area much greater than the same amount of colloidal silver, which enables nanosilvers to be used as a surface coating for various applications [16–18]. Silver nanoparticles, like every other nanoparticle, can be produced using either a top-down or bottom-up approach. In the bottom-up approach, nanoparticles can be synthesized by self-assembly using chemical and green-mediated synthesis and in the top-down approach, desired materials are resized from bulk materials by different physical treatments [19–21]. Figure 1 shows different methods of silver nanoparticle production[22].

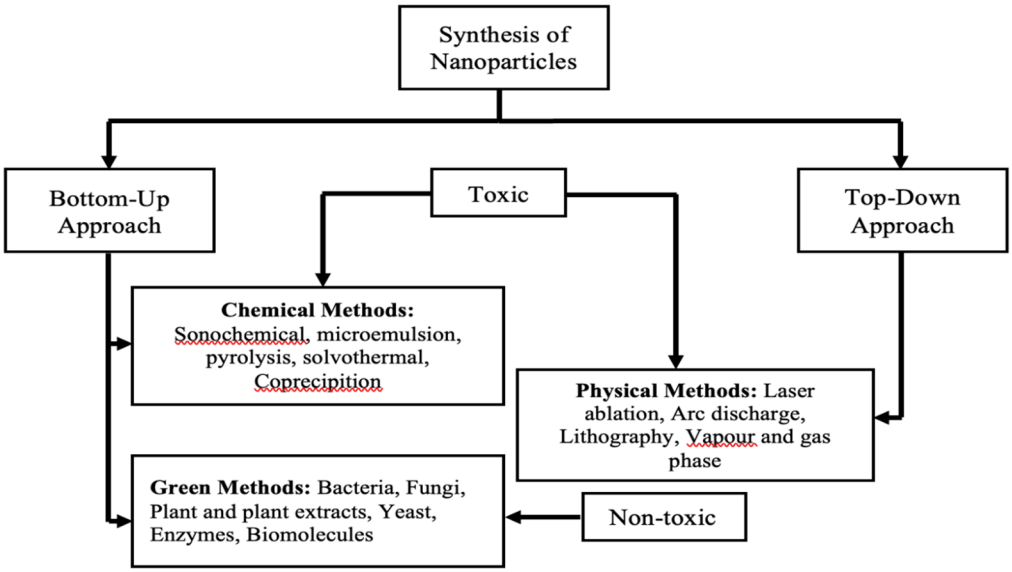

Figure 1. Chemical, Physical and Green synthesis of silver nanoparticles.

Among the three techniques for silver nanoparticle synthesis, chemical methods are more widely used because of the availability of readily accessible raw materials and established workflows. Although Physical methods are also popular due to the high maintenance costs of equipment and the complexity of procedures, they are less prominent than chemical methods. With growing concern for a safer environment, an alternative approach to producing silver nanoparticles is essential. As chemical and physical methods of AgNp synthesis can be toxic and harmful to the environment, newer, more sophisticated green syntheses have recently been explored and reported.

2. Chemical and Physical Methods of Silver Nanoparticle Synthesis

Because of simpler equipment and long-known procedures, chemical methods are widely used to develop silver nanoparticles. The main mechanism of silver nanoparticle synthesis is similar across all methods. Silver ions are reduced to a metallic form by reducing agents, ultimately accumulating to form nanoparticles. Because of its low cost, silver nitrate is the most commonly used reagent in the synthesis of silver nanoparticles. The most commonly used reducing agents in silver nanoparticle synthesis are Trisodium citrate, Ascorbic acid, Alanine, and Oleic acid. The most commonly used capping agents that are used in the production of silver nanoparticles are Daxad 19, DBSA (dodecylbenzene sulfonic acid), Glycerol, polyvinylpyrrolidone, Sodium oleate, and Tannic acid [23,24]. Capping agents can also control the size of the silver nanoparticle produced. Table 1 shows variations in silver nanoparticle size synthesized under different experimental conditions.

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Table 1. Different sizes of silver nanoparticles produced at different experimental condition [25].

Precursor	Reducing Agent	Capping agent	Diameter (nm)	Experimental Condition
$Na_3C_6H_5O_7$	$AgNO_3$	$Na_3C_6H_5O_7$	10–80	Boiling point
$C_6H_8O_6$	$AgNO_3$	Daxad 19	15-26	Boiling point
$C_3H_7NO_2$/NaOH	$AgNO_3$	DBSA	8.9	90℃, 60 min
$C_{18}H_{34}O_2$	$AgNO_3$	PVP	20-100	90℃
$C_6H_8O_6$	$AgNO_3$	$C_{18}H_{33}NaO_2$	5-100	100-160℃, 15-20 min
$Na_3C_6H_5O_7$	$AgNO_3$	$Na_3C_6H_5O_7$	30–96	Boiling point, pH=5.7-11.1
$Na_3C_6H_5O_7$	$AgNO_3$	Tannic Acid	10-100	90℃

Using chemical synthesis, it is difficult to obtain silver nanoparticles of a specific size. Also, extra steps are needed to stop silver nanoparticles from aggregating. Additionally, Silver nanoparticle synthesis from chemical methods can result in the development of toxic by-products [26]. Moreover, most of the reducing and capping agents used in these procedures can be toxic to the environment [27]. The physical method of silver nanoparticle synthesis involves processes such as evaporation, condensation, and laser ablation. Table 2 presents different synthesis methods of nanosilvers.

Table 2. Synthesis conditions of silver nanoparticles and their characterization techniques.

Coating	Reducing agent	Biological Activity	Physical Characterization Techniques	Reference
Polydiallyldimethylammonium chloride capped	Methacrylic acid polymers	Antimicrobial	Ultraviolet-visible spectroscopy, and Reflectance spectrophotometry.	[28]
Polymethacrylic acid	Methacrylic acid polymers	Antibacterial	Ultraviolet-visible spectroscopy, and Reflectance spectrophotometry.	[28]
Uncoated	Ascorbic acid	Antibacterial	Ultraviolet-visible spectroscopy and	[29]

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			Energy filtered transmission electron microscopy	
Chitosan loaded	Polysaccharide chitosan	Antibacterial	Fourier transform infrared, Transmission electron microscopy, X-ray diffraction, Thermogravimetric analysis, and Differential scanning calorimetry	[30]
Uncoated	Hydrazine and D-glucose	N/A	Ultraviolet-visible spectroscopy, and Transmission electron microscopy	[31]
PVP coated	NaBH4	N/A	Ultraviolet-visible spectroscopy, Transmission electron microscopy, Energy-dispersive spectroscopy, Dynamic light scattering, and Flow field-flow fractionation	[32]

Production of nanoscale silver via chemical and physical methods can be expensive, time-consuming, and eco-friendly. To overcome these problems, the biological production of nanosilver has been investigated. This green-mediated synthesis uses reducing agents such as bacteria, fungi, and plant extracts instead of conventional toxic chemical reducing agents. Various studies have been reported that show these green syntheses can be harmless to the environment, as well as possess various activities that can be potentially used in different medical applications[33].

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3. Green Synthesis

To address the problems associated with conventional silver nanoparticle synthesis, various green-mediated production methods have been studied. Producing silver nanocomposites using conventional physical and chemical methods is expensive, toxic, and environmentally harmful. Green-mediated production of nanosilvers can be done via three routes.

1. Microorganisms: Bacteria, Yeasts, Fungi, etc.
2. Plant and plant extracts.
3. Membrane support, DNA template, diatoms, and pigments.

A summary of each of the synthesis processes is discussed in the further sections of this chapter. For the successful synthesis of silver nanoparticles, a metal-ion solution and biological reducing agents are required. Natural reducing agents generally have components that act as capping and subsidizing agents, which is why using biological reducing agents proved more effective, as no extra capping and subsidizing agents are needed[34]. The biological agents used in green synthesis can come from various sources. Although most research has used plant extracts, bacteria and fungi have also been shown to be excellent candidates for this process. After the production, centrifugation is performed to extract the silver nanoparticles in powder form. This can also be done by drying the silver nanoparticle suspension. Characterization techniques such as ultraviolet-visible spectroscopy, scanning electron microscopy(SEM), transmission electron microscopy (TEM), X-ray diffraction analysis (XRD), Zeta potential analysis, Thermo-Gravimetric Analysis, and Inductive Coupled Fourier transform infrared spectroscopy are performed to characterize the synthesized silver nanoparticles[35–38].

3.1. Synthesis of Silver Nanoparticles Using Bacteria

The preparation of inorganic materials using organic reducing agents may seem new, but the first report of such an experiment was published in 1999. Klaus and his team fabricated silver-based crystalline nanoparticles using Pseudomonas stutzeri AG259[39]. Even before this report, Gadd et al. reported silver accumulation in Pseudomonas stutzeri AG259[40]. Although the mechanism by which bacteria synthesize silver nanoparticles remains incompletely understood, several hypotheses have been proposed. The most common hypothesis is reducing silver ions from Ag^{+} to elemental silver, which can accumulate as silver nanoparticles inside the bacterial cells[41–43]. This makes the procedure a bottom-up approach, the schematic of which is shown in the Figure 2 [44].

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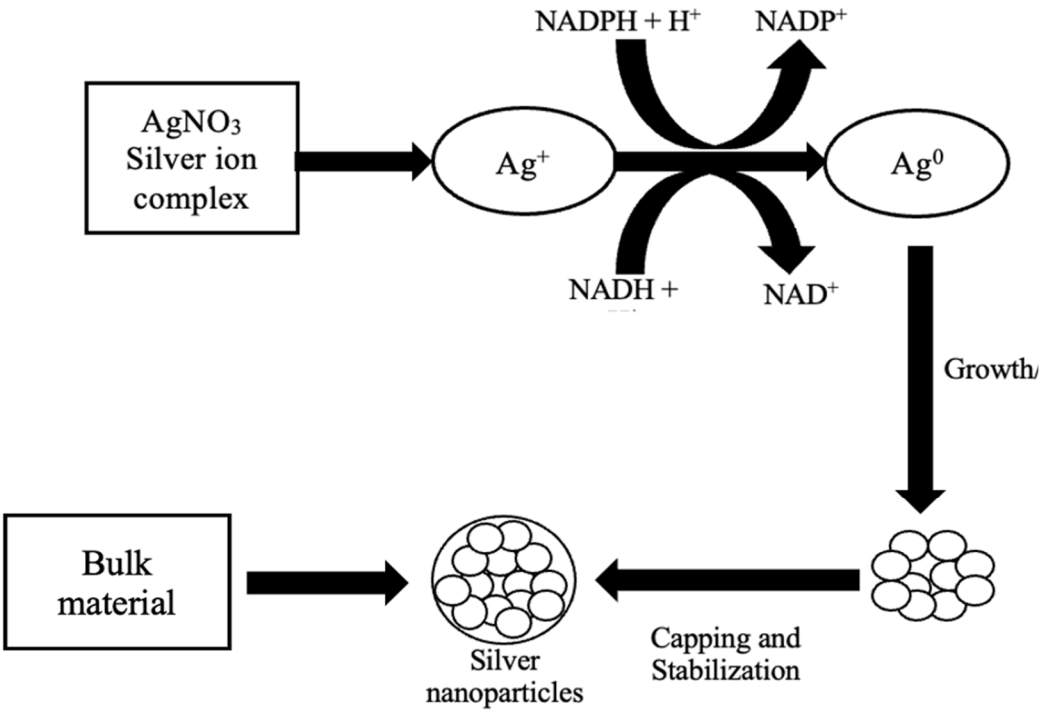

Figure 2. Bottom-up approach of silver nanoparticle synthesis.

Synthesis of silver nanoparticles using bacteria can be done in two ways: extracellular or intracellular. In extracellular synthesis, silver nanoparticles accumulate outside the bacterial cell, whereas in intracellular synthesis, this occurs inside the cell. Extracellularly produced silver nanoparticles vary in size and shape depending on the bacteria [45,46]. In this case, the protein or enzyme secreted from bacterial cell walls and membranes actively participates in the conversion of Ag^{+} to Ag^{0}. Silver nanoparticles produced in this way are used in various applications, such as medical imaging, optoelectronics, and biosensing technologies, because they are easily separated by high-speed centrifugation [47,48]. Table 3 shows various bacteria used in the production of silver nanoparticles.

Table 3. Different gram-positive and gram-negative bacteria used in silver nanoparticle synthesis.

Bacteria	Shape	Type	Size (nm)	Location	Reference
Streptomyces sp. 09 PBT 005	Spherical	Gram-positive	198–595	Extracellular	[49]
Streptomyces sp. SS2	Spherical	Gram-positive	67.95 ± 18.52	Extracellular	[50]
Streptomyces glaucus	Spherical	Gram-positive	4–25	Extracellular	[51]

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Bacillus megaterium	Hexagonal and cubical	Gram-positive	15-50	Extracellular	[52]
Bhargavaea indica strain DC1	Spherical	Gram-positive	30-=100	Extracellular	[53]
Bacillus flexus	Spherical and Triangular	Gram-positive	12-65	Extracellular	[54]
Staphylococcus epidermidis	Oval, rod, and triangular	Gram-positive	<60	Intracellular	[55]
Arthrobacter sp. B4	Face-centered cubic	Gram-positive	9-72	Extracellular	[56]
Pseudomonas stutzeri AG259	Triangular, hexagonal	Gram-negative	200	Cell poles	[57]
Pseudomonas aeruginosa	Spherical and Pseudospherical	Gram-negative	25-45	Extracellular	[58]
Pseudomonas sp.	Variable	Gram-negative	50	Extracellular	[59]
Moganella sp.	Quasi-spherical	Gram-negative	10-40	Extracellular	[60]
Limnothrix sp. 37-2-1	Elongated	Gram-negative	14-31	Extracellular	[61]

3.2. Development of Silver Nanoparticles Using Plant Extract

Plant extracts are another route for synthesizing green-mediated silver nanoparticles. Using plants and plant extracts makes manufacturing silver nanoparticles easier, as these extracts are abundant and contain numerous functional groups that play a vital role in reducing silver ions. Different compounds, such as polysaccharides, tannins, saponins, phenolics, terpenoids, flavones, alkaloids, proteins, enzymes, vitamins, amino acids, and alcoholic components from leaves, roots, latex, bark, stem, and seeds from plant extracts, are used to reduce silver ions and ultimately to produce silver nanoparticles. Figure 3 shows SEM images of silver nanoparticles produced using Aloe Vera plant extract in different thermal conditions [62].

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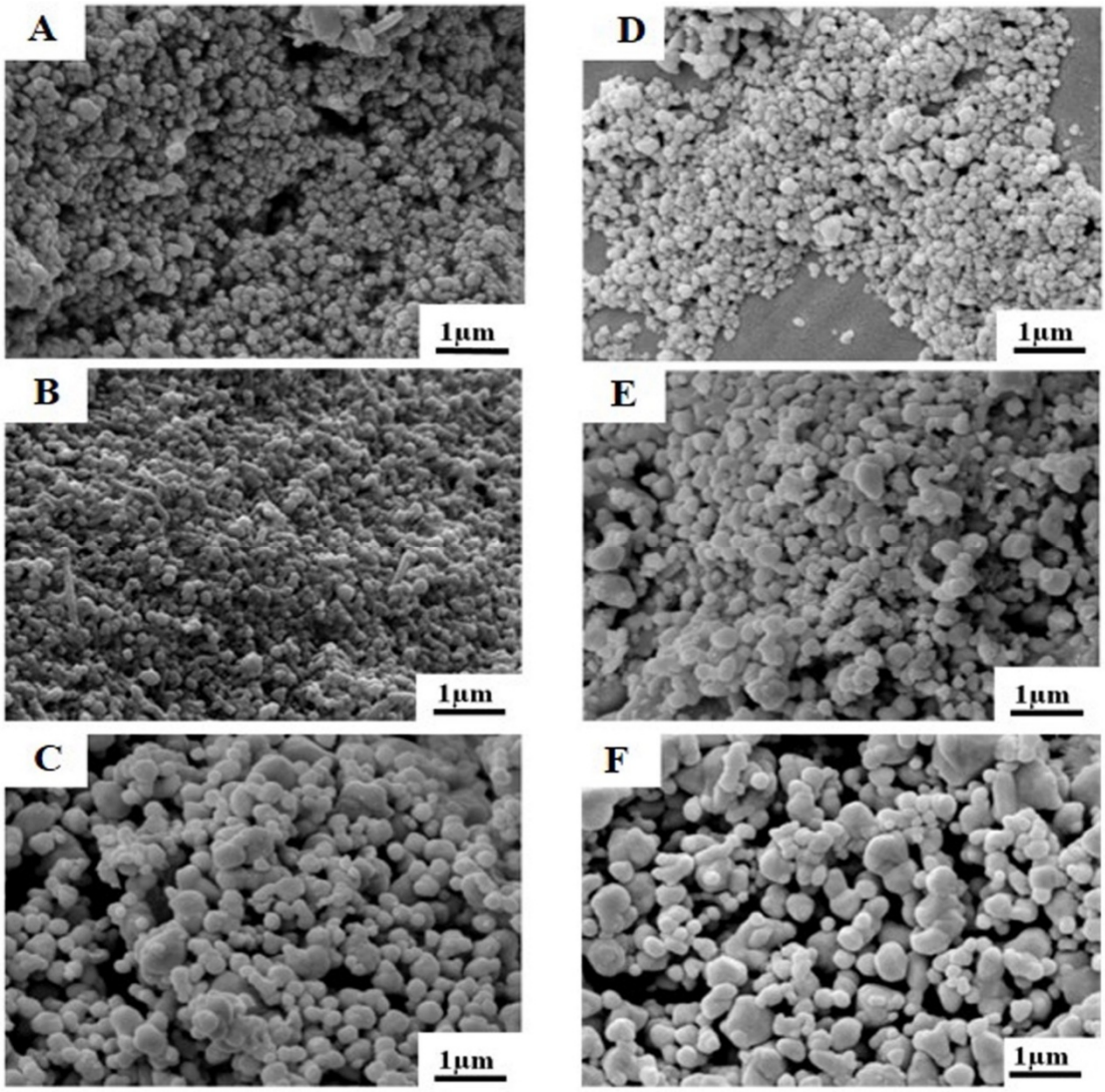

Figure 3. SEM images of silver nanoparticles in different conditions (A) 100 °C for 6 hours (B) 150 °C for 6 hours, (C) 200 °C for 6 hours, (D) 100 °C for 12 hours, (E) 150 °C for 12 hours, and (F) 200 °C for 12 hours [62].

4. Application of Silver Nanoparticles

Green-mediated silver nanoparticles, because of their eco-friendly synthesis, can be used in many applications. Figure 4 shows different applications of silver nanoparticles[63].

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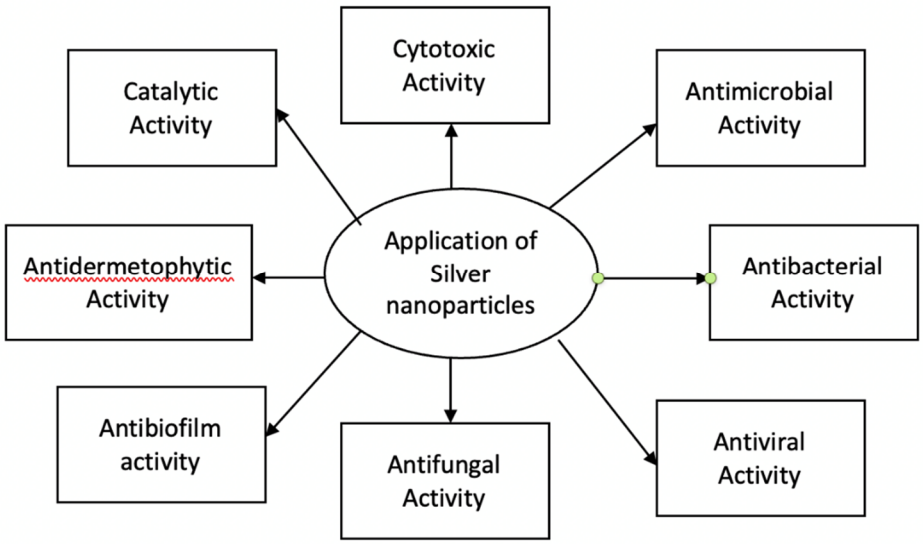

Figure 4. Common applications of silver nanoparticles [63].

4.1. Antibacterial Activities

Because of their smaller size and larger surface area, silver nanoparticles have been reported to work against bacteria[64]. The smaller size allows silver nanoparticles to enter bacterial cells comparatively easily and the greater affinity towards sulfur and phosphorus allows silver nanoparticles to attach to biomolecules that have sulfur and phosphorus in them (sulfurs for proteins and phosphorus for DNA)[65,66]. The mechanism of the antibacterial characteristics of silver nanoparticles can be explained in seven steps[67].

- Silver ions that are released by silver nanoparticles first adhere to bacterial cell membranes and then enter the cells by penetrating the wall.
- Silver nanoparticles stop protein synthesis by denaturing ribosomes.
- Silver ions deactivate respiratory enzymes, which ultimately stops the production of ATP.
- The electron transport chain is broken, which releases reactive oxygen species that can disrupt cytoplasmic membranes.
- Interruption of DNA replication.
- Denaturation of the cell membrane.
- Perforation of the cell membrane, which ultimately results in the release of organelles from inside the bacterial cell.

Several pieces of research have reported that silver nanoparticles synthesized from bacteria showed antibacterial activity against different gram-positive (B. subtilis, B. cereus, E. hirae, S. aureus, S. epidermis, and S. pyogenes) and gram-negative (E. coli, K.planticola, K. pneumoniae, P. vulgaris, P. aeruginosa, Salmonella sp., S. flexneri, and V. cholera) bacteria [68–70].

4.2. Antifungal Activity

As mentioned before, silver nanoparticles have a higher surface-to-volume ratio, enabling greater interaction with fungi. This property can cause oligodynamic effects that ultimately result in changes in cell membrane permeability, protein denaturation, and interruption of DNA replication. Silver nanoparticles have been shown to have antifungal activity against many fungal species, including Phoma glomerata, Phoma herbarum, Fusarium semitectum, Trichoderma sp., and Candida albicans. Silver nanoparticles made from green methods were also shown to enhance the activity of Fluconazole that shows inhibitory activities against Candida albicans, Pterolepis glomerata, and Trichoderma harzianum[71].

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4.3. Catalytic and Antiviral Activity

Some organic compounds can be subject to toxicity and pollution, but some research findings have been reported that show silver nanoparticles reducing those compounds, ultimately reducing the toxicity of those compounds [72–75]. In the presence of Sodium borohydride (NaBH4), nanosilvers have been reported to reduce methylene blue and 4-nitrophenol[76,77]. Silver nanoparticles also have antiviral activity against potent viruses. Some reports showed silver nanoparticles inducing chemokines and cytokines production, which can inhibit HIV viruses[78–82].

5. Source of Silver Nanoparticles in the Environment

Nanosilvers can be released into the environment either from natural sources or anthropogenic sources. Various reports have reported the presence of silver nanoparticles from natural sources, such as mining areas and river waters [83,84]. Researchers reported a reduction of silver ions in the presence of Humic Acid. Humic acid is a natural reducing agent containing many functional groups, such as quinones, ketones, aldehydes, phenols, and hydroxyls, which induce metal ion reduction[85]. Another study reported a reduction of silver ions in the presence of dissolved organic matter and sunlight[86]. Although there are some reports of natural production, the primary route of silver nanoparticle release is through anthropogenic sources. Silver nanoparticles can be released into the environment from electronic devices, textile and manufacturing industries, medical devices, etc.

6. Toxic Effects of Silver Nanoparticles

Nanosilvers, regardless of their synthesis methods, can induce toxicity in various environmental components. Toxicity induced by biological media by silver nanoparticles can be determined in three steps:

- Surface oxidation
- Release of silver ions
- Interaction with biological macromolecules

Silver nanoparticles can react with membrane proteins and activate specific signaling pathways and ultimately inhibiting cell proliferation. Silver nanoparticles can also penetrate the cell by diffusion and cause mitochondrial dysfunction, which can result in the production of ROS that ultimately can damage biological molecules such as DNA and proteins, causing cell proliferation [87–90]. A schematic of the interaction of silver nanoparticles can be shown in Figure 5 [91].

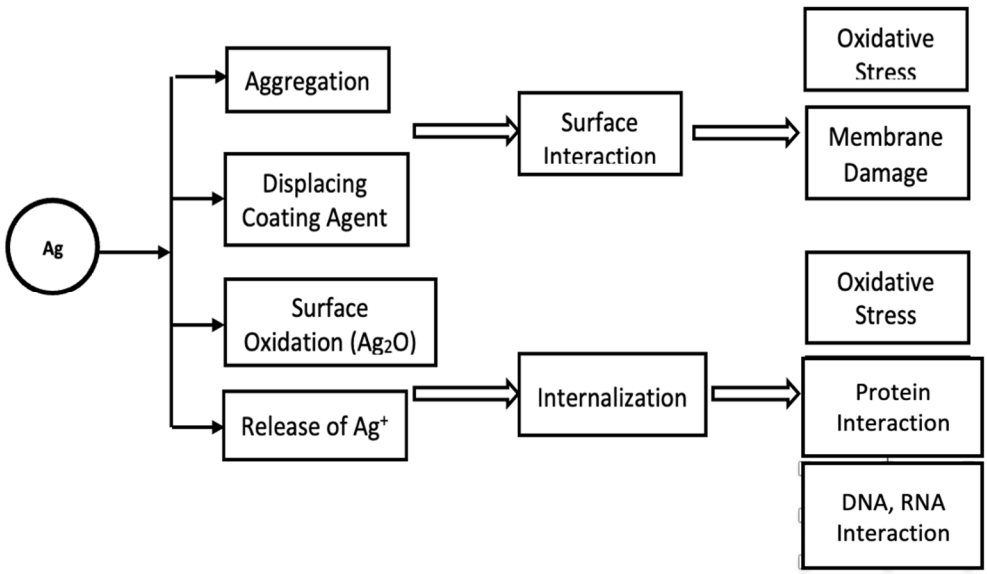

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Figure 5. Silver nanoparticles' interaction with different components of the environment [91].

Although it is still undecided which is the source of silver nanoparticle toxicity. Some studies have tried to debunk this question about silver nanoparticles or silver ions. A toxicity study of silver nanoparticles toward Chlamydomonas reinhardtii was reported by researchers. Cystine was added with silver nanoparticles, which decreased the number of silver ions, ultimately resulting in reduced toxicity of silver nanoparticles[92]. Although it's not yet conclusively determined how much of a role silver nanoparticles play alone in toxicity, many studies report that silver ions certainly contribute to the intensity of induced toxicity.

6.1. Phytotoxicity of Silver Nanoparticles

Many cases of silver nanoparticles poduction using plant extracts have been reported recently. These silver nanoparticles can be harmful to different plants. The mechanism by which silver nanoparticles affect plants is the same as the main mechanism of silver nanoparticle toxicity, which has already been discussed in this chapter. Table 4 demonstrates various reported phytotoxicity results induced by silver nanoparticles in plants.

Table 4. Phytotoxicity results induced by silver nanoparticles in plants.

Diameter (nm)	Concentration	Plants	Results	References
24-55	0-80 mg/L	*Allium cepa*	Development of reactive oxygen species and cell death.	[93]
18-34	0.30-60 mg/L	*Oryza sativa L.*	Damage to cell structure, development of reactive oxygen species, a decline of soluble carbohydrates, and tissue death in root	[94]
47	1-3 mM	Mustard	Reduced seedlings production and oxidative stress	[95]
5-50	800µg/Kg	*Vicia faba L.*	Reduced germination. Reduced root length.	[96]
41	100–5000 mg/L	*Arabidopsis thaliana R*	Decreased root length. Reactive oxygen species accumulation. Induced Ca+ in the cytoplasm.	[97]
12.9 ± 9.1	0.01, 0.05, 0.1, 0.5, 1 mg/L	*Capsicum annuum*	Reduction in plant heights. Increase in cytokines in cells.	[9]

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20	75-300 µg/L	*Arabidopsis thaliana*	Prolonged vegetative and shortened reproductive growth.	[99]
<100	100-500 mg/L	*Cucurbita pepo*	Reduced rate of transpiration	[100]
10	0.2-1 mg/L	*Arabidopsis thaliana*	Reduced chlorophyll. Increased anthocyanin. Greater lipid peroxidation. A dose-dependent increase in Reactive oxygen species production.	[101]
6,20	0.5, 5, 10 mg/L	*Spirodela polyrhiza*	A dose-dependent increase in the amount of reactive oxygen species, peroxidase, and glutathione. Reduced internal thylakoids.	[102]
5-25	0, 5, 10, 20, 40 mg/L	*Phaseolus radiates; Sorghum bicolor*	Inhibited growth of plants	[103]
20	100 mg/L	*Green asparagus*	Increased ascorbic acid and chlorophyll amount	[104]
10	1,2,5,8,10 mg/L	*Wolffia globosa*	Oxidative damage. Increased malondialdehyde (MDA) content. Reduced contents of chlorophyll a, carotenoids, and soluble protein.	[105]
100	50-100 µg/L	*Arabidopsis thaliana*	Greater accumulation of Amino Acids.	[106]
10	0.5, 1.5, 2.5, 3.5, 5 mg/kg	*Triticum aestivum*	Reduced root length. Caused oxidative stress in roots. Induced expression of a metallothionein gene involved in detoxification.	[107]

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25	50, 500, 1000 mg/L	*Oryza sativa*	Cell wall damage. Damaged the vacuoles of root cells.	[108]

6.2. Toxicity Towards Mammals

Table 5 shows various reported toxicity results induced by silver nanoparticles in mammals (Rats and mice). Some studies have reported neurological toxicity in mammalian cell lines induced by silver nanoparticles. Zhaowei et al. injected 10-6, 5×10-6, and 10-5 g/ml of silver nanoparticles of the size of 32.74- 380.25 nm into Rat hippocampal slices and found decreased amplitude of voltage-gated sodium current, which hints toward action potential changes[109]. Trickler et al. reported increased blood-brain barrier (BBB) permeability when they introduced 25-, 40-, and 80-nm silver nanoparticles into rat brain microvessel endothelial cells at a concentration of 50 μg/cm3 [110]. Polyvinylpyrrolidone-coated silver nanoparticles, 75 ± 20 nm in size, incubated in astroglial-rich primary cultures for four hours, showed Upregulation of metallothioneins in cells [111].

Table 5. Toxicity results induced by silver nanoparticles in mammals (Rats and mice).

Size (nm)	Model	Administration	Dose	Toxicity Effects	References
20,100	Rats	i.v.: 28 days	6 mg/kg b.w./day	Only 20 nm AgNPs are toxic. Reduced body weight. Enlarged liver and spleen. Increased liver enzyme activity. Modification of RBC and immune parameters.	[112]
20	Rats	Oral: 800 days	500 mg/kg b.w./day	Reduced body weight. Larger cholesterol and LDL-cholesterol amount A smaller amount of triglycerides. Greater plasmatic alanine transaminase activity. Larger production of liver and cardiac superoxide anion. Increased levels of IL-6 and TNF-α in the liver.	[113]
43.6 ± 6.4	Mice	i.p.: 24 and 72 hours	26, 52 and 78 mg/kg b.w/day	Increased liver enzyme activity. Oxidative DNA damage in lymphocytes. Cell death in the liver. Histopathological changes in the liver.	[114]

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35-45	Mice	Oral: 14 days	50 µl (concentration:20 and 50 ppm)	Increased liver enzyme activity. Histopathological changes in the liver.	[115]
20	Rats	i.v.: Single injection	238-263 µg/kg b.w./day	No change of Glutathione in the liver. Greater mRNA expression of IL-8, IL-1 receptor, and TNF-α.	[116]
22,42, and 71	Mice	Oral: 14 days (22,71 nm) and 28 days (42 nm)	1 mg/kg b.w./day	No change in body weight. Greater amount of TGF-β in serum. Increased level of cytokines. Increased distribution of Natural killer cells. Increased IgE production. No histopathological changes in the liver and kidneys.	[117]
56	Rats	Oral: 90 days	30, 125 and 500 mg/kg b.w./day	Reduced body weights. Increased alkaline phosphatase activity. An increased amount of cholesterol. Increased number of monocytes. No other changes in hematological parameters.	[118]

6.3. Toxic Effects in Aquatic Environment

Although the effects of silver nanoparticles on aquatic animals are not widely studied, it can be hypothesized that silver nanoparticles can pose a threat to aquatic life, as silver ions can continuously be released from silver nanoparticles. Many pieces of research have been conducted by researchers using zebrafish, silver barbs, and goldfish to examine the possible harmful effects of silver nanoparticles on aquatic animals[119–121]. Although the number of fishline studies has been limited due to ethical issues, numerous reports support the toxic effects of silver nanoparticles on aquatic animals. Table 6 shows the effects of silver nanoparticles of different sizes on aquatic vertebrates and algal species under different conditions.

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Table 6. Effect of silver nanoparticles of different sizes on some aquatic vertebrates and algae species under different conditions.

Organism	Size(nm)	Shape	Concentration	Exposure time	Results	References
Zebrafish embryo	20-30	Spherical	10-20 ppt	72 hours	Penetration of silver nanoparticles. Aggregation and silver nanoparticles on the skin and circulatory system.	[122]
Zebrafish	10-20	Spherical	0.4 – 4 ppm	2–36 days	Defects in fin regeneration. Penetration into organelles and cells.	[123]
Zebrafish	26.6+ 8.8 (Metal oxide coated)	Spherical	1000 mg/L	48 hours	Distinct gene expression profile. AgNP's binding with gills.	[124]
Eurasian Perch	81(PVP coated)	Elliptical	63-300 µg/L	2 days	AgNP's binding with gills.	[125]
Brown trout	10-35	Spherical	10-100 µg/L	10 days	Silver nanoparticles accumulation in gills and liver. Oxidative stress in gills.	[126]
Ceriodaphnia dubia	20-30(Metal oxide coated)	Spherical	0.46mg/L-6.18 mg/L	48 hours	Organic matter-dependent AgNP toxicity	[127]

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Daphnia pulex	20-30 ($Na_3C_6H_5O_7$ coated)	Spherical	0.04 mg/L	48 hours	Low toxicity.	[124]
Zebrafish embryo	5-20 (BSA or potato starch coated)	Spherical with borohydride	5-100 mg/L	72 hours	Accumulation in the nucleus, blood, and nervous system	[128]
Thalassiosira weissflogii	60-70 (PVP coated)	Not determined	0.02 to 0.0002 nM	48 hours	Reduced cell growth. Reduced Photosynthesis. Reduced chlorophyll production.	[129]

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Silver nanoparticles can also play a vital role in polluting water. Silver nanoparticles, due to their antimicrobial activities, can reduce the growth of bacteria and other microorganisms, which are essential for water treatment. Additionally, these particles can act against microorganisms in another water source, ultimately disrupting the ecosystem of a certain area [130]. These antimicrobial properties of silver nanoparticles can also harm the soil microbial community, thereby seriously degrading soil quality and ultimately disrupting ecosystems. With the increasing use of silver nanoparticles in many diverse fields, the risk of excess amount silver ions in the environment is also increasing. Although the number of studies is limited, many reports have shown that silver nanoparticles can be harmful in certain environments.

7. Properties and Applications of Green-Mediated Silver Nanoparticles

As mentioned before, silver nanoparticles can have excellent antimicrobial properties, and if these nanoparticles are produced from plant or plant extracts, the antimicrobial properties can increase much more than traditionally prepared silver nanoparticles. When modified by surfactants such as sodium dodecyl sulfate and polyoxyethylene sorbitan monooleate, silver nanoparticles show excellent antibacterial activity against potent bacterial species. But when modified with sodium dodecyl sulfate nanoparticles, showed an enhanced ability to work against bacteria [131,133]. A research study by Sondi et al. reported no potential growth of bacterial species such as E. coli, Vibrio cholerae, Pseudomonas aeruginosa, and Syphilis typhus using a high-angle annular dark-field scanning transmission electron microscopy technique [134]. Figure 6 shows SEM images of silver nanoparticles interacting with different bacterial species [135].

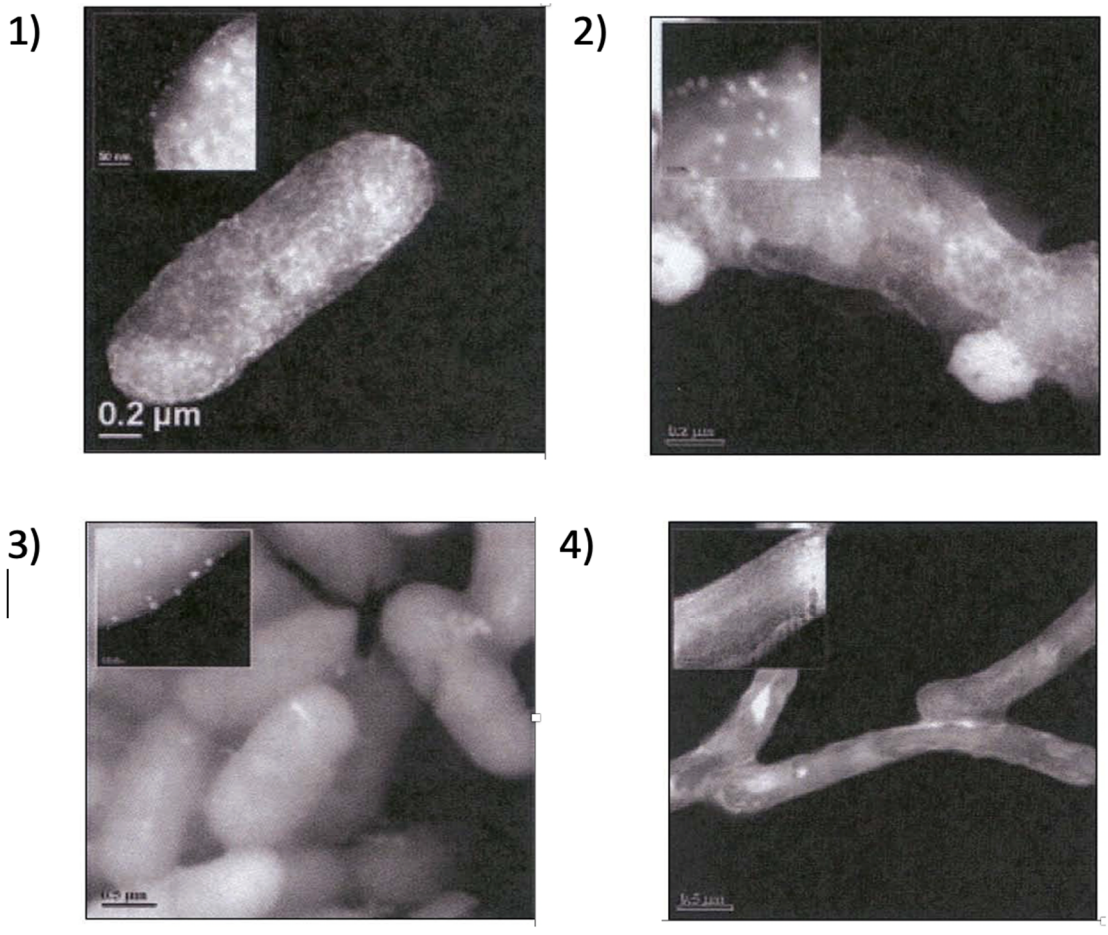

Figure 6. Scanning Electron Microscopy images of silver nanoparticle interaction with 1) *E. coli*, 2) *Vibrio cholerae*, 3) *Pseudomonas aeruginosa*, and 4) *Syphillis typhus*.(Reprinted with permission from [135]).

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Silver nanoparticles prepared from plants and plant extracts have been proven to be effective against biofilms. Biofilms are layers of microbes and can be a major reason for infection. Studies have shown that biofilms are responsible for more than 80% of infectious diseases. Various studies have been reported where the antibiofilm activity of silver nanoparticles is examined [136–141]. As silver nanoparticles have a greater mass-to-volume ratio and better adhesion capacity, these nanoparticles can attach to biofilms and can penetrate easily [142–146].

8. Conclusions and Future Aspects

While chemical and physical methods for silver nanoparticle (AgNP) synthesis are well-established, constraints including high maintenance costs and environmental toxicity have necessitated the development of eco-friendly alternatives. Green synthesis has emerged as a viable solution, utilizing natural reducing agents and producing non-toxic byproducts. These green-mediated routes have proven efficient and sustainable, yielding particles with unique properties suitable for a wide range of "magical" applications across various industries. The versatility of AgNPs is demonstrated across multiple sectors. Their catalytic activity is utilized in fields ranging from textiles to electronic manufacturing. Furthermore, AgNPs exhibit exceptional antimicrobial, antibacterial, antiviral, and antifungal properties, as well as specific cytotoxic effects. These characteristics have led to their integration into the agricultural and medical sectors, particularly in the development of active food packaging and infectious disease control. Despite these advancements, the rising use of AgNPs raises significant toxicity concerns. AgNPs can negatively impact both harmful and beneficial microorganisms, as well as plant and aquatic life, if environmental release is not strictly controlled. While the exact mechanisms of toxicity—whether derived from the nanoparticles themselves or from the silver ions they release—remain under investigation, evidence suggests that the extent of toxicity depends heavily on the concentration of silver ions.It is hypothesized that incorporating materials capable of binding silver ions to AgNPs could significantly reduce toxicity. Currently, most toxicological data is derived from studies on plants and aquatic organisms. To gain a comprehensive understanding of the potential risks to human health, future research must prioritize extensive studies on terrestrial animals and mammals.

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