

Ecofriendly Synthesis of Silver Nanoparticles as Antimicrobial Active Agents from Its Cationic Precursors

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Abstract: This review presents a comprehensive survey on the green synthesis of silver nanoparticles from silver nitrate precursor using plant extracts along with their characterization and antimicrobial activity assessment. The synthesis of silver nanoparticles through a green chemistry approach is increasingly in demand because it is environmentally friendly, easy to do, and efficient, especially for the purpose of antimicrobial active ingredients in disinfectant and antiseptic formulas. Green synthesis of silver nanoparticles can be carried out using silver nitrate as a silver precursor and plant extracts as a source of bioreductants and capping agents. The synthesis products are then characterized using UV-Vis spectroscopy to analyze their size and stability, SEM and TEM to analyze their size, shape, and surface morphology, FTIR to analyze the presence and changes of functional groups and chemical bonds, and XRD to determine the crystal structure. Several other characterization methods can also be used according to the research objectives. The obtained silver nanoparticles have a significant ability to kill bacteria so that they can increase the effectiveness of the performance of disinfectant formulas and antimicrobial formulations made from plant extracts and are more environmentally friendly.

Keywords: antimicrobial activity, characterization, green synthesis, plant extract, silver nanoparticles

Abstrak: Tinjauan ini menyajikan survei komprehensif tentang sintesis hijau AgNPs dari prekursor perak nitrat menggunakan ekstrak tanaman beserta karakterisasi dan uji aktivitas antimikrobanya. Sintesis AgNPs melalui pendekatan kimia hijau semakin diminati karena ramah lingkungan, mudah dilakukan, dan efisien, terutama untuk tujuan bahan aktif antimikroba dalam formula disinfektan dan antiseptik. Sintesis hijau AgNPs dapat dilakukan menggunakan AgNO_3 sebagai prekursor perak dan ekstrak tanaman sebagai sumber bioreduktor dan capping agents-nya. Produk sintesis selanjutnya dikarakterisasi menggunakan spektroskopi UV-Vis untuk menganalisis ukuran dan kestabilannya, SEM and TEM untuk menganalisis ukuran, bentuk, dan morfologi permukaannya, FTIR untuk menganalisis keberadaan dan perubahan gugus fungsi dan ikatan kimianya, dan XRD untuk menentukan struktur kristal. Beberapa metode karakterisasi yang lain juga dapat digunakan sesuai dengan tujuan penelitiannya. Nanopartikel perak yang diperoleh memiliki kemampuan signifikan untuk membunuh bakteri sehingga dapat meningkatkan efektivitas kinerja formula disinfektan maupun formula sediaan anti mikroba yang terbuat dari ekstrak tumbuhan dan lebih ramah lingkungan.

Kata kunci: aktivitas antimikroba, karakterisasi, sintesis hijau, ekstrak tanaman, nanopartikel perak

INTRODUCTION

One of the environmental health problems is caused by pathogenic bacteria attack. Therefore, researchers are trying to find methods and ingredient formulas to inhibit the growth of these bacteria. Bacteria are single cell microorganisms. The size of a bacterial cell is generally 0.5 - 1.0 μm (500 – 1000 nm) and has three basic shapes, namely spheric or coccus, rod or bacillus, and spiral (Kaiser 2021). Prevention of harm caused by bacteria can be done by using antiseptics or disinfectants (Singh &

Mijakovic 2022). However, most antiseptics and disinfectants are made from not environmentally friendly and toxic chemical such as ethanol solvent, sodium metasilicate, triclosan, and antimicrobial active ingredients (Watoni *et al.* 2022). One effort to overcome this problem is to use safer antimicrobial active ingredients, namely metallic nanoparticles (Eker *et al.* 2025; Liao *et al.* 2025).

Nanoparticles have sizes in the range of 1 – 100 nm (Abbas *et al.* 2024; Almatroudi 2020; Dechakupt *et al.* 2026; Eker *et al.* 2024; Rakib-Uz-Zaman *et al.*

2022). Compared to their constituent larger particles of the bulk materials, nanoparticles exhibit improved properties based on specific features such as better size, distribution, and morphology (Bekele *et al.* 2026; Dechakupt *et al.* 2026; Rakib-Uz-Zaman *et al.* 2022). Metal nanoparticles are smaller than microorganism size, so that these nanoparticles can penetrate microbial cell walls (Eker *et al.* 2024; Rakib-Uz-Zaman *et al.* 2022; Siddiqi *et al.* 2018). Nanoparticles react with chemical species in cells and the cell wall so that the microbes death (Thiruvengadam & Bansod 2020; Wang *et al.* 2017). One of effective antimicrobial agent still being studied is silver nanoparticles (AgNPs) (Amaliyah *et al.* 2022; Cheng *et al.* 2022; Escárcega-González *et al.* 2018; Estevez *et al.* 2025; Kabeya *et al.* 2025; Khaldoun *et al.* 2025; Mahmud *et al.* 2022; Singh & Mijakovic 2022).

AgNPs can kill microbes through in vitro and in vivo chemical reactions (Bhosale *et al.* 2015; Bruna *et al.* 2021). AgNPs can attack bacterial cell walls and penetrate them, so they can damage cell walls and membranes (Rakib-Uz-Zaman *et al.* 2022). In fact, AgNPs can form highly reactive free radicals that can kill bacteria. In addition, AgNPs can also form silver ions in cells and inactivate bacterial enzymes and produce reactive oxygen species which can also attack bacterial cells (Tābāran *et al.* 2020).

AgNPs have been shown to have significant antimicrobial activity, non-toxic and stable (Nahar *et al.* 2020; Offor *et al.* 2021; Thiruvengadam & Bansod 2020; Wang *et al.* 2017). Therefore, they can be used as an antimicrobial active ingredient in eco-friendly antiseptics and disinfectants (Bhosale *et al.* 2015; Bruna *et al.* 2021; Enan *et al.* 2021; Fibriana *et al.* 2020; Islam *et al.* 2026; Warsito 2020). In addition, AgNPs are easily synthesized by applying physical, chemical, and bioreduction (green synthesis) methods. Previous research reports described the advantages of AgNPs synthesis through the bioreduction method using plant extracts or green synthesis compared to biological, physical and chemical methods (Ansari & Alzohairy 2018; Gavade *et al.* 2015).

Physical methods of AgNPs synthesis can be carried out through a heating process at high temperatures which requires a lot of energy and expensive equipment costs so it is seen as inefficient (Rakib-Uz-Zaman *et al.* 2022). The synthesis of AgNPs using chemical methods requires chemical reducing agents that are toxic and not environmentally friendly (Bekele *et al.* 2026; Chadha *et al.* 2024; Rakib-Uz-Zaman *et al.* 2022). To obtain small nanoparticles, synthesis through chemical methods requires NaBH_4 as a reducing agent or synthetic polymers such as polyvinyl chloride (PVC), polyethylene glycol (PEG), polyvinyl alcohol (PVA), and hydroxyethyl cellulose (HEC) as stabilizers (Almatroudi 2020; Ansari & Alzohairy 2018; Khaldoun *et al.* 2025; Thiruvengadam & Bansod

2020). All of these stabilizers are also toxic and not environmentally friendly. Green synthesis approach is currently a trend in environmentally friendly metal synthesis (Ahmad *et al.* 2025; Basaiawmoit *et al.* 2026; Dikshit *et al.* 2021; Jannik 2025; Usman *et al.* 2024). One of green synthesis approach use plant extract as biological sources of reducing compounds (Aryasa & Artini 2023; Elias *et al.* 2025; Hajizadeh *et al.* 2024; Hamadi *et al.* 2026; Karakaş *et al.* 2023; Rakib-Uz-Zaman *et al.* 2022; Shereen *et al.* 2024) (Barad & Ambechada 2024; Hussain *et al.* 2023a; Rakib-Uz-Zaman *et al.* 2022). In the bioreduction process, plant extracts not only function as reducing agents, but also as capping agents or stabilizing agents (Forough & Khalil 2010; Kuswaha 2026; Mohamed 2025; Mussin *et al.* 2021; Remya *et al.* 2022; Sujatha *et al.* 2026).

AgNPs synthesis is applied through a bioreduction process from silver ion precursors is seen as more environmentally friendly, easy to perform, and more efficient (Ahmad *et al.* 2025; Ansari & Alzohairy, 2018; Jafari *et al.* 2015; Mohamed *et al.* 2021; Kuswaha 2026; Lestari *et al.* 2019; Polivanova *et al.* 2021; Rakib-Uz-Zaman *et al.* 2022; Smitha *et al.* 2022; Sujatha *et al.* 2026). The use of plant extract eliminate the need of toxic reducing agents and support a simple, cost-effective, and environmentally benign route for nanoparticle production (Ahmad *et al.* 2025; Alharbi *et al.* 2022; Aryasa & Artini 2023; Basaiawmoit *et al.* 2026; Jannik 2025; Karakaş *et al.* 2023; Kuswaha 2026; Mohamed 2025; Rakib-Uz-Zaman *et al.* 2022; Sujatha *et al.* 2026; Wasilewska *et al.* 2023). Plant extracts as a source of bioreductors are easy to find and widely available (Bekele *et al.* 2026; Hussain *et al.* 2023b, 2023a). This biosynthetic process can be carried out at room temperature (Watoni *et al.* 2022; Singh *et al.* 2021). That is why, the synthesis of AgNPs using bioreduction method is a superior green synthesis approach (Bhosale *et al.* 2015; Simon *et al.* 2021).

The antimicrobial activity depends on the size and morphology of the nanoparticles (Pérez-Díaz *et al.* 2015; Polivanova *et al.* 2021). Therefore, the process of AgNPs synthesis must be followed by characterization to determine their size and morphology (Ali *et al.* 2026; Asif *et al.* 2022; Desu *et al.* 2025; Jain *et al.* 2021; Kaabour *et al.* 2026; Lima *et al.* 2024; Marković *et al.* 2024; Nkosi *et al.* 2024; Riaz *et al.* 2026; Sakilam & Reddy 2023; Galatage *et al.* 2021; Tunç 2024). Nanoparticles formed can be analyzed using a UV-Vis spectroscope and Fourier transform infrared (FTIR) spectroscope (Bhosale *et al.* 2015; Jannik 2025; Thomas *et al.* 2014). The size of the nanoparticles and their morphology can be determined using a transmission electron microscope (TEM) and a scanning electron microscope (SEM) (Bhosale *et al.* 2015; Enan *et al.* 2021; Jannik 2025; Marslin *et al.* 2015; Thomas *et al.* 2014).

This review article aims to report the results of research in the last thirteen years regarding the synthesis of AgNPs through the bioreduction process of silver cations using the procedure for submitting research articles based on keywords related to the title of this review article. The procedure for compiling a review of this article is a suitable and effective guide, especially for novice researchers, because the procedure is easy to do, but can compile a large number of journal articles. These journals became a source of inspiration in determining the title and topic of this review article. The author search and collect the literature through the Google searching engine to find research articles in pdf format in the period 2010 – 2026. This searching was able to collect 1085 articles published by more than 150 publishers. From the collection of articles, 1046 (96,64%) are original research journals, 11 (1.01%) are article review journals, 9 (0.83%) are papers/reports, 3 (0.28%) are books, and 16 (1.47%) are theses and dissertations. These data indicate that there are still few article reviews on AgNPs and their antimicrobial applications, so writing article review is still considered important to provide broader information. Of all these articles, a total of 125 articles were reported in this article review. The reported review includes the AgNPs synthesis procedure, characterization, and antimicrobial activity testing.

OUTLINE OF RESEARCH PROCEDURE

General green synthesis of AgNPs was carried out by adding a certain volume of bioreductor extract solution to a certain concentration of AgNO_3 (Figure 1) (Elias *et al.* 2025). The composition of solution mixture of the precursor with bioreductor extract was varied to obtain the optimum. Optimization is generally carried out to determine the volume ratio of precursors to their bioreductors, temperature, and proper heating time. The colloidal AgNPs obtained was then characterized using a UV-Vis spectrometer, SEM, TEM, PSA, XRD, FTIR, and others (Elias *et al.* 2025; Jain *et al.* 2021; Kuswaha 2026; Mohamed 2025; Rakib-Uz-Zaman *et al.* 2022; Siddiqi *et al.* 2018). The UV-Vis spectrometer is used to determine surface plasmon resonance (SPR) (Adhikari *et al.*

2022; Elias *et al.* 2025; Kuswaha 2026; Mohamed 2025). SEM was used to determine the morphology and distribution of particles (Adhikari *et al.* 2022; Mohamed 2025). TEM and PSA were used to determine the average particle size (Watoni *et al.* 2022; Hassanvand *et al.* 2022; Kambale *et al.* 2020). XRD spectroscopy was used to determine the elemental composition, structure and crystal size of AgNPs (Adhikari *et al.* 2022; Elias *et al.* 2025; Hassanvand *et al.* 2022; Mohamed 2025). FTIR is used to identify the functional groups of bioreductor compounds such as hydroxyls, alkynes, alkanes, alkenes, and esters which indicate a redox reaction between the bioreductor compound and silver ions (Akintelu *et al.* 2020; Elias *et al.* 2025; Meer *et al.* 2022; Mohamed 2025). Final procedure is antimicrobial assessment of the AgNPs product.

PLANT EXTRACT MEDIATED GREEN SYNTHESIS OF SILVER NANOPARTICLES

AgNPs green synthesis is the cationic bioreduction method using plant extracts. According to the phytochemicals in their extract, certain plant parts as stems, roots buds, leaves, seeds and rhizomes have been utilized to synthesize AgNPs (Figure 2) (Alharbi *et al.* 2022). Bioreductor compounds can simultaneously act as stabilizing agents, making them more environmentally friendly (Alharbi *et al.* 2022; Kuswaha 2026; Mohamed 2025). AgNPs synthesis scheme from Ag^+ precursors are shown in Figure 3. Silver ions (Ag^+) receive electrons from the reducing agent and converted to be the metallic form (Ag^0), which finally aggregates to form stable AgNPs (Almatroudi 2020).

The Role of Plant Extract in Green Synthesis

It is vital to understand the process and metabolic pathways that contribute to the manufacture of metal nanoparticles to establish a good strategy for AgNPs green synthesis. Silver nitrate (AgNO_3) has so far been seen as a good precursor. One strong reason for the ease of reduction of silver ions into AgNPs is the high standard reduction potential of Ag^+/Ag , which is around 0.80 V (Christian *et al.* 2014; Xing *et al.* 2018). Almost all plant extracts containing secondary

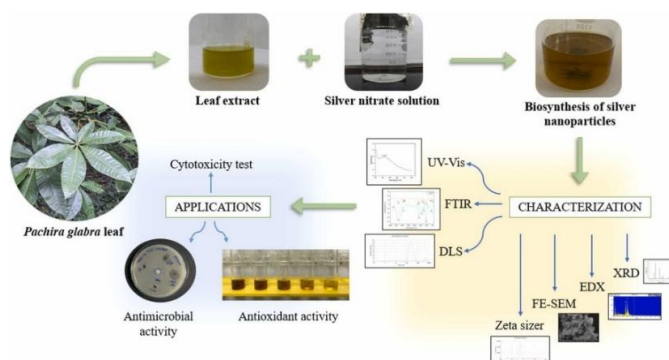


Figure 1. General research prosedure in green synthesis of AgNPs (Elias *et al.* 2025)

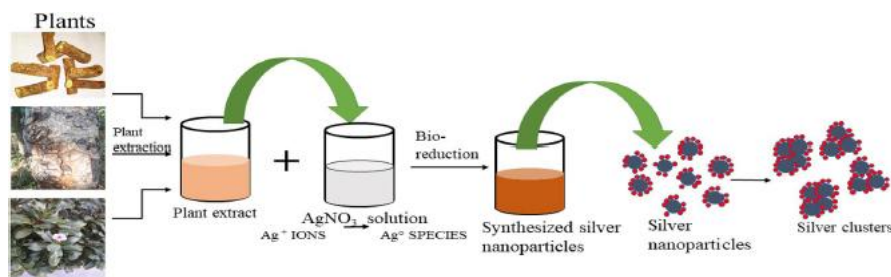


Figure 2. Schematic representation of AgNPs synthesis from Ag^+ precursors using plant extract bioreductors (Jain *et al.* 2021)

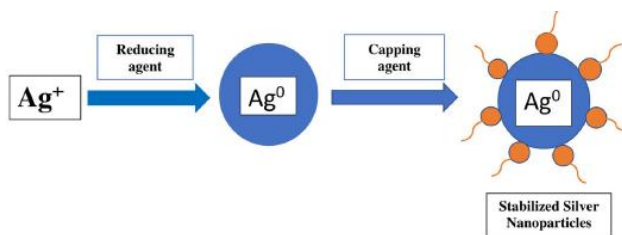


Figure 3. Outline formation of silver nanoparticles through green synthesis approach

metabolites such as xanthone and their derivatives, flavonoids, alkaloids, coumarins, and anthocyanins can be used as bioreductors in the synthesis of AgNPs (Almatroudi 2020; Bekele *et al.* 2026; Jannik 2025; Kuswaha 2026).

Theoretically, the process of forming AgNPs occurs through the stages of bioreduction of silver cations (Ag^+) to form silver atoms (Ag^0), nucleation of silver atoms to form atomic clusters (AgNPs), and stabilization of AgNPs by capping agents (Almatroudi 2020; Kuswaha 2026). In this case, apart from being a bioreductor, plant extracts also act as capping agents (Almatroudi 2020; Bhosale *et al.* 2015; Fibriana *et al.* 2020; Joshi *et al.* 2025; Kuswaha 2026). One of the studies describing the process of forming silver nanoparticles is shown in Figure 4 (Alharbi *et al.* 2022). There is a possibility that the tautomeric transformation of flavonoids from the enol form to the keto form can release reactive hydrogen atoms which reduce silver ions (Ag^+) into Ag^0 atoms. The Ag^0 atoms that are formed then undergo aggregation and clustering by bioreductant molecules through coordination bonds to form nanometer-sized clusters of AgNPs. Thus, in the formation of AgNPs, the secondary metabolite molecules in plant extracts simultaneously act as bioreductants and capping agents.

Possible Mechanism in AgNPs Formation

AgNPs is formed through three stages, namely ion reduction, grouping, and formation of nanoparticles. According to several studies, the -OH group found in flavonoids will be responsible for the reduction of silver ions to AgNPs (Alharbi *et al.*

2022; Susanti *et al.* 2022). The mechanism of reduction-oxidation of silver ions with flavonoid molecules is described in Figure 4 (Alharbi *et al.* 2022). Compounds such as flavonoids, terpenoids, and polyphenols donate electrons to reduce Ag^+ , while functional groups like hydroxyl and carbonyl assist in nucleation and growth (Jannik 2025). An example of the mechanism of bioreduction of Ag^+ cations to form AgNPs using the bioreductor compound quercetin is shown in Figure 5 (Jain & Mehata 2017). The size and stability of the AgNPs formed depend on the experimental conditions such as the nature of bioreducing plant extracts, the concentration of silver precursors, pH, and the concentration of reducing agents (Alharbi *et al.* 2022; Saxena *et al.* 2016).

Visual Observation of AgNPs Products

The bioreduction process can be observed visually based on the color changes of plant extract liquid and AgNO_3 solution (Polivanova *et al.* 2021; Rautela *et al.* 2019). The color change of the liquid plant extract from brownish black to a lighter color after adding a colorless silver nitrate solution shows formation of AgNPs (Fibriana *et al.* 2020; Mlalila *et al.* 2017). Other studies have shown that color change of the mixture solution from yellow to brown or brown to black indicates the formation of AgNPs and their surface plasmon resonance (SPR) (Jafari *et al.* 2015; Jannik 2025; Lestari *et al.* 2019; Polivanova *et al.* 2021; Sheikholeslami *et al.* 2016). The difference in color change depends on reducing organic compounds contained in each type of plant extract. In general, organic compounds that can act as

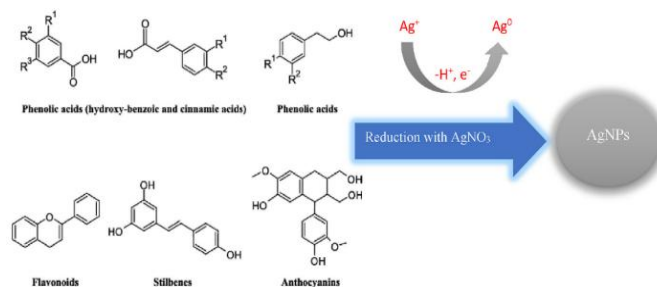


Figure 4. Description of the formation of AgNPs through bioreduction reactions (Alharbi *et al.* 2022).

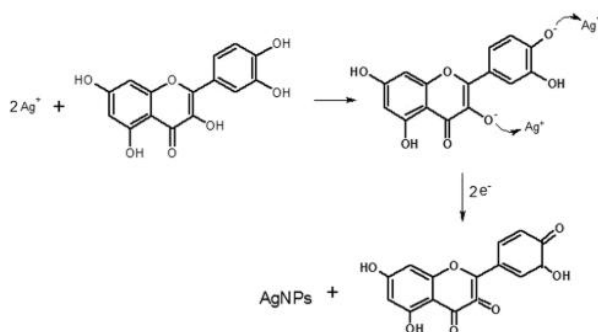


Figure 5. Reduction mechanism of silver ions to AgNPs by quercetin molecule (Jain & Mehata 2017).

bioreductor compounds are carbohydrates, enzymes, flavonoids, terpenoids, polyphenols, and alkaloids (El-Shahaby *et al.* 2013; Jannik 2025; Rautela *et al.* 2019). The success of AgNPs synthesis using the cationic bioreduction method can be evaluated using a UV-Vis spectrometer which shows the stability of the nanoparticles at a single maximum wavelength of 418 - 450 nm which is stable (Akintelu *et al.* 2020; Enan *et al.* 2021; Kambale *et al.* 2020; Sheikholeslami *et al.* 2016).

The Role of Synthesis Parameters

The formation and properties of AgNPs depend on multiple factors including extract plant concentration, pH, temperature, reaction time, and AgNO₃ concentration. The concentration of plant extract determines the balance between reduction and capping, influencing particle uniformity (Jannik 2025). A higher extract-to-precursor ratio typically provides more reducing and capping agents, leading to faster reduction and better stabilization, often yielding smaller particles. However, an excess can sometimes lead to over-capping and aggregation. This parameter must be optimized for each plant-extract system, as there is no universal ideal condition, representing a significant challenge for scalable reproducibility (Alharbi *et al.* 2022; Amaliyah *et al.* 2022; Amin *et al.* 2026; Bekele *et al.* 2026; Mulyana *et al.* 2024; Sulaiman *et al.* 2024; Rakib-Uz-Zaman *et al.* 2022; Rizki *et al.* 2026; Salih *et al.* 2024; Varghese *et al.* 2024). Alkaline pH (e.g., 8–10) often favours the deprotonation of phenolic –OH groups, enhancing their reducing power and

leading to smaller, more monodisperse AgNPs (Alharbi *et al.* 2022; Amaliyah *et al.* 2022; Bekele *et al.* 2026; Hajizadeh *et al.* 2024; Jannik 2025; Mohamed *et al.* 2022; Mulyana *et al.* 2024; Rakib-Uz-Zaman *et al.* 2022). Elevated temperature generally accelerate reduction kinetics, leading to a higher nucleation rate (Jannik 2025). This temperature often results in a larger number of smaller nuclei and, consequently, smaller size of final AgNPs (Alharbi *et al.* 2022; Amaliyah *et al.* 2022; Hajizadeh *et al.* 2024; Mohamed *et al.* 2022; Rakib-Uz-Zaman *et al.* 2022). Additionally, reaction time and AgNO₃ precursor concentration play a key role in controlling particle growth and surface plasmon resonance (RPS) of produced AgNPs (Alharbi *et al.* 2022; Bekele *et al.* 2026; Mlalila *et al.* 2017; Rakib-Uz-Zaman *et al.* 2022; Sujatha *et al.* 2026). Optimization of these parameters ensures reproducible nanoparticle synthesis with desirable physicochemical and biological properties.

CHARACTERIZATION

The most famous very common methods which are applied for the nanoparticle synthesis and characterization are Ultraviolet–Visible (UV) spectroscopy, Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), Fourier Transform Infrared (FTIR) Spectroscopy, and X-Ray Diffraction (XRD) Spectroscopy. UV spectroscopy was used to analyze the size and stability, SEM, TEM, and Field Emission Scanning Electron Microscopy (FESEM) were used to provide detail size, shape, and morphology, FTIR was used to

analysis functional groups, XRD was used to determine the crystal structure of AgNPs, and Dynamic Light Scattering (DLS) was used to measure size distribution. Characterization techniques for synthesized AgNPs are summarized in Table 1

PROPOSED MECHANISM OF ANTIMICROBIAL ACTIVITY

The real mechanisms of antibacterial activities which carried out through AgNPs are nearly well-debated topic. In general, there are four theories that explain the mechanism of the antimicrobial activity of AgNPs (Liao *et al.* 2025). First, AgNPs react with bimolecules and act as catalytic cofactors against reactive oxygen species (ROS) such as residual oxygen (O_2), hydroxyl radicals ($\bullet OH$), superoxide anion (O_2^-), and hydrogen peroxide (H_2O_2) produced by cell oxidative metabolism when these active oxygen species are produced or catalyzed by cell enzymes that cause the microbe to die (Dechakupt *et al.* 2026; Thiruvengadam & Bansod, 2020). Secondly, silver metal ions are absorbed into cells by penetrating the cell walls and inhibiting enzymatic activity in cells due to their interactions with protein

functional groups and nucleic acids which affect their physiological processes (Dechakupt *et al.* 2026; Liao *et al.* 2025). Third, physical interaction. Gram-negative bacteria are more susceptible to nanoparticle attack than Gram-positive bacteria because their cell wall structure is thinner and helps release silver ions from the nanoparticles into the cell. In addition, Gram negative bacteria have a higher affinity for positive ions due to their electrostatic interactions (Dechakupt *et al.* 2026; Liao *et al.* 2025). Fourth, internalization into cells. Smaller particles diffuse more easily into cells through endocytosis followed by the release of AgNPs positive ions which causes oxidative stress and increases the number of ROS in cells which in turn causes cell death. So, this antimicrobial activity can be confirmed to occur on the outside of the cell wall as well as inside the cell (Dechakupt *et al.* 2026; Liao *et al.* 2025).

The antimicrobial activity of AgNPs is influenced by the size, shape, charge, and surface conditions of the particles. The smaller the particle size, the faster the catalytic antimicrobial reaction (Thiruvengadam & Bansod 2020). Therefore, AgNPs have better antimicrobial activity than bulk phase silver (Smitha *et al.* 2022). Spherical AgNPs have higher

Table 1. General impotent techniques of AgNPs characterization

Technique	Purpose	Observation	References
UV-Vis Spectroscopy	Confirm nanoparticle formation	Absorption peak at 420 nm, surface plasmon resonance (SPR), nanomaterial stability, and size particle prediction	(Ahmad <i>et al.</i> 2025; Ali <i>et al.</i> 2026; Elias <i>et al.</i> 2025; Watoni <i>et al.</i> 2022; Islam <i>et al.</i> 2026; Jannik, 2025; Joshi <i>et al.</i> 2025; Meer <i>et al.</i> 2022; Mohamed, 2025; Rakib-Uz-Zaman <i>et al.</i> 2022; Salnus <i>et al.</i> 2022)
FTIR	Detect functional groups in capping agents	$-OH$, $-C=O$, $-NH$, $C\equiv C$, $C=C$, $C-H$, and $C-O$ bands	(Ahmad <i>et al.</i> 2025; Elias <i>et al.</i> 2025; Watoni <i>et al.</i> 2022; Islam <i>et al.</i> 2026; Jannik 2025; Joshi <i>et al.</i> 2025; Meer <i>et al.</i> 2022; Mohamed 2025; Parajuli <i>et al.</i> 2025; Salnus <i>et al.</i> 2022; Sujatha <i>et al.</i> 2026)
SEM/TEM, FESEM	Analyze morphology, shape, and size	Spherical particles (20–60 nm)	(Ahmad <i>et al.</i> 2025; Ali <i>et al.</i> 2026; Elias <i>et al.</i> 2025; Islam <i>et al.</i> 2026; Jannik 2025; Joshi <i>et al.</i> 2025; Mohamed 2025; Parajuli <i>et al.</i> 2025; Salnus <i>et al.</i> 2022; Sujatha <i>et al.</i> 2026)
XRD	Identify crystalline structure and phase purity	Face-centered cubic (FCC) structure	(Ahmad <i>et al.</i> 2025; Elias <i>et al.</i> 2025; Islam <i>et al.</i> 2026; Jannik, 2025; Mohamed 2025; Parajuli <i>et al.</i> 2025; Sujatha <i>et al.</i> 2026)
DLS	Measure size distribution	Average 45 nm	(Elias <i>et al.</i> 2025; Jannik 2025; Mlalila <i>et al.</i> 2017; Sujatha <i>et al.</i> 2026)

antimicrobial activity compared to nanoparticles in the form of wire, cube, triangle, and decahedron, because they have a higher rate of mobility, both outside and inside, when penetrating the cell wall (Raza *et al.* 2016). AgNPs with an uncoated surface are more reactive than those with a coated surface because they can interact directly with the cell wall and penetrate the cell wall without being hindered by the surface layer. The influencing factors and the alleged antimicrobial mechanism of AgNPs are shown in Figure 5. Based on antimicrobial activity test using wall diffusion method, the larger the clear zone diameter, the higher its antimicrobial activity (Lestari *et al.* 2019). Referring to the clear zone diameter, antibacterial activity were categorized as follows: diameter > 20 mm is very strong, 11-20 mm is strong, 6-10 mm is moderate and < 5 mm is weak.

RECENT REVIEW OF GREEN SYNTHESIS, CHARACTERIZATIONS, AND ANTIMICROBIAL ASSESSMENTS

Many plant extracts have been used for green synthesis of AgNPs. Green synthesis of AgNPs using *Solanum incanum* leaf extract produce the nanoparticles that role as antibacterial active agents against *Escherichia coli* (*E. coli*) and *Staphylococcus aureus* (*S. aureus*). Characterization of the AgNPs using FTIR, UV-visible spectroscopy, and XRD confirming successful synthesis with average particle sizes of 23.28 nm. The antibacterial activity of the AgNPs using the disc-diffusion method demonstrated significant antibacterial activity. These findings underscore the potential of *Solanum incanum*-mediated AgNPs as eco-friendly antimicrobial agents. (Dhaif-Allah *et al.* 2025).

Green synthesis of AgNPs was also attained utilizing an aqueous rhizome extract of *Curcuma*

longa (Cl). The synthesized Cl-AgNPs was performed utilizing some instruments. UV-vis spectroscopy substantiated successful synthesis of Cl-AgNPs, as there was a change in SPR peak from $\lambda_{\max}$ 416 nm to $\lambda_{\max}$ 423 nm. XRD showed that the nature of Cl-AgNPs is crystalline and FCC structure. The average size of the crystallites was observed to be 16 nm through Debye-Scherrer equation. SEM/TEM analysis depicted that the size range of the AgNPs are of 30-70 nm and spherical in shape. Additionally, antibacterial assessment of the Cl-AgNPs through the broth dilution method and well-diffusion method showed that Cl-AgNPs are effective in inhibiting *E. coli* (Gram-negative) as well as *S. aureus* (Gram-positive), with 8 mm and 6 mm inhibition zones, respectively.

In another study, AgNPs were synthesized using extracts of the *Ascomycetous mushrooms* *Geopora sumneriana* and *Verpa bohemica* as eco-friendly reducing and capping agents. UV-Vis. analysis confirmed nanoparticle formation through a characteristic SPR band at ~420–450 nm, while FESEM revealed predominantly spherical to hexagonal nanoparticles. XRD analysis confirmed the crystalline nature of AgNPs with a FCC structure, and FTIR results indicated the involvement of biomolecules such as proteins, phenolics, and polysaccharides in nanoparticle reduction and stabilization. Evaluation for their antibacterial efficacy through minimum inhibitory concentration (MIC) determination exhibited strong antibacterial activities against *Aspergillus niger*, *Penicillium chrysogenum*, *Pythium ultimum*, *Escherichia coli*, *Salmonella gallinarum*, and *Staphylococcus aureus*. pAgNPs synthesis using *Musa paradisiaca* and *Musa sapientum* extracts also produce potential antimicrobial agents. UV-vis absorption in the 400–

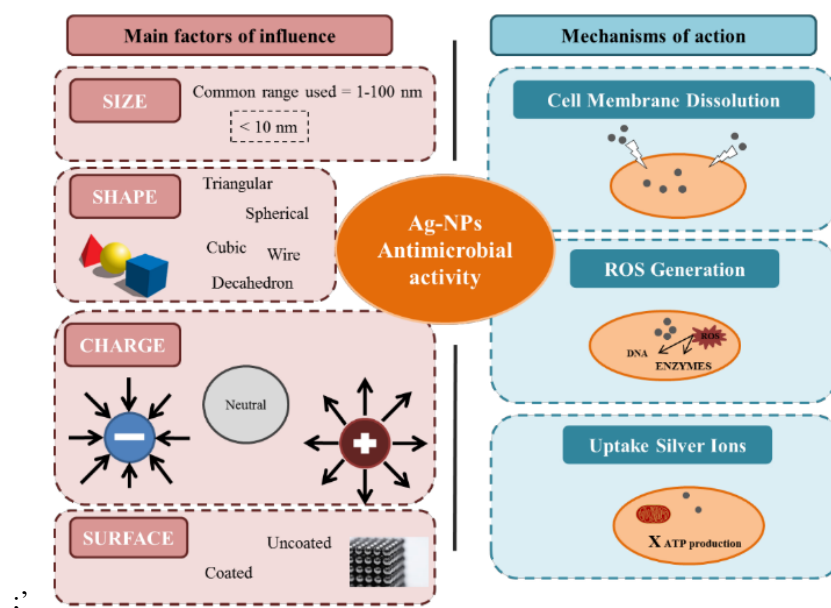


Figure 5. Influential factors and prediction of the antimicrobial mechanism of AgNPs (Raza *et al.* 2016)

450 nm range indicated SPR peak of AgNPs. Samples analyses using SEM revealed the presence of particles within 8–40 nm. FTIR spectroscopy unveiled the presence of several organic functional groups on the surface of AgNPs, indicating the presence of phytochemicals from plant extracts. Thin layer chromatography (TLC) of the phytochemicals capping agents from AgNPs identified multiple groups of secondary metabolites. These phytochemical capping agents exhibited antibacterial activities against *Staphylococcus aureus*, *Escherichia coli*, and *Pseudomonas aeruginosa*, with MIC of 62.5 to 1000 µg/mL. These results suggest the presence of antimicrobial phytochemicals on biosynthesized AgNPs, highlighting the promise of green nanoparticle synthesis as a valuable approach in bioprospecting antimicrobial agents (Kabeya *et al.* 2025).

Green AgNPs using *Ocimum sanctum* leaf extract can be carry out efficiently. Absorption of AgNPs using UV-vis spectroscopy showed SPR peak centered at 420 nm. XRD analysis showed intense peaks at 37.81°, 45.01°, 63.91°, and 78.0°, corresponding to Bragg's reflections at 111, 200, 220, and 311, respectively, with an average particle size of

approximately 18 nm. The reduction of Ag⁺ was monitored using Atomic Absorption Spectroscopy (AAS), which revealed a rapid decrease from 2.73 ppm to 0.023 ppm within four minutes, driven by the active reducing agents in the *O. sanctum* extract. The SEM image confirmed the spherical shape of the AgNPs, with an average size of 23.82 ± 4.17 nm. FTIR spectroscopy identified absorption peaks at 1635 cm⁻¹ and 3430 cm⁻¹, associated with the amide bond of proteins and O–H stretching in alcohols and phenolic compounds, respectively. The synthesized AgNPs exhibited significant antimicrobial activity. The inhibition zone measured indicating strong antimicrobial potential even at low dosages (Sulaiman *et al.* 2024). A summary of green synthesis of AgNPs from plant extracts is presented in Table 2.

OCCUPATIONAL EXPOSURE LIMITS AND CONTROLLING EXPOSURES

With the increased production and widespread commercial use of silver nanoparticles (AgNPs), human and environmental exposure to silver nanoparticles are inevitably increasing. Silver

Table 2. Green synthesis of AgNPs from plant extracts and their antimicrobial activity testing

Plant Extract Sources	Particle size and Morphology	Characterization Methods	Microbes Tested	Antimicrobial Test		References
				Methods	Results	
<i>Bryophyllum pinnatum</i> (Lam.) leaf extract	-	FTIR	<i>Pseudomonas aeruginosa</i> , <i>Escherichia coli</i> , <i>S. aureus</i> , and <i>Bacillus subtilis</i>) bacteria	Agar-well diffusion method	Superior antibacterial activity compared with the <i>B. pinnatum</i> (Lam.) extract alone	(Sahu <i>et al.</i> 2026)
<i>Curcuma longa</i> (Cl).	30-70 nm, spherical	UV-vis spectroscopy, DLS, FTIR, XRD, SEM, EDAX, and TEM	<i>E. coli</i> (Gram-negative) and <i>S. aureus</i> (Gram-positive)	broth dilution and well-diffusion methods	High antibacterial capability	(Amin <i>et al.</i> 2026)
<i>Ascomycetous mushrooms Geopora sumneriana</i> and <i>Verpa bohemica</i>	30–50 nm, spherical to hexagonal	UV-visible spectroscopy, Field Emission Scanning Electron Microscopy (FESEM), XRD, FTIR	<i>Aspergillus niger</i> , <i>Penicillium chrysogenum</i> , <i>Pythium ultimum</i> , <i>E. coli</i> , <i>Salmonella gallinarum</i> , and <i>S. aureus</i>	Minimum inhibitory concentration (MIC) determination	Strong antimicrobial potential	(Talie <i>et al.</i> 2026)
<i>Dolichos lablab</i> aqueous seed extract	15.67 nm, face-centered cubic	UV-vis spectroscopy, FTIR, XRD	<i>E. coli</i> (Gram-negative) and <i>S. aureus</i> (Gram-positive)	Well diffusion method	<i>S. aureus</i> was more susceptible to the treatment than <i>E. coli</i>	(Bekele <i>et al.</i> 2026)

Table 2. Green synthesis of AgNPs from plant extracts and their antimicrobial activity testing (Continued)

Plant Extract Sources	Particle size and Morphology	Characterization Methods	Microbes Tested	Antimicrobial Test		References
				Methods	Results	
<i>Candida glabrata</i>	74.96 to 100.40 nm, spherical	UV-vis spectroscopy, XRD, scanning electron microscopy (SEM) with energy-dispersive X-ray (EDX)	<i>E. coli</i> , <i>Shigella Dysenteriae</i> , <i>Aeromonas Hydrophila</i> , and <i>Enterococcus faecalis</i>	Agar well diffusion method	Significant antimicrobial activity	(Ali <i>et al.</i> 2026)
<i>Acanthus ilicifolius</i> leaves extract	86.86 nm, spherical, polydisperse particles	UV-Vis spectr, FTIR, atomic force microscopy (AFM), and SEM-EDX	<i>Pseudoalteromonas ostreae</i> , <i>Vibrio parahaemolyticus</i> , and <i>Shewanella khirikhana</i>	Disk diffusion assays	Strong bioactivity	(Islam <i>et al.</i> 2026)
<i>Solanum incanum</i> leaf extract	23.28 nm, spherical	UV-Vis. Spectr., FTIR, XRD	<i>E. coli</i> and <i>S. aureus</i>	Disc-diffusion method	Significant antibacterial activity	(Dhaif-Allah <i>et al.</i> 2025)
<i>Musa paradisiaca</i> and <i>Musa sapientum</i>	8–40 nm, spherical	UV-Vis. Spectr., TEM, XRD, FTIR. TLC	<i>Staphylococcus aureus</i> , <i>Escherichia coli</i> , and <i>Pseudomonas aeruginosa</i>	Minimum inhibitory concentration (MIC) determination	Significantly enhanced antibacterial effectiveness	(Kabeya <i>et al.</i> 2025)
<i>Sida schimperi</i> Hochst. ex A. Rich leaves extract.	26.27 nm, crystallite	UV-Vis. Spectr., XRD, FTIR	Gram-positive (<i>S. aureus</i> and <i>S. epidermidis</i>) and Gram-negative (<i>E. coli</i> and <i>Klebsiella Pneumonia</i>) bacteria	Disc diffusion method	Effectively inhibited the growth bacteria	(Moges & Misskire 2025)
<i>Acacia nilotica</i> Leaf Extract	10-50 nm, spherical	SEM, EDX, FTIR	<i>Staphylococcus aureus</i> and <i>Escherichia coli</i>	Agar well agar diffusion method.	potential in combating harmful microorganisms	(Prakash & Khalkho 2025)
<i>Neem and turmeric</i> extracts	4-14.81 nm, spherical	UV-Vis. Spectr., SEM, EDX/EDS, and XRD	<i>S. aureus</i> , <i>S. mutans</i> , and <i>Lactobacillus species</i>	Agar well diffusion method	Notable antimicrobial activity	(Singh <i>et al.</i> 2025)
<i>Solanum nigrum</i> leaf extract	3.45-8.79 nm,	HPLC, FTIR, TEM, EDX, zeta potential	<i>P. tardicrescens</i> , <i>F. circinatum</i> , and <i>Phoma spp.</i>	Fungal growth inhibition (%)	Potent applications to wood samples.	(Abd-Elhamed <i>et al.</i> 2025)
<i>Azadirachta indica</i> (Neem) fruit pulp extract	< 40 nm, spherical	TEM, AFM, XRD, DLS, FTIR, UV-vis. Spectr.	<i>E. coli</i> , <i>salmonella typhi</i> , <i>S. aureus</i> and <i>S. pyogenes</i>	Kirby-disc Bauer's diffusion technique	Good antibacterial activity	(Alampally <i>et al.</i> 2025)

Table 2. Green synthesis of AgNPs from plant extracts and their antimicrobial activity testing (Continued)

Plant Extract Sources	Particle size and Morphology	Characterization Methods	Microbes Tested	Antimicrobial Test		References
				Methods	Results	
<i>Pachira glabra</i> Pasq. leaf extract	18 nm, crystallite	UV-vis. Spectr, FTIR, DLS, FE-SEM, EDS, XRD	<i>E. coli</i> and <i>S. aureus</i>	Well diffusion method	Demonstrated biological activities (antimicrobial, antioxidant and cytotoxic effects)	(Elias <i>et al.</i> 2025)
tulsi (<i>Ocimum tenuiflorum</i>) and neem (<i>Azadirachta indica</i>) leaf extracts	21 nm, crystallite	XRD, UV-Vis. Spectr.	<i>S. aureus</i> , <i>P. Aeruginosa</i> , and <i>E. coli</i>	Agar well diffusion method	Strong antibacterial activity	(Prathibha <i>et al.</i> 2024)
<i>Adathoda vasica</i> , <i>Plectranthus amboinicus</i> , <i>Pimenta dioica</i> leaves extract		UV-vis. Spectr.	<i>E. coli</i> , <i>Salmonella</i> spp., <i>Pseudomonas</i> spp., and <i>Staphylococcus</i> spp.	Well diffusion method on Mueller-Hinton agar (MHA)	Significant inhibitory effects	(Dufaida <i>et al.</i> 2024)
<i>Ocimum sanctum</i> leaf extract	18 nm, spherical	UV-vis. spectr., SEM, XRD, FTIR, AAS	<i>Escherichia coli</i> ,	Agar well diffusion method	Strong antimicrobial potential	(Sulaiman <i>et al.</i> 2024)
<i>Camellia sinensis</i> leaf	61.24-99.66 nm, crystallite	AFM, XRD, HPLC	<i>Staphylococcus aureus</i>	Disc-diffusion method and MIC determination	Significant antibacterial activity	(Salih <i>et al.</i> 2024)
<i>Azadirachta indica</i> (neem)	-	UV-vis. spectr.,	<i>Escherichia coli</i> , <i>Capnodium</i> spp	Agar well diffusion method	Significant antibacterial and antifungal activities	(Barad & Ambechada 2024)
<i>Ocimum tenuiflorum</i> and <i>Ocimum gratissimum</i>	-	-	<i>Streptococcus mutans</i> , <i>Enterococcus faecalis</i> , <i>C. albicans</i> , <i>Lactobacillus acidophilus</i> , and <i>S. aureus</i> .	Agar well diffusion method	Positive inhibitory activity against all tested bacterial strains	(Varghese <i>et al.</i> 2024)

Table 2. Green synthesis of AgNPs from plant extracts and their antimicrobial activity testing (Continued)

Plant Extract Sources	Particle size and Morphology	Characterization Methods	Microbes Tested	Antimicrobial Test		References
				Methods	Results	
<i>Lycopersicon esculentum</i> peel	186 nm, quasispherical crystal	UV-vis. spectr., DLS, FTIR, HR-TEM), and XRD	<i>B. subtilis</i> , <i>E. coli</i> , <i>K. Quasipneumoniae</i> , <i>S. typhi</i> , <i>S. sonnei</i> , <i>L. Monocytogenes</i> , <i>A. solani</i> , <i>A. flavus</i> , <i>C. albicans</i> , <i>F. oxysporum</i> , and <i>R. oryzae</i> .	Agar well diffusion method	Positive inhibition action against <i>B. subtilis</i> , <i>E. coli</i> , <i>K. quasipneumoniae</i> , <i>S. typhi</i> , and <i>S. sonnei</i>	(Ali <i>et al.</i> 2024)
<i>Lepidium draba</i>	20–35 nm, spherical	TEM, FTIR, XRD, DLS, and zeta potential	<i>E. coli</i> , <i>S. aureus</i> , <i>Enterococcus faecalis</i> , <i>Klebsiella pneumoniae</i> , and <i>Candida albicans</i>	Broth micro dilution method for MIC determination	Strong antibacterial activity against Gram-negative and Gram-positive bacteria	(Hajizadeh <i>et al.</i> 2024)
<i>Mentha piperita</i> leaves	20-50 nm, spherical	XRD, SEM, and UV Vis. Spectr.	<i>Pseudomonas aeruginosa</i> , <i>Klebsiella Aerogenes</i> , <i>Salmonella</i> , <i>S. aureus</i> and <i>E. coli</i>	Agar well diffusion (AWD) method	Potent antibacterial activity against Gram-negative and Gram-positive bacteria	(Hussain <i>et al.</i> 2023a)
<i>Apples, oranges, potatoes, red pepper, white onion, garlic and radish</i>	9-30 nm, spherical	XRD, TEM, and UV Vis. Spectr.	<i>S. aureus</i> , <i>Bacillus cereus</i> , <i>E. coli</i> , and <i>Candida krusei</i>	Broth micro dilution method for MIC determination	The size of AgNPs influent their antimicrobial activity.	(Wasilewska <i>et al.</i> 2023)
<i>Egyptian propolis</i>	9.43 nm, spherical	FTIR, XRD, Zeta potential, TEM, SEM, and EDX	<i>S. aureus</i> and <i>E. coli</i>	Agar well diffusion method	Effective antimicrobial product to be used in infections	(Mohamed <i>et.</i> 2022)
<i>Piper retrofractum</i> fruit extract	1–5 nm, spherical	UV-Vis. Spectr., FTIR, FESEM, XRD, and TEM	<i>S. aureus</i> and <i>E. coli</i>	Agar well diffusion method	Strong antibacterial activity	(Amaliyah <i>et al.</i> 2022)

Table 2. Green synthesis of AgNPs from plant extracts and their antimicrobial activity testing (Continued)

Plant Extract Sources	Particle size and Morphology	Characterization Methods	Microbes Tested	Antimicrobial Test		References
				Methods	Results	
<i>Flos Sophorae Immaturus</i> extract	25-40 nm, spherical	UV-Vis spectr., XRD, FTIR, X-ray Photoelectron Spectroscopy (XPS), DLS, and TEM	<i>E. coli</i> , <i>P. aeruginosa</i> , and <i>S. aureus</i>	Agar well diffusion and MIC method	Excellent anti-bacterial activity, anti-bacterial activities	(Cheng <i>et al.</i> 2022)
<i>Syzygium cymosum</i> leaf extract	17.2-35.3 nm, spherical	UV-Vis spectr., XRD, FTIR, XPS, DLS, and TEM	<i>Bacillus subtilis</i> , <i>E. coli</i> and <i>Salmonella typhi</i> .	MIC method, CellTox Green Assay, Trypan Blue Dye Exclusion Assay	Strong anti-bacterial activity against all the tested bacterial strains	(Mahmud <i>et al.</i> 2022)

Table 3. The scientific values used in the derivation of the NIOSH Recommended Exposure Limit (REL) for silver nanomaterials

Rat Effect Endpoint and Sex	Rat PoD, $\mu\text{g}/\text{m}^3$	Total DAF	HEC, $\mu\text{g}/\text{m}^3$	Total UF	OEL Estimate (8-hour TWA), $\mu\text{g}/\text{m}^3$
Liver bile duct hyperplasia, BMCL ₁₀ , female	50.5	1	50.5	25	2.0
Pulmonary inflammation, BMCL ₁₀ , pooled data for male and female	62.8	2.72	23.1	25	0.92
Lung function decrement, LOAEL, female	49	2	25	75	0.33
Lung and liver effects, NOAEL, male and female	133	2	67	100	0.67

nanoparticles (AgNPs) exhibit antimicrobial properties, but their unique reactivity causes significant cytotoxicity and genotoxicity. Safety data confirms they can accumulate in the lungs, liver, and kidneys, inducing oxidative stress, DNA damage, and apoptosis. While silver dusts, consisting of micro-sized particles and soluble compounds have established occupational exposure limits (OELs), silver nanoparticles exhibit different physicochemical properties from bulk materials.

In manufacturing and integration of AgNPs into various products, large amounts of AgNPs can be released into air from production equipment. Workers in these facilities have the potential to become highly exposed to AgNPs. The highest occupational exposure to AgNPs may be occur during the production of the AgNPs. National Institute for Occupational Safety and Health (NIOSH) recommends that risk management control practices be implemented so that worker exposures to silver nanomaterials do not exceed the NIOSH REL of 0.9 $\mu\text{g}/\text{m}^3$ (8-hour time-weighted average/TWA),

measured as arespirable airborne mass concentration (Kuempel *et al.* 2021). Summary of the scientific values used in the derivation of the NIOSH recommended exposure limit (REL) for silver nanomaterials is presented in Table 3.

Controlling exposures to occupational hazards is the fundamental method of protecting workers. Table 4 provides examples of the types of engineering and other exposure control measures that could be used at various processes and job tasks to help control worker exposures to silver nanomaterials. In some cases, a combination of approaches may be necessary to accomplish exposure control goals (such as installing a continuous liner system inside a ventilated booth).

Table 4. Engineering controls to reduce silver exposures below the NIOSH RELs

Process and/or Task Activity	Potential Sources of Exposure	Exposure Controls
Pilot and Research & Development Operations	Generally <i>small quantities</i> of AgNPs/silver nanowires (AgNWs) (such as µg and mg) during • Synthesis of AgNPs/AgNWs, including chemical vapor deposition, solution phase synthesis, and dry powder dispersion • Harvesting of AgNPs after synthesis • Removal of silver nanomaterials from a substrate • Powder transfer (AgNPs/ AgNWs) • Reactor cleaning	• Constant-velocity fume hood or nanomaterial enclosure with High-Efficiency Particulate Air (HEPA)-filtration exhaust when warranted • HEPA-filtration exhaust enclosure (such as glove box isolator) • Biologic safety cabinet • Note: Local Exhaust Ventilation (LEV) or some type of enclosure control (glove box) may be required at the reactor and during the harvesting of material.
Research Laboratory Operations	Generally <i>small quantities</i> of AgNPs/AgNWs (such as µg and mg) during • Handling (such as mixing, weighing, blending, transferring) of AgNPs/AgNWs in free powder form or sonication of AgNP or AgNW liquid suspension	• Constant-velocity fume hood or nanomaterial-handling enclosure with HEPA-filtration exhaust when warranted • HEPA-filtration exhaust enclosure (such as glove box isolator) • Biologic safety cabinet
Manufacturing and Synthesis of AgNPs and AgNWs	Generally <i>large quantities</i> of AgNPs/AgNWs (≥ kg amounts) during • Synthesis of AgNPs (chemical vapor deposition, solution phase synthesis, and dry powder dispersion) • Harvesting of AgNPs after synthesis • Removal of silver nanomaterials from a substrate • Powder transfer of silver nanomaterials • Drum and bag filling • Reactor cleaning • Coating of AgNPs/AgNWs	• Dedicated ventilated room (such as a downflow room) for reactor with HEPA-filtration exhaust, potentially in conjunction with localized controls listed below • LEV at source of potential exposure when isolation or total enclosure of the process is not possible • Ventilated bagging/weighing stations and/or unidirectional down-flow ventilation booth • Non-ventilation options, including a continuous liner off-loading system for bagging operations • Ventilated bag dumping stations for product Transfer

Table 4. Engineering controls to reduce silver exposures below the NIOSH RELs (Continued)

Process and/ or Task Activity	Potential Sources of Exposure	Exposure Controls
Use of AgNPs and AgNWs to produce enabled materials	1. Generally <i>small quantities</i> of AgNP/AgNW powder or liquid suspensions during - Mixing, weighing, and transferring of AgNPs/AgNWs - Incorporation of AgNPs/AgNWs into matrices and coatings - Spraying of AgNPs/AgNWs on surfaces	1. Options - Transfer of AgNPs/AgNWs in sealed, unbreakable, labeled containers - Constant velocity fume hood or nanomaterial handling enclosure (with filtered exhaust when warranted) - HEPA-filtration exhaust enclosure (such as glove box isolator) - Biologic safety cabinet
	2. Generally <i>large quantities</i> of AgNPs or AgNWs in powder or liquid suspensions during - Blending or pouring into other matrices - Impregnating of textile materials and spray coating of surfaces	2. Options Isolation techniques such as a dedicated ventilated room or process enclosure with HEPA-filtration exhaust
	3. <i>Small pieces</i> of AgNP- and AgNW-enabled textiles, fabrics, materials, and composites during handling: Grinding, sanding, cutting, drilling, or other mechanical energy applied to materials containing AgNPs or AgNWs	2. Options - Process-based controls such as ventilated bagging/weighing station and unidirectional down-flow booth - Non-ventilation options such as continuous liner off-loading systems for bagging operations - Ventilated bag dumping stations for product transfer 3. Options For small pieces of AgNP/AgNW-enabled textiles, fabrics, materials, and composites - Constant-velocity fume hood or nanomaterial handling enclosure with filtered exhaust when warranted - HEPA-filtration exhaust enclosure (such as glove box isolator) - Biologic safety cabinet - Localized dust-suppression techniques, including ventilation-based (power tool-type) or mist/water-based, where appropriate For large pieces of AgNP/AgNW-enabled materials/composites, where use of isolation techniques (such as large ventilated enclosures) are not feasible - Ventilated process enclosure or unidirectional down-flow booth with HEPA-filtered exhaust - LEV at exposure source with HEPAfiltered exhaust - Localized dust-suppression techniques, including ventilation-based (power tool-type) or mist/water-based, where appropriate

Table 4. Engineering controls to reduce silver exposures below the NIOSH RELs (Continued)

Process and/or Task Activity	Potential Sources of Exposure	Exposure Controls
Processes requiring application of high temperatures to Ag metals and alloys	Fumes generated during brazing, soldering, welding, and melting of Ag and Ag alloys	• LEV-based welding fume control approaches should be used, including ventilated enclosing hoods, fixed slot/plenum ventilated worktables, or moveable capture hoods (such as a welding fume extraction unit) • Process-based controls, such as ventilated production welding booths, may be required for large-scale applications where fumes may be generated

CONCLUSION

In conclusion, research on AgNPs and their activity as an antimicrobial agent is still very relevant to be developed. AgNPs can be synthesized using plant extract bioreductors with a particle size of around 10 – 100 nm without the need for chemical capping agents. The variation in particle size depends on the type of plant extract as the source of the bioreductor compound. AgNPs have good antimicrobial activity against several Gram-negative and Gram-positive bacteria, so they have the potential to be used as an antimicrobial active agent in antiseptic and disinfectant formulas. Spherical AgNPs have strong antimicrobial activity against microbial tested. Therefore, further research is needed to obtain spherical and stable AgNPs. It is also necessary to report research articles on the manufacture of environmentally friendly antiseptics and disinfectants that use AgNPs as an active antimicrobial ingredient.

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