Methods to Synthesize Silver Nanoparticles

CD Bioparticles

Silver (Ag) is a transition metal with high electrical and thermal conductivity. Silver is widely known for its medical and therapeutic benefits. It can be made into coins, containers, solutions, foils, sutures, and colloids, such as lotions and ointments. The medical properties of silver have been discovered for more than 2000 years. Since the 19th century, silver-based compounds have been associated with antibacterial applications.

Table 1. Synthesis of silver nanoparticles with different shapes through chemical, physical and biological methods.

Method	Reducing agent or solvent	Stabilizer or surfactant	Particle size	Shape
Chemical method	Trisodium citrate	Trisodium citrate	30–60 nm	Spherical
Chemical method	$NaBH_4$	Dodecanoic acid (DDA)	~7 nm	Spherical
Chemical method	Ethylene glycol	PVP	17 ± 2 nm	Spherical
Chemical method	Paraffin	Oleylamine	10–14 nm	Spherical
Chemical reduction	Hydrazine hydrate	Bis(2-ethylhexyl) (sulfosuccinate AOT)	2–5 nm	Spherical
Photo chemical reduction (X-ray radiolysis)	X-ray	–	28 nm	Spherical
Physical synthesis	Electrical arc discharge	Sodium citrate	14–27 nm	Spherical

(continued)

Table 1. (continued)

Physical synthesis	TX-100, UV	TX-100	30 nm	Spherical
Biological synthesis	Bacillus sp.	Bacillus sp.	5–15 nm	Spherical
Biological synthesis	Lactobacillus	Lactobacillus Proteins	6–15.7 nm	Spherical
Biological synthesis	*Shewanella oneidensis*	*Shewanella oneidensis*	2–11 nm	Spherical
Biological synthesis	Fungus T. viride	*Trichoderma viride*	5–40 nm	Spherical
Biological synthesis	*Cassia angustifolia*	*Cassia angustifolia*	9–31 nm	Spherical
Biological synthesis	*Daucus carota*	*Daucus carota*	20 nm	Spherical
Biological synthesis	Bacillus strain CS 11	Bacillus strain CS 11	42–92 nm	Spherical
Biological synthesis	*Aspergillus niger*	*Aspergillus niger*	1–20 nm	Spherical
Biological synthesis	*Arbutus unedo leaf* extract	*Arbutus unedo leaf* extract	3–20 nm	Spherical
Chemical method	Ethylene glycol	PVP	–	Cubic
Chemical method	Pentanediol (H-1.5 PDO)	PVP	–	Cubic
Chemical method	Ethylene glycol	PVP	30–50 nm	Cubic
Photochemical	Carboxymethylated chitosan (CMCTS)	Carboxymethylated chitosan (CMCTS)	2–8 nm	Cubic
Biological synthesis	Leaf extracts from *Eucalyptus macrocarpa*	Leaf extracts from *Eucalyptus macrocarpa*	10–50 nm (mean crystallite size = 38±2 nm)	Cubic
Wet-chemical	Sodium borohydride in the presence of sodium citrate	–	4 ± 2 nm	Nanorods
Chemical method	Potassium tartaric	PVP	–	Nanorods
Chemical method (soft, solution-phase)	Ethylene glycol	–	Diameters of 30–40 nm	Nanowires
Wet chemical	Ascorbic acid	–	In diameter 30–40 nm	Nanowires
Microwave technique	Ethylene glycol	PVP	–	Nanowires
Chemical method (polyol)	Ethylene glycol	PVP	–	Nanobars
Chemical reduction	Hydrazine hydrate	PVP	50–200 nm	Triangular
Microwave-assisted	Ethylene glycol monoalkyl ethers	PVP	–	Nanoprisms

In biology and biomedical research, silver nanoparticles (AgNPs) are important due to their physical and chemical properties. Silver products have strong inhibitory and bactericidal effects and have been used for centuries to prevent and care for various diseases, especially infections. AgNPs are considered to have antifungal, anti-inflammatory, anti-viral, and anti-platelet activities. AgNPs have been considered for a variety of physical, biological, and pharmaceutical purposes. They can be designed to have different forms, including particles, rods, squares, lines, films, and coatings (Table 1). Synthetic methods can be divided into physical, chemical, and biological methods (Figure 1). Advantages and disadvantages of each are shown in Table 2.

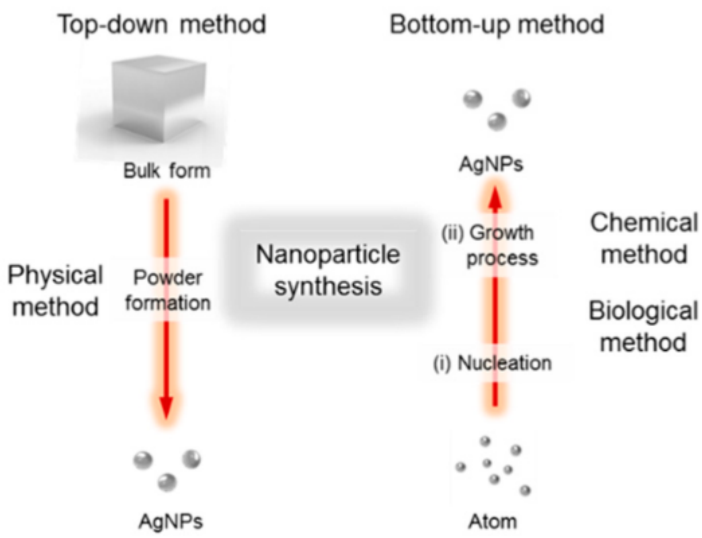

Figure 1. Diverse synthesis routes of silver nanoparticles.

Table 2. Synthesis methods of silver nanoparticle and the corresponding advantages and disadvantages

Synthesis methods	Advantages	Disadvantages
Physical methods	Absence of chemical reagents and by-products; Size uniformity	High energy consumption; Time-consuming for thermal stability; Surface structural defects
Chemical methods	Controllable silver content; Narrow size distribution	Employ of highly deleterious organic solvents
Biological methods	Facile and mild; Large-scale; Eco-friendly; Cost effective; Biocompatible; Long-term stable	Ambiguous action mechanism; Pretreatment of organic matter; Potential bacterial contamination and transfection

Physical methods

Table 3. Synthesis of silver nanoparticles by means of physical methods.

Method	Shape	Silver size (nm)
Laser ablation	Spherical	31
Laser ablation	Spherical	12−29
Laser ablation	Irregular	27−41
Laser ablation	Spherical	27−120
Laser ablation	Spherical	6.48
Laser ablation	Spherical	4−18
Laser ablation	Spherical	5−13
Laser ablation	Spherical	20−51
Laser ablation	Irregular	15−20
Laser ablation	Spherical	7.9−16.2
Laser ablation	Spherical	2.5−8.5
Laser ablation	Spherical	10.6±2.6
Laser ablation	Spherical	9−15
Laser ablation	Spherical	50
Laser ablation	Spherical	5−50
Small ceramic heater	Spherical	6−21.5
Thermal decomposition	Spherical	9.5± 0.7
Thermal decomposition	Spherical	14.4±3.3
Thermal decomposition	Spherical	4−7
Thermal decomposition	Spherical	4.7
Thermal decomposition	Spherical	8.0±1.3
Thermal decomposition	Spherical	40−50

- Evaporation–condensation

  Evaporation-condensation is the physical method for synthesizing AgNPs. It is usually carried out using a tube furnace at atmospheric pressure that is reliable for synthesizing various sizes of nanoparticles. However, the tube furnace takes up a lot of space, consumes a lot of energy while increasing the ambient temperature around the source material, and requires a lot of time to achieve thermal stability. A typical tube heating furnace requires more than a few kilowatts of power consumption and a warm-up time of around ten minutes to reach a stable working temperature.

- Laser ablation

  In another study, AgNPs were synthesized using laser ablation in solution. During the preparation process, the AgNPs were washed with distilled water and placed in a quartz cell filled with 5 mL of high-pressure liquid chromatography (HPLC) grade water. The study was performed using a laser with a repetition frequency of 10 Hz and a pulse width of 5-9 ns. The results show that the average AgNPs size is 12 nm under the action of 532 nm laser, and that prepared under 1064 nm laser is 31 nm. This study concluded that the particle size distribution depends on the laser wavelength. The change in particle size is affected by the laser light absorbed by the particles. Laser ablation is a green technology that can produce stable AgNPs in a variety of dispersion media without using metal precursors and reducing agents. The produced colloid has high purity and unique surface characteristics without any by-products. In principle, these characteristics make AgNPs produced by this method one of the best candidates for antimicrobial applications. However, productivity has not been sufficient for direct use in the industrial sector.

- Thermal decomposition

  In another study, Lee and Kang synthesized AgNPs by thermal decomposition. Their method involves an aqueous solution of $AgNO_3$ and sodium oleate. Spherical AgNPs with an average particle size of 9.5±0.7 nm can be obtained by reacting at room temperature to 290°C for 1h under a slow heating rate of 2°C/min.

Chemical methods

- Chemical reduction

  Chemical reduction is the most used method to synthesize AgNPs using organic and inorganic reducing agents (Table 4). This is because the metal surface has free electrons in the conduction band and positively charged nuclei, which continues to produce a colored silver solution through a single process. Long-lasting silver clusters can be formed, confirming the synthesis of AgNPs. Generally, different reducing agents such as sodium citrate, ascorbate, sodium borohydride ($NaBH_4$), elemental hydrogen, polyol process, N,N-dimethylformamide (DMF), ascorbic acid, poly(ethylene glycol)-block copolymers, hydrazine, and ammonium formate can be used to reduce silver ions (Ag^+) in aqueous or non-aqueous solutions by one-pot method.

Table 4. Synthesis of silver nanoparticles using chemical reduction.

Silver salt	Reduction agent	Stabilizer/capping agent	Silver size (nm)
$AgNO_3$	Aniline	Etyltrimethlyammonium bromide	10–30
$AgNO_3$	D(+)-Glucose and NaOH	-	8 and 24
$AgNO_3$	D-Glucose	Carboxy methyl cellulose, NaOH	5–15
$AgNO_3$	Ethylene glycol	Poly(vinyl pyrrolidone)	50–175
$AgNO_3$	Ethylene glycol	Poly(vinyl pyrrolidone)	8–10
$AgNO_3$	Ethylene glycol	Poly(vinyl pyrrolidone)	17±2
$AgNO_3$	Ethylene glycol	-	17–70
$AgNO_3$	Gallic acid	Gallic acid	7–89
$AgNO_3$	Glucose	Poly(vinyl pyrrolidone)	20–80
$AgNO_3$	Hydrazine hydrate and citrate of sodium	Sodium dodecyl sulfate	10–20
$AgNO_3$	Hydrazine hydrate and sodium citrate	Sodium dodecyl sulfate	10–20
$AgNO_3$	NaOH	Alkali lignin (low sulfonate)	5–100
$AgNO_3$	Poly(ethylene glycol)	Poly(ethylene glycol)	15–30
$AgNO_3$	Poly(ethylene glycol)	-	10–80
$AgNO_3$	Poly(vinyl pyrrolidone) and gelatin	Glucose, fructose, lactose, and sucrose	35
$AgNO_3$	Sodium borohydride	Tri-sodium citrate	~5
$AgNO_3$	Sodium borohydride	-	3.5–6

- Microemulsion techniques

  Microemulsion technology has excellent properties such as low interfacial tension, large surface area, good thermodynamic stability, and the ability to dissolve incompatible liquids. The microemulsion method is flexible that it can organically organize the particle size control mechanism, geometry, morphology, uniformity, and specific surface area. A microemulsion containing silver ions is mixed with another microemulsion containing a reducing agent, as shown in Figure 2. The collision and coalescence of the droplets lead to the reduction of silver ions in the water core and produce silver precipitation.

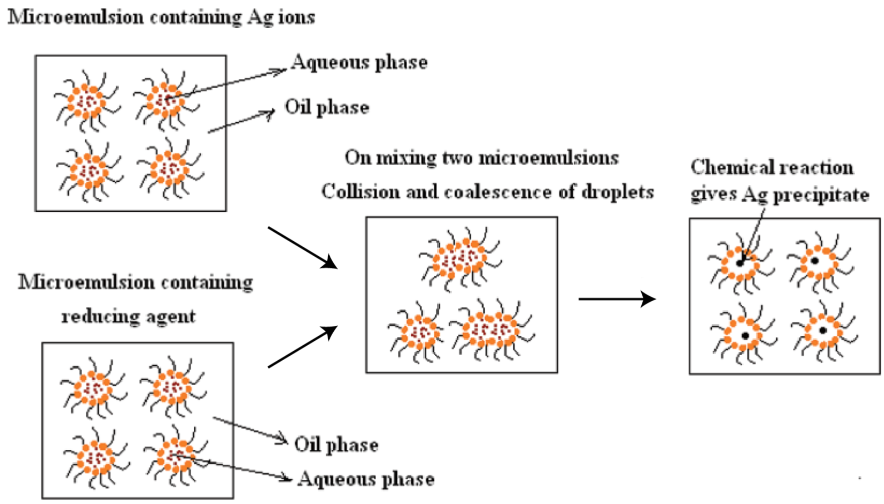

Figure 2. Schematic of the synthesis of AgNPs with water-in-oil (w/o) microemulsion.

- Microwave-assisted synthesis

  Contrary to traditional heating techniques, microwave synthesis uses variable-rate microwave radiation to reduce AgNPs. This technology gives up a faster reaction and provides a higher AgNPs concentration under the same temperature and exposure conditions. Zhao *et al*. developed a simple, environmental friendly, and efficient method for synthesizing uniform spherical AgNPs. Sodium alginate is used as a stabilizer and reducing agent to synthesize AgNPs in an aqueous medium treated by microwaves. The AgNPs prepared by this method are homogeneous and stable in solution at room temperature (25°C) for 6 months without any signs of agglomeration.

Biological methods

In recent years, the biological synthesis has received more attention. It designed to minimize the negative impact on the environment. The use of chemical methods to synthesize AgNPs requires three main components: silver salt, reducing agent, and stabilizer, or capping agent. In biological methods, reducing agents and stabilizers are replaced with molecules obtained from organisms such as plants, bacteria, fungi, yeast, and algae.

- Using plant extracts

  Plant extracts can be used as reducing agents to synthesize AgNPs and provide an environmental friendly alternative. As a naturally occurring resource, its cost is low, and the resources are abundant. Table 5 shows several plant extracts used to synthesize AgNPs from their leaves, seeds, roots, and fruits. Song *et al*. proposed a biological method using leaf extracts of five plants such as Pine, Persimmon, Ginkgo, Magnolia, and Platanus as reducing agents. The results show that the reaction temperature, leaf fluid concentration and $AgNO_3$ can control the size of AgNP. Studies have shown that from the perspective of synthesis rate and conversion rate, the magnolia leaf is the best reducing agent for the synthesis of AgNPs. This method can synthesize AgNPs with an average particle size of 15-500 nm.

Table 5. Plant-mediated synthesis of silver nanoparticles.

No.	Plant	Average size (nm)
1	Barley, flax, ryegrass	0.6–2
2	*Lycopersicon esculentum mill, Piper pedicellatum, Centella asiatica l., Azadirachta indica* leaf, *Triphala*	30–40, 2–3, 30–50, 43 and 59 respectively
3	Mangosteen leaf extract	50
4	*Tragia involucrata, Cymbopogon citronella, Solanum verbascifolium* and *Tylophora ovata* leaf extracts	32, 36, 41 and 28 respectively
5	*Clitoria ternatea* and *Solanum nigrum* leaf extracts	10–50
6	*Cinnamomum tamala* leaf extract	10
7	*Murraya koenigii* leaf extract	10–25
8	*Azadirachta indica* leaf extract	34
9	*Ananas comosus* leaf extract	12
10	*M. balbisiana, Azadirachta indica* and *O. tenuiflorum*	200
11	Seaweed *Gracilaria birdiae*	20.3–94.9
12	Pepper leaf broth	5–60
13	*Desmodium* plant	10
14	*Rumexhymenose palus* root extracts	2–40
15	*Catharanthus roseus* leaf extract	35–55

- Using fungus as reduction agents

  In addition to plant extracts, fungi can also be used to synthesize AgNPs (Table 6). Mukherjee *et al.* recommend synthesizing AgNPs using the fungus *Verticillium*. The study found that the average particle size of AgNP is 25±12 nm. In addition, *Fusarium oxysporum* was also used as a biological reducing agent to synthesize AgNPs. 10^{-3} M silver nitrate was mixed with 10g of *Fusarium oxysporum* in a conical flask filled with 100mL of distilled water. This method can be used to prepare spherical and occasionally triangular AgNPs with a particle size ranging from 5 to 15 nm.

Table 6. Fungus-mediated synthesis of silver nanoparticles.

Fungus	Size (nm)	Shape	Location
Aspergillu flavus	8.92	Spherical	Cell wall
A. fumigatus	-	-	Extracellular
A. terreus	1–20	Spherical	Extracellular
Cladosporium cladosporioides	10–100	-	-
Coriolus versicolor	25–75, 444–491	Spherical	Extracellular and intracellular
Humicola sp.	5–25	Spherical	Extracellular
Macrophomina phaseolina	5–40	Spherical	Cell-free filtrate
P. fellutanum	5–25	Spherical	Extracellular
P. nalgiovense AJ12	25 ± 2.8	Spherical	Cell-free filtrate
P. sajor-caju	30.5 ± 4.0	Spherical	Extracellular
Trichoderma asperellum	13–18	Nanocrystalline	Extracellular
T. viride	5–40	Spherical	Extracellular
T. viride	2–5	Spherical	Cell free extract

- Using microorganisms as reduction agents

In recent years, microorganisms such as bacteria (Table 7) and yeast have been considered as alternative reducing agents for the rapid AgNPs synthesis. Shahverdi et al. proposed using the culture supernatants of *Klebsiella pneumonia, Escherichia coli,* and *Enterobacter cloacae*. The results show that AgNPs can be synthesized within 5 minutes, with an average particle size of 52.5 nm. Recently, Shanthi *et al.* used a probiotic strain *B. licheniformis* Dahb1 as a silver nitrate-reducing agent to synthesize AgNPs. Placing the probiotic in a flask with sterile nutrient broth and incubating at 37°C for 24 hours can obtain spherical AgNP with a particle size of 18-63 nm. Table 6 summarizes the various microorganisms used to synthesize AgNPs.

Table 7. Bacteria-mediated synthesis of silver nanoparticles.

Bacteria	Size (nm)	Shape	Location
Acinetobacter calcoaceticus	8–12	Spherical	Extracellular
A. haemolyticus MMC8	4–40	-	Extracellular
Enterobacter aerogenes	25–35	Spherical	Extracellular
Escherichia coli	42.2–89.6	Spherical	Extracellular
Klebsiella pneumoniae	15–37	Spherical	Extracellular
Morganella sp.	10–40	Quasispherical	Extracellular
Proteus mirabilis	10–20	Spherical	Extracellular and intracellular
Pseudomonas aeruginosa SM1	6.3±4.9	Spherical, disk-shaped	Extracellular
Vibrio alginolyticus	50–100	Spherical	Extracellular and intracellular
Xanthomonas oryzae	14.86	Spherical, triangular, rod-shaped	Extracellular
B. flexus	12 and 65	Spherical and triangular	Extracellular
Exiguobacterium sp.	5–50	Spherical	Extracellular
Ureibacillus thermosphaericus	10–100	Spherical	Extracellular

In summary, physical, chemical, and biological methods are used to synthesize AgNPs. Physical methods have the disadvantages of large space requirements, high energy consumption, and a long time to achieve thermal stability. The chemical method can produce AgNPs easily, but the toxicity of its by-products is a major issue. Biological methods are getting popular because of their environmental friendliness and low cost.

Creative Diagnostics provides a comprehensive list of silver nanoparticles with different surface properties in multiple sizes. Silver nanoparticles produced with our proprietary protocols are highly monodisperse with a narrow size distribution. Please visit our website to see more.

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