A review on biosynthesis of silver nanoparticles and their biocidal properties

Khwaja Salahuddin Siddiqi1, Azamal Husen2* and Rifaqat A. K. Rao3

Abstract

Use of silver and silver salts is as old as human civilization but the fabrication of silver nanoparticles (Ag NPs) has only recently been recognized. They have been specifically used in agriculture and medicine as antibacterial, antifungal and antioxidants. It has been demonstrated that Ag NPs arrest the growth and multiplication of many bacteria such as Bacillus cereus, Staphylococcus aureus, Citrobacter koseri, Salmonella typhi, Pseudomonas aeruginosa, Escherichia coli, Klebsiella pneumonia, Vibrio parahaemolyticus and fungus Candida albicans by binding Ag/Ag+ with the biomolecules present in the microbial cells. It has been suggested that Ag NPs produce reactive oxygen species and free radicals which cause apoptosis leading to cell death preventing their replication. Since Ag NPs are smaller than the microorganisms, they diffuse into cell and rupture the cell wall which has been shown from SEM and TEM images of the suspension containing nanoparticles and pathogens. It has also been shown that smaller nanoparticles are more toxic than the bigger ones. Ag NPs are also used in packaging to prevent damage of food products by pathogens. The toxicity of Ag NPs is dependent on the size, concentration, pH of the medium and exposure time to pathogens.

Keywords: Silver nanoparticles, Antimicrobial activity, Antioxidant activity, Green synthesis, Toxicity mechanism

Introduction

Nanoparticles exhibit novel properties which depend on their size, shape and morphology which enable them to interact with plants, animals and microbes [1–7]. Silver nanoparticles (Ag NPs) have shown excellent bactericidal properties against a wide range of microorganisms [8–11]. They are prepared from different perspectives, often to study their morphology or physical characteristics. Some authors have used chemical method [12] and mistaken it with green synthesis, although they have done it inadvertently. The Ag NPs and their application in electronics, catalysis, drugs and in controlling microorganism development in biological system have made them eco-friendly [1, 8, 9, 13]. Biogenic synthesis of Ag NPs involves bacteria, fungi, yeast, actinomycetes and plant extracts [1, 10, 11, 13–15]. Recently, a number of parts of plants such as flowers, leaves and fruits [1], besides enzymes, have been used for the synthesis of gold and silver nanoparticles. The size, morphology and stability of nanoparticles depend on the method of preparation, nature of solvent, concentration, strength of reducing agent and temperature [1, 6, 10, 11].

Of all the nanoparticles developed and characterized thus far, Ag NPs assume a significant position owing to their inherent characteristic of acting as an antimicrobial agent even in solid state. Although, its significance was recognized much earlier, it was not well exploited except for its use in oriental medicine and in coins. It is estimated that nearly 320 tons of Ag NPs are manufactured every year and used in nanomedical imaging, biosensing and food products [16, 17].

There is a continuous increase in the number of multidrug resistant bacterial and viral strains due to mutation, pollution and changing environmental conditions. To circumvent this predicament scientists are trying to develop drugs for the treatment of such microbial infections. Many metal salts and metal nanoparticles have been found to be effective in inhibiting the growth of many infectious bacteria. Silver and Ag NPs occupy a prominent place in the series of such metals which are used as antimicrobial agents from time immemorial [18,
Silver salts are used to inhibit the growth of a variety of bacteria in human system. They are used in catheters, cuts, burns and wounds to protect them against infection [20, 21]. Das et al. [22] have reported that small sized Ag NPs are excellent growth inhibitors of certain bacteria. Ag NPs synthesized from silk sericin (SS), a water-soluble protein extracted from silk worms at pH 11, contain hydrophilic proteins with highly polar groups like hydroxyl, carboxyl and amino functional groups. Molecules containing the above functional groups act as reducing agents for AgNO₃ to produce elemental silver. Aramwit et al. [23] have suggested that the hydroxyl groups of SS are supposed to form complex with silver ions and prevent their aggregation or precipitation [24, 25]. Ag NPs in elemental state may be segregated due to large molecules present in the solvent but may not be complexed as both of them are neutral. The antibacterial activity of SS-capped Ag NPs against gram positive and gram negative bacteria has been screened. It was found that MIC falls between 0.001 and 0.008 mM for both types of microorganisms namely Staphylococcus aureus, Bacillus subtilis, Pseudomonas aeruginosa, Acinetobacter baumannii and Escherichia coli.

Although, several reviews have been published on the fabrication and characterization of silver nanoparticles, very limited reports are available on their green synthesis, biocidal properties and mechanism of action [8, 9, 13, 16, 23]. Thus, in this review, we have attempted to give a comprehensive detail of the biosynthesis of Ag NPs from herbal extracts, fungi and bacteria. Their potential as antimicrobial agent and the mechanism of their action has also been discussed.

**Synthesis and characterization of silver nanoparticles**

In general, metallic nanoparticles are produced by two methods, i.e. “bottom-up” (buildup of a material from the bottom: atom by atom, molecule by molecule or cluster by cluster) and “top-down” (slicing or successive cutting of a bulk material to get nano-sized particle) [1]. The “bottom-up” approach is usually a superior choice for the nanoparticles preparation involving a homogeneous system wherein catalysts (for instance, reducing agent and enzymes) synthesize nanostructures that are controlled by the catalyst itself. However, the “top-down” approach generally works with the material in its bulk form, and the size reduction to nanoscale is achieved by specialized ablations, for instance thermal decomposition, mechanical grinding, etching, cutting, and sputtering. The main demerit of the top-down approach is the surface structural defects. Such defects have significant impact on the physical features and surface chemistry of metallic nanoparticles. Several methodologies are available for the synthesis of Ag NPs namely, chemical methods [26–29]; physical methods [30–32] and biological methods [1, 10, 11]. Chemical method of synthesis can be subdivided into chemical reduction, electrochemical, irradiation-assisted chemical and pyrolysis methods [33]. Ag NPs synthesis in solution requires metal precursor, reducing agents and stabilizing or capping agent. Commonly used reducing agents are ascorbic acid, alcohol, borohydride, sodium citrate and hydrazine compounds. Sotiriou and Pratsinis [28] have shown that the Ag NPs supported on nanostructured SiO₂ were obtained by flame aerosol technology, which allows close control of silver content and size. Also, silver/silica nanoparticles with relatively narrow size distribution were obtained by flame spray pyrolysis [29]. However, physical methods do not require lethal and highly reactive chemicals and generally have a fast processing time. These methods include arc-discharge [31], physical vapor condensation [30], energy ball milling method [34] and direct current magnetron sputtering [32]. Physical methods have another advantage over chemical methods in that the Ag NPs have a narrow size distribution [32], while the main demerits are consumption of high energy [32]. Thus, biological synthesis of Ag NPs from herbal extract and/or microorganisms has appeared as an alternative approach as these routes have several advantages over the chemical and physical methods of synthesis. It is also a well-established fact that these routes are simple, cost-effective, eco-friendly and easily scaled up for high yields and or production [1–3]. Biosynthesis of metal and metal oxide nanoparticles using biological agents such as bacteria, fungi, yeast, plant and algal extracts has gained popularity in the area of nanotechnology [1–3, 5, 6, 10, 11].

Plants and their parts contain carbohydrates, fats, proteins, nucleic acids, pigments and several types of secondary metabolites which act as reducing agents to produce nanoparticles from metal salts without producing any toxic by-product. The details have been provided in Table 1. Similarly, biomolecules such as enzymes, proteins and bio-surfactants present in microorganisms serve as reducing agents. For instance, in many bacterial strains, bio-surfactants are used as capping and/or stabilizing agents (Table 2).

Extracellular synthesis of Ag NPs comprises of the trapping of metal ions on the outer surface of the cells and reducing them in the presence of enzymes or biomolecules, while intracellular synthesis occurs inside the microbial cells. It has been suggested that the extracellular synthesis of nanoparticles is cheap, favors large-scale production and requires simpler downstream processing. Thus, the extracellular method for the synthesis of nanoparticles is preferable [164] in comparison to the intracellular method. Ganesh Babu and Gunasekaran [165] and Kalimuthu et al.
### Table 1 Plant-mediated synthesis of silver nanoparticles

| Plant                  | Plant part          | Size and shape                                      | Phytoconstituents responsible for reduction of silver nitrate                                                                 | Key references |
|------------------------|---------------------|-----------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------|----------------|
| Aloe vera              | Leaf gel (removed skin) | 5–50 nm; octahedron                                 | Flavanones and terpenoids                                                                                                      | Logaranjan et al. [35] |
|                        | Leaf                | 70.7–192.02 nm; spherical (size varies through change of times and temperatures) | Lignin, hemicellulose and pectins                                                                                               | Tippayawat et al. [36] |
|                        | Leaf                | Size varies in accordance to different parameters; spherical | Flavonoids, terpenoids and phenols                                                                                             | Moosa et al. [37] |
| Mangifera indica       | Seed                | 14 nm; spherical and hexagonal                       | Phenolic compounds, gallotannins and tannin                                                                                   | Seekanth et al. [38] |
| Erigeron bonariensis   | Leaf                | 13 nm; spherical                                     | Flavonoids, steroids, glycosides, triterpenes, sugars and caffeoyl derivatives                                                  | Kumar et al. [39] |
| Myristica fragrans     | Bark and seeds      | Spherical, polydispersed                             | Secondary metabolites                                                                                                           | Jelin et al. [40] |
| Momordica charantia    | Leaf                | 11 nm; spherical                                     | Momorcharins, momordol, momordious, momordin, charantin, charine, cucuritanes, cucurbitins, goyaglycosides, goyasaponins    | Ajitha et al. [41] |
| Carambola              | Fruit               | 16, 13, 12 nm at pH 4, 7, 10 respectively          | Polysaccharides, polyols and ascorbic acid                                                                                       | Chowdhury et al. [42] |
| Rubus glaucus          | Fruit               | 12–50 nm; spherical                                  | Phenolic groups and flavonoids                                                                                                   | Kumar et al. [43] |
| Prunus serotina        | Fruit               | 20–80 nm (blue LED) 40–100 nm (white solar); spherical | Chlorogenic acid, catechin, proanthocyanidin, and flavonol glycosides                                                          | Kumar et al. [44] |
| Piper nigrum           | Seeds               | 10–60 nm; rod shaped                                | Polysaccharides, amino acids, alkaloids, proteins and vitamins                                                                   | Mohapatra et al. [45] |
| Nigella sativa         | Leaf                | 15 nm; spherical                                     | Alkaloids, ascorbic acid, saponins, glycosides, amino acids, flavonoids like catechin, apigenin, gallic acid and benzoates especially vanillic acid | Amooaghaie et al. [46] |
| Calotropis gigantean   | Flower              | 10–50 nm; spherical                                  | –                                                                                                                                | Pavani et al. [47] |
| Acmella oleracea       | Flower              | 2–20 nm; spherical                                   | Allic benzenes, phenolic, amino acids, proteins, alcoholic compounds, terpenes and terpenoids                                    | Raj et al. [48] |
| Piper betle            | Leaf                | 48–83 nm; spherical                                  | –                                                                                                                                | Kamachandran et al. [49] |
| Morinda tinctoria      | Leaf                | 80–100 nm; spherical and rod                         | Ascorbic acid, niacin, copper and iron                                                                                         | Vennila and Prabha [50] |
| Trigonella foenum-graecum | Seeds              | 20–50 nm; spherical                                  | Saponins and alkaloids                                                                                                         | Meena and Chouhan [51] |
| Picrasma quassioides   | Bark                | 1.75–66.5 nm; spherical                              | –                                                                                                                                | Seekanth et al. [52] |
| Rosa 'Andelli'         | Petals              | 0.5–14 nm; spherical                                 | Polyphenols and flavonoids                                                                                                       | Suarez-Cerda et al. [53] |
| Salvadora persica      | Stem                | 1–6 nm; spherical                                    | Phenolic compounds                                                                                                              | Tahir et al. [54] |
| Artemisia absinthium   | Aerial parts        | 5–20 nm; round shaped                               | Phenolic compounds and flavonoids                                                                                               | Ali et al. [55] |
| Chelidonium majus      | Aerial parts        | DLS-253.3 nm; spherical, quasi-spherical             | Flavonoids and alkaloids                                                                                                        | Barbinta-Patrascu et al. [56] |
| Calotrops procera      | Flower              | 35 nm; face centered cubic                           | Tannins, triterpenes, flavonoids, steroids, alkaloids and cardiac glycosides                                                    | Babu and Prabu [57] |
### Table 1 continued

| Plant                | Plant part | Size and shape                        | Phytoconstituents responsible for reduction of silver nitrate                                                                 | Key references       |
|----------------------|------------|----------------------------------------|-----------------------------------------------------------------------------------------------------------------------------|----------------------|
| Sterculia acuminata  | Fruit      | ~ 10 nm; spherical                     | Ascorbic acid, gallic acid, phenolic compounds, pyrogallol, methyl gallate and polyphenolic compounds                        | Bogireddy et al. [58]|
| Terminalia cuneata   | Bark       | 25–50 nm; spherical                    | Tannins, saponins, triterpenoids, flavonoids, gallic acid, ellagic acid and phytosterols                                       | Edison et al. [59]   |
| Cirsium japonicum    | Plant      | 4–8 nm; spherical                      | Saponins, proteins and flavonoids                                                                                           | Khan et al. [60]     |
| Isatis tinctoria      | Plant      | 10–15 nm; spherical                    | Saponins and flavonoids                                                                                                | Ahmad et al. [61]    |
| Aegle marmelos       | Fruit      | 225 nm; spherical, hexagonal, roughly circular | Phytosterols, flavonoids, alkaloids, triterpenoids and amino acids                                                                 | Velmurugan et al. [62]|
| Trachyspermum ammi    | Seeds      | 36 nm; cubic                           | Fatty acids, proteins, flavonoids and alkaloids                                                                             | Chouhanand Meena [63]|
| Eucalyptus globulus  | Leaf       | 19–43 and 5–25 nm with and without microwave treatment respectively | Alkaloids and flavonoids                                                                                                     | Ali et al. [64]      |
| Cydonia oblonga       | Seeds      | 38 nm; face-centered cubic             | Flavonones, terpenoids, proteins and amino acids                                                                            | Zia et al. [65]      |
| Hydrocotyle asiatica | Leaf       | 21 nm; spherical                       | Flavonoids and glycosides                                                                                                   | Devi et al. [66]     |
| Lantana camara       | Leaf       | 338 nm; spherical                      | Flavonoids, proteins, saccharides secondary metabolites like alkaloids, tannins, saponins, carbohydrates, steroids and triterpenoids | Manjamadha and Muthukumar [67]|
| Nyctanthes arbor-tristis | Seeds     | 50–80 nm; spherical                    | Carbohydrates and phenolic compounds                                                                                      | Baru et al. [68]     |
| Pennyroyal sp.        | Leaf       | 19.14 ± 9.791 nm; spherical            | –                                                                                                                            | Sedaghat et al. [69] |
| Saraca indica         | Leaf       | 23 ± 2 nm; spherical                   | Flavonoids and steroids                                                                                                     | Perugu et al. [70]   |
| Terminalia chebula    | Fruit      | 30 nm; distorted spherical             | Flavonoids and steroids                                                                                                     | Edison et al. [71]   |
| Euphorbia amygdaloides| Plant      | 7–20 nm; spherical                     | –                                                                                                                            | Cicek et al. [72]    |
| Pedalium murex        | Leaf       | 50 nm; spherical                       | Flavonoids, alkaloids, steroids, rosins, saponins and proteins                                                           | Anandalakshmi et al. [73]|
| Chelidonium majus     | Root       | 15.42 nm; spherical                    | –                                                                                                                            | Alishah et al. [74]  |
| Salacia chinensis     | Powdered plant | 20–80 nm; spherical, rods, triangular, hexagonal | Flavonoids, saponins, proteins, carbohydrates and phenolics                                                                  | Jadhav et al. [75]   |
| Tamarindus indica     | Seed coat  | ~ 12.73 nm                             | Flavonoids, tannin and saponins, Proteins                                                                                   | Ramamurthi et al. [76]
| Parkia roxburghii     | Leaf       | 5–25 nm; poly dispersed, quasi-spherical | –                                                                                                                            | Paul et al. [77]     |
| Aristolochia indica   | Leaf       | 32–55 nm; spherical                    | Alcohol and phenolic compounds and proteins                                                                               | Shanmugam et al. [78]|
| Cerasus serrulata     | Leaf       | 10–50 nm; spherical                    | –                                                                                                                            | Karthik et al. [79]  |
| Matricaria camomilla  | Flower     | 8–35 nm; spherical                     | Terpenoids, flavones and polysaccharides                                                                                 | Parlinska-Wojtan et al. [80]|
|                      | Flower     | ~ 5.5 nm; spherical                    | Phenolics, carbonyl and amines or alcohol groups                                                                              | Ocsoy et al. [81]    |
|                      | Fruits     | ~ 15.4 nm; spherical                   | Phenolics, flavonoids, terpenoids and vitamins                                                                               | Swamy et al. [82]    |
| Plant                  | Plant part | Size and shape                  | Phytoconstituents responsible for reduction of silver nitrate                                                                 | Key references |
|-----------------------|------------|---------------------------------|-------------------------------------------------------------------------------------------------------------------------------|----------------|
| *Alpinia calcarata*   | Root       | 5–15 nm; quasi-spherical        | Proteins, flavonoids and polyphenols                                                                                         | [83]           |
| *Salvia molesta*      | Leaf       | 12.46 nm; spherical             | Alkaloids, flavonoids, tannins, phenols, sugars and proteins                                                                   | [84]           |
| *Helicteres isora*    | Root       | 16–95 nm; spherical             | Steroids, terpenoids, alkaloids, carbohydrates and phenolic compounds                                                         | [85]           |
| *Mukia madrasapatana* | Leaf       | 158 nm; spherical               | Phenolic compounds                                                                                                             | [86]           |
| *Ficus benghalensis*  | Bark       | 60 nm; spherical                | Flavonoids, terpenoids and phenols                                                                                           | [87]           |
| *Azadirachta indica*  | Leaf       | 34 nm; spherical and irregular shape | Flavanoids and terpenoids                                                                                                       | [88]           |
| *Adathoda vasica*     | Leaf       | 10–50 nm; spherical             | Alkaloids compounds                                                                                                            | [89]           |
| *Amaranthus gangeticus* | Leaf     | 11–15 nm; globular and polycrystalline | Amino acids                                                                                                                     | [90]           |
| *Phlomis*             | Leaf       | 25 nm; spherical                | Glycosides such as flavonoids, iridoids, diterpenoids and other phenolic compounds                                             | [91]           |
| *Syzygium alternifolium* | Fruit    | 4–48 nm; spherical              | Phenols and primary amines of proteins                                                                                         | [92]           |
| *Abelia quanzensis*   | Bark       | 10–80 nm; spherical             | Proteins                                                                                                                       | [93]           |
| *Allamanda cathartica* | Flower    | 39 nm; spherical                | (E,E)-geranyl linalool, n-pentacosane, 1,8-cineole and n-tricosane                                                             | [94]           |
| *Carica papaya*       | Peel       | 10–30 nm; spherical             | Vitamins (C, K, E), amino acids, carbohydrates, β-carotene, lycopene and polyphenols                                          | [95]           |
| *Vitis vinifera*      | Leaf       | 200 nm; spherical               | Hydroxyl groups and phenolic compounds mainly myricetin, ellagic acid, kaempferol and gallic acid                             | [96]           |
| *Solanum indicum*     | Leaf       | 10–50 nm; spherical             | Phenolic compounds                                                                                                             | [97]           |
| *Tectona grandis*     | Leaf       | 26–28 nm; spherical             | Phenols                                                                                                                       | [98]           |
| *Soymida lebrifuga*   | Leaf       | 10–20 nm; spherical             | Phenolic groups, amino acids, aliphatic and aromatic amines, amidel-I and amidel-II                                            | [99]           |
| *Cardiospermum halicacabum* | Leaf | SEM-less than 100 nm; spherical | Polyphenols and phenol                                                                                                         | [100]          |
| *Ammonnina baccifera* | Root       | 105–125 nm; spherical           | Polyphenols, flavonoids and proteins                                                                                           | [101]          |
| *Diospyros paniculata* | Root      | 17 nm (avg); spherical          | Phenolics and proteins                                                                                                         | [102]          |
| *Simarouba glauca*    | Leaf       | 33–50 nm; spherical             | Amino groups and hydroxyl groups                                                                                              | [103]          |
| *Origanum majorana*   | Leaf       | 40–70 nm; feather and 26–60 nm; spherical, cubical respectively | Proteins and phenolic compounds                                                                                              | [104]          |
| *Salmalia malabarica* | Gum        | 7 ± 2 nm; spherical             | Carbonyl and hydroxyl group                                                                                                     | [105]          |
| *Psidium guajava*     | Leaf       | 10–90 nm; spherical             | Leucocyanidin, flavonoids, tannins, saponins, carotenes, vitamin C, B6 and carbohydrates                                    | [106]          |
| *Allium cepa*         | Bulb       | –                               | –                                                                                                                               | [107]          |
| *Justicia glauca*     | Leaf       | 10–20 nm; spherical             | Phenolic compounds                                                                                                             | [108]          |
| *Skimmia laureola*    | Leaf       | Irregular, spherical, hexagonal  | Tritepenoids, skimmiol and coumarins                                                                                                | [109]          |
| Plant                          | Plant part | Size and shape       | Phytoconstituents responsible for reduction of silver nitrate                                                                                                                                                                                                 | Key references |
|-------------------------------|------------|----------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------|
| *Andrographis echioides*      | Leaf       | ~ 68.06 nm; cubic    | Carbohydrates, tannins, saponins, flavonoids, alkaloids, quinones, glycosides, triterpenoids, phenols, steroids, phytosteroids and anthraquinones                                                                                                                          | Elangovan et al. [110] |
| *Putranjiva roxburghii*       | Leaf       | 5.74 nm; spherical   | Amino groups                                                                                                                                                                                                                                                   | Ali et al. [111]  |
| *Ixora coccinea*              | Flower     | 5–10 nm; spherical   | Alkaloids, tannins, glycosides, flavonoids, saponins, terpenes and carboxydrates                                                                                                                                                                                 | Nalvottula et al. [112] |
| *Emblica officinalis*         | Fruit      | 10–70 nm; spherical  | Alkaloids, phenolic compounds, amino acids and tannins                                                                                                                                                                                                          | Ramesh et al. [113] |
| *Hibiscus rosa-sinensis*      | Petals     | ~ 18.79 nm; spherical| Proteins                                                                                                                                                                                                                                                        | Nayak et al. [114] |
| *Bauhinia variegata*          | Leaf       | 32 nm; spherical, triangular, truncated triangles, decahedral | Reducing sugar, saponins, anthraquinone, alkaloids and terpenoids                                                                                                                                                                                               | Govindarajan et al. [115] |
| *Pteridium aquilinum*         | Leaf       | SEM-35–65 nm; spherical | Phenols, alkaloids, tannins, flavonoids, proteins, carbohydrates, saponins, glycosides, steroids and triterpenoids                                                                                                                                                   | Panneerselvam et al. [116] |
| *Aristolochia indica*          | Leaf       | 30–55 nm; spherical and cubical | Phenols                                                                                                                                                                                                                                                        | Murugan et al. [117] |
| *Cassia roxburghii*           | Leaf       | ~ 32 nm; spherical, triangular, truncated triangles, decahedral | –                                                                                                                                                                                                                                                              | Muthukumaran et al. [118] |
| *Anisomeles indica*           | Leaf       | TEM-18–35 nm; SEM-50–100 nm; spherical | Alcohols, phenols and carboxylic group                                                                                                                                                                                                                          | Govindarajan et al. [119] |
| *Hybanthus enneaspermus*      | Plant      | 16–26 nm; spherical, hexagonal, triangular | Proteins                                                                                                                                                                                                                                                       | Suman et al. [120] |
| *Amaranthus dubius*           | Leaf, stem, root | Stem: 30–35 nm; Root: 18–21 nm; Leaf: 18–21 nm | Polyphenol compounds and aldehydes                                                                                                                                                                                                                               | Sigamoney et al. [121] |
| *Ziziphus jujiuba*            | Fruit      | 2.575 nm; spherical  | Alcohols and phenols                                                                                                                                                                                                                                             | Sreekanth et al. [122] |
| *Chrysophyllum oliviforme*    | Leaf       | 25 nm; flower       | Flavonoids, saponins, catechin tannins, traces of anthraquinones, reducing sugars and phenolic compounds                                                                                                                                                       | Varghese et al. [123] |
| *Plumeria alba*               | Flowers    | ~ 36.19 nm; spherical | Amino, carboxylic and sulfhydryls                                                                                                                                                                                                                               | Mata et al. [124] |
| *Impatiens balsamina*         | Flowers    | 5–40 nm; spherical   | Alkaloids, tannins, glycosides, flavonoids, saponins, terpenes and carboxydrates                                                                                                                                                                               | Nalavothula et al. [125] |
| *Fraxinus excelsior*          | Leaf       | 25–40 nm; spherical and polydisperse | Flavonoids, alkaloids, glycosides, terpenoids, phenolic compounds, amino acid residues and peptides of proteins                                                                                                                                                 | Parveen et al. [126] |
| *Pongamia pinnata*            | Leaf       | AFM-15–35 nm; spherical | Alkaloids, glycosides, flavonoids, saponins, carbohydrates, tannins, phenolic compounds, and fat                                                                                                                                                               | Priya et al. [127] |
| *Pongamia pinnata*            | Seed       | 5–30 nm; spherical   | Pongaflavanol, tunicatachalcone, pongamol, galactoside and glybanchalcone                                                                                                                                                                                       | Beg et al. [128] |
| *Areca catechu*               | Nut        | 18.2 and 24.3 nm; spherical | Polyphenols                                                                                                                                                                                         | Rajan et al. [129] |
| *Ficus talboti*               | Leaf       | 9–12 nm; spherical   | Flavonoids, alkaloids, saponins, phenolic compounds, tannins, phytosterol and glycosides                                                                                                                                                                        | Arunachalam et al. [130] |
| Plant                  | Plant part | Size and shape                                      | Phytoconstituents responsible for reduction of silver nitrate                                                                 | Key references           |
|-----------------------|------------|-----------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------|---------------------------|
| *Sida cordifolia*     | Leaf       | 10–30 nm; spherical, prism                         | Alkaloids, quinazolines, cryptoleptins, phytosterols, flavonoids and saponins                                                 | Srinithya et al. [131]    |
| *Clerodendrum phlomidis* | Leaf      | TEM 10–15 nm; SEM 23–42 nm; spherical              | Phenolics, flavonoids, terpenoids and steroids                                                                             | Sriranjani et al. [132]  |
| *Theobroma cacao*     | Pod husk   | 4–32 nm; face-centered cubic                        | Proteins and phenolic compounds                                                                                                | Lateef et al. [133]       |
| *Ficus carica*        | Fruit      | 20–80 nm (thermal approach), 10–30 nm (ultra sonication approach); spherical | –                                                                                                                            | Kumar et al. [134]       |
| *Parkia speciosa Hassk* | Pod       | 20–50 nm; predominantly spherical                  | –                                                                                                                            | Fatimah [135]             |
| *Boerhaavia diffusa*  | Whole plants | 25 nm; spherical                                      |                                                                                                                             | Vijay Kumar et al. [136] |
| *Pelargonium endlicherianum* | Roots     | Different size; spherical                           | Gallic acid, apocynin and quercetin                                                                                            | Karatoprak et al. [137]   |
| *Artocarpus heterophyllus* | Seeds     | 10.78 nm; irregular                                | Lectin—a single major protein                                                                                              | Jagtap and Bapat [138]   |
| *Ceropegia thwaitesii* | Leaf       | 100 nm; spherical                                   | Triterpenoids; and methoxy groups of protein                                                                               | Muthukrishnan et al. [139]|
| *Alternanthera sessilis* | Leaf      | 30 nm; various shape                                | Alkaloid, tannins, ascorbic acid, carbohydrates and proteins                                                               | Niramuthi et al. [140]    |
| *Dryopteris crassirhizoma* | Rhizome  | 5–60 nm; almost spherical                           | Alcohol, amines, alkanes, carboxylic acid and ester                                                                       | Lee et al. [141]          |
| *Leptadenia reticulata* | Leaf      | 50–70 nm; crystalline, face centered and spherical | Phenolics, terpenoids, polysaccharides and flavones                                                                       | Swamy et al. [142]        |
| *Ipomoea batatas*     | Root       | TEM 30–120 nm; AFM 50–200 nm; polygonal            | Glycoalkaloids, mucin, dioscin, choline, polyphenols and anthocyanins                                                       | Wang et al. [143]         |
| *Sambucus nigra*      | Fruit      | 26 nm; spherical                                    | Polyphenols                                                                                                                | Moldovan et al. [144]     |
| *Millettia pinnata*   | Flower     | 16–38 nm; spherical                                 | Multi-functional aromatic group                                                                                             | Rajakumar et al. [145]    |
| *Coptis chinensis*    | Plant extract | 15 nm; spherical                                      | Polyphenols                                                                                                                | Ahmad et al. [146]        |
| *Lycium barbarum*     | Fruit      | 3–15 nm; spherical                                  | Tannins, flavanoids, ascorbic acid and alkaloids                                                                         | Dong et al. [147]         |
| *Embelia ribes*       | Seed       | 20–30 nm; crystalline, uniform and spherical        | Alkaloids, quinones, proteins, reducing sugars and saponins                                                               | Dhayalan et al. [148]     |
| *Zizyphus xylopyrus*   | Bark       | 60–70 nm; spherical                                  | Reducing agents                                                                                                            | Maria et al. [149]        |
have demonstrated that the intracellular synthesis requires additional steps for instance, ultrasound treatment or reactions with suitable detergents to release the synthesized silver nanoparticles. Further, the rate of biosynthesis of Ag NPs and their stability is a significant part in industrial production. Therefore, a proper monitoring of reaction conditions is also important (Fig. 1).

From bacteria

In recent years, the potential of biosynthesis of Ag NPs using bacteria has been realized [15, 153, 156–159]. For instance, *Pseudomonas stutzeri* AG259—isolated from silver mine was used to produce Ag NPs inside the cells [167]. In addition, several bacterial strains (gram negative as well as gram positive) namely *A. calcoaceticus*, *B. amyloliquefaciens*, *B. flexus*, *B. megaterium* and *S. aureus* have been used for both extra- and intracellular biosynthesis of Ag NPs [168–174]. These Ag NPs are spherical, disk, cuboidal, hexagonal and triangular in shape. They have been fabricated using culture supernatant, aqueous cell-free extract or cells (Table 3). Saifuddin et al. [14] have demonstrated an extracellular biosynthesis of Ag NPs (~ 5–50 nm) using a combination of culture supernatant of *B. subtilis* and microwave irradiation in water. Shahverdi et al. [15] have reported rapid biosynthesis of Ag NPs (within 5 min) using the culture supernatants of *K. pneumonia*, *E. coli* and *Enterobacter cloacae*. Saravanan et al. [172] have also reported an extracellular synthesis of Ag NPs using *B. megaterium* cultured supernatant, within minutes in presence of aqueous solutions of Ag+ ions.

Rapid synthesis of Ag NPs has been achieved by the interaction of a bacterial strain S-27, belonging to *Bacillus flexus* group and 1 mM AgNO3 in aqueous medium [173]. The colourless supernatant solution turned yellow and finally brown. Its UV–vis spectrum exhibited a sharp peak at 420 nm due to the surface plasmon resonance (SPR) of silver nanoparticles. Anisotropic nanoparticles of 12 and 65 nm size were stable in the dark for 5 months at room temperature although their slow degradation cannot be prevented. They were crystalline with a face centered cubic structure. These nanoparticles were found to be effective against multidrug resistant gram positive and gram negative bacteria. The colour intensity and rate of interaction depend on the concentration of the reacting components.

Das et al. [174] have reported extracellular biosynthesis of Ag NPs from the *Bacillus* strain (CS11). The interaction of 1 mM AgNO3 with the bacteria at room temperature yielded nanoparticles within 24 h which showed a peak at 450 nm in UV–vis spectrum. Their size from TEM analysis was found to range between 42 and 92 nm (Table 3).

From fungi

Biosynthesis of Ag NPs from both pathogenic and non-pathogenic fungi has been investigated extensively [10, 164, 213–215] (Table 4). It has been reported that silver ions are reduced extracellularly in the presence of fungi to generate stable Ag NPs in water [214, 216].

Syed et al. [224] have also reported the extracellular synthesis of Ag NPs from thermophilic fungus *Humicola*...
sp. All manipulations were done in aqueous medium at room temperature. Mycelia were suspended in 100 mL of 1 mM AgNO₃ solution in an Erlenmeyer flask at 50 °C and the mixture was left in a shaker for 96 h at pH 9 and monitored for any change in colour. The solution showed a change in colour from yellow to brown due to the formation of Ag NPs [222]. It is a simple process for the extracellular synthesis of Ag NPs from *Humicola* sp. TEM micrograph showed nicely dispersed nanoparticles mainly of spherical shape ranging between 5 and 25 nm. They are crystalline with a face centered cubic structure [236]. IR spectrum of Ag NPs in the suspension showed peaks at 1644 and 1523 cm⁻¹ assigned to amide I and amide II bands of protein corresponding to –C=O and N–H stretches. Owaid et al. [237] have reported the biosynthesis of Ag NPs from yellow exotic oysters mushroom, *Pleurotus cornucopiae* var. *citrinopileatus*. The dried basidiocarps were powdered, boiled in water and the supernatant was freeze dried. Different concentrations of hot water extract of this lyophilized powder were mixed with 1 mM AgNO₃ at 25 °C and incubated for 24, 48 and 72 h. Change in colour from yellow to yellowish
brown exhibited an absorption peak at 420 and 450 nm in UV–vis region which is the characteristic of spherical silver nanoparticles. The width of the absorption peak suggests the polydispersed nature of nanoparticles [221]. IR spectrum of Ag NPs exhibited absorption peaks at 3304, 2200, 2066, 1969, 1636, 1261, 1094 and 611 cm$^{-1}$ for different groups. Although, authors have indicated the presence of polysaccharide and protein in the mushroom they

| Table 3 Bacteria-mediated synthesis of silver nanoparticles |
|---------------------------------|---------------------|-----------------|-----------------|
| **Bacteria**                     | **Size and shape**  | **Location**    | **Key references** |
| Acinetobacter calcoaceticus      | 8–12 nm; spherical  | Extracellular   | Singh et al. [175] |
| A. haemolyticus MMC8              | 4–40 nm             | Extracellular   | Gaidhani et al. [176] |
| Aeromonas sp. SH10                | 64 nm               | Extracellular and intracellular | Moung et al. [177] |
| Bordetella sp.                    | 63–90 nm            | Extracellular   | Thomas et al. [179] |
| Enterobacter aerogenes            | 25–35 nm; spherical | Extracellular   | Karthik and Radha [180] |
| Escherichia coli                  | 42.2–89.6 nm; spherical | Extracellular | Gurunathan et al. [181] |
| Geobacter sulfurreducens          |                     | Extracellular   | Law et al. [182] |
| Gluconobacter roseus             | 10 nm               | Extracellular   | Krishnanraj and Berchmans [183] |
| Idiomarina sp.                   | 25 nm               | Intracellular   | Seshadrhi et al. [184] |
| Klebsiella pneumoniae            | 15–37 nm; spherical | Extracellular   | Duraisamy and Yang [185] |
| Morganella sp.                   | 10–40 nm; quasispherical | Extracellular | Panik et al. [186] |
| Proteus mirabilis                | 10–20 nm; spherical | Extracellular and intracellular | Samidi et al. [187] |
| Pseudomonas aeruginosa SM1        | 6.3 ± 4.9 nm; spherical, disk-shaped | Extracellular | Srivastava and Constanti [188] |
| 8–24 nm; spherical               |                      | Extracellular   | Kumar and Mamidyala [189] |
| 5–25 nm; quasispherical          |                      | Inintracellular | Otaqasa [190] |
| Rhodobacter sphaeroides          | Spherical 3–15      | Extracellular   | Bai et al. [191] |
| Rhodopseudomonas palustris        | Spherical 5–20      | Extracellular   | Chun-Jing and Hong-Juan [192] |
| Shewanella oneidensis MR-1       | 2–16 nm; spherical  | Extracellular   | Debabov et al. [193] |
| 93 nm; cuboidal                  |                      | Extracellular   | Oves et al. [194] |
| Vibrio alginolyticus             | 50–100 nm; Spherical | Extracellular and intracellular | Rajeshkumar et al. [195] |
| Xanthomonas oryzae               | 14.86 nm; spherical, rod-shaped | Extracellular | Narayanan and Sakhthivel [196] |
| Yersinia enterocolitica           | 10–80 nm            | Extracellular   | Purgalmi et al. [197] |
| Bacillus sp.                     | 5–15 nm             | Extracellular and periplasmic space | Pugazhenthiran et al. [198] |
| B. cereus                        | 4–5 nm              | Intracellular   | Ganesh Babu and Gunasekar [165] |
| B. flexus                       | 12 and 65 nm; spherical and triangular | Extracellular | Priyadarshini et al. [173] |
| B. licheniformis Dahb1           | 18.69–63.42 nm; spherical | Cell free extract | Shanthi et al. [199] |
| B. safensis LAU 13               | 5–30 nm; spherical  | Extracellular   | Lateef et al. [200] |
| B. methylotrophicus DC3          | 10–30 nm; spherical | –               | Wang et al. [201] |
| B. subtilis                      | Triangular, hexagonal | Extracellular | Kannan et al. [202] |
| B. subtilis MTCC 3053            | 20–60 nm; polydispersed(AgCl) | – | Paulikumar et al. [203] |
| B. thuringiensis                 | 43.52–142.97 nm     | Extracellular   | Banu et al. [204] |
| Brevibacterium casei             | 10–50 nm; spherical | Intracellular   | Kalishwaralal et al. [205] |
| Corynebacterium SH09             | 10–15 nm            | Extracellular   | Zhang et al. [206] |
| Enterococcus faecalis            | 10–80 nm            | Extracellular   | Purgalmi et al. [197] |
| Exiguobacterium sp.              | 5–50 nm; spherical  | Extracellular   | Tamboli and Lee [207] |
| Geobacillus stearothermophilus    | 5–35 nm; spherical  | Extracellular   | Fayaz et al. [208] |
| Lactobacillus mindensis          | 2–20 nm; spherical  | Extracellular   | Dhoondia and Chakraborty [209] |
| Rhodococcus sp.                  | 10–15 nm; spherical | Extracellular   | Otari et al. [210] |
| Staphylococcus epidermidis       | 10–80 nm            | Extracellular   | Purgalmi et al. [197] |
| Thermoactinomyces sp.            | 20–40 nm; spherical | Extracellular   | Deepa et al. [211] |
| Ureibacillus thermosphaericus    | 10–100 nm; spherical | Extracellular | Juibari et al. [212] |
have ignored their stretching frequencies in the IR spectrum. However, the peak at 3304 has been assigned to \( \nu (\text{OH}) \) of carboxylic acid and those at 2200 and 1969 cm\(^{-1} \) have been attributed to unsaturated aldehydes. The other peaks below 1500 cm\(^{-1} \) are due to unsaturated alkaloids.

The field emission scanning electron and high-resolution transmission electron micrograph suggested that the Ag NPs are spherical with average size ranging between 20 and 30 nm.

Very recently, Al-Bahrani et al. [230] reported biogenic synthesis of Ag NPs from tree oyster mushroom Pleurotus ostreatus. Dried aqueous extract of mushroom (1–6 mg/mL) and 1 mM AgNO\(_3\) were mixed and incubated in the dark for 6–40 h. The colour change from pale yellow to dark brownish yellow indicated the formation of silver nanoparticles. The UV–vis spectrum showed a sharp and broad absorption band at 420 nm. They are polydispersed nanoparticles of 10–40 nm with an average size of 28 nm. Several fungi namely, Aspergillus flavus, A. fumigatus, Fusarium oxysporum, Fusarium acuminatum, F. culmorum, F. solani, Metarhizium anisopliae, Phoma glomerate, Phytophthora infestans, Trichoderma viride, Verticillium sp. have been used for both extracellular and intracellular biosynthesis of Ag NPs [10, 164, 216–219, 222]. These nanoparticles are of various sizes and shapes (Table 4).

From plants

Plant related parts such as leaves, stems, roots, shoots, flowers, barks, seeds and their metabolites have been successfully used for the efficient biosynthesis [1, 238] of nanoparticles (Fig. 1). Very recently, Beg et al. [128] have reported green synthesis of Ag NPs from seed extract of Pongamia pinnata. The formation of nanoparticles was confirmed by an absorption max at 439 nm. The well dispersed nanoparticles with an average size of 16.4 nm had zeta potential equal to \(-23.7\) mV which supports dispersion and stability. Interaction of Ag NPs with human serum albumin was investigated and showed negligible change in \( \alpha \) helics. In a very recent publication Karatoprak et al. [137] have reported green synthesis of Ag NPs from the medicinal plant extract Pelargonium endlicherianum. The plant containing gallic acid, apocynin and quercetin act as reducing agents to produce silver nanoparticles. Phytomediated synthesis of spherical Ag NPs from Sambucus nigra fruit extract has been reported by Moldovan et al. [144]. XRD analysis showed them to be crystalline. The in vivo antioxidant activity

| Fungus                     | Size and shape                      | Location                  | Key references                     |
|----------------------------|-------------------------------------|---------------------------|------------------------------------|
| Aspergillus flavus         | 8.92 nm; spherical                  | Cell wall                 | Vigneshwaran et al. [217]          |
| A. fumigatus               |                                     | Extracellular             | Bhainsa and D’Souza [218]         |
| A. terreus                 | 1–20 nm; spherical                  | Extracellular             | Li et al. [219]                    |
| Cladosporium cladosporioides| 10–100 nm                           | Extracellular             | Balaji et al. [220]                |
| Coriolus versicolor        | 25–75, 444–491 nm; spherical        | Extracellular and intracellular | Sanghi and Verma [221]         |
| Fusarium oxysporum         | 20–50 nm; spherical                 | Extracellular             | Ahmad et al. [222]                |
|                           | 5–50 nm                             | Extracellular             | Durán et al. [164]                |
| Humicola sp.               | 5–25 nm; spherical                  | Extracellular             | Senapati et al. [223]             |
| Macrophomina phaseolina    | 5–40 nm; spherical                  | Cell-free filtrate        | Chowdhury et al. [225]            |
| Pedicoccus pentosaceus     |                                     | Extracellular             | Shalverdi et al. [15]             |
| Penicillium brevicompactum | 58.35 ± 17.88 nm                    | Extracellular             | Shaligram et al. [226]            |
| P. fellutanum              | 5–25 nm; spherical                  | Extracellular             | Kathiresan et al. [215]           |
| P. naigiovense AJ12        | 25 ± 2.8 nm; spherical              | Cell-free filtrate        | Maliszewksa et al. [227]          |
| Phaenerochaeta chrysosporium| 5–200 nm; pyramidal                 | Extracellular             | Vigneshwaran et al. [228]         |
| Phoma glomerata            | 60–80 nm; spherical                 | Extracellular             | Birla et al. [229]                |
| Pleurotus ostreatus        | < 40 nm; spherical                  | Extracellular             | Al-Bahrani et al. [230]           |
| P. sajor-caju              | 30.5 ± 4.0 nm; spherical            | Extracellular             | Vigneshwaran et al. [231]         |
| Trichoderma asperellum     | 13–18 nm; nanocrystalline           | Extracellular             | Mukherjee et al. [232]            |
| T. reesei                  | 5–50 nm                             | Extracellular             | Vahabi et al. [233]               |
| T. viride                  | 5–40 nm; spherical                  | Extracellular             | Fayaz et al. [234]                |
| T. viride                  | 2–5 nm; spherical                   | Cell free extract         | Kumari et al. [235]               |
|                           | 40–65 nm; rectangular               |                           |                                    |
|                           | 50–100 nm; penta/hexagonal (Obtained at varying pH, reaction time and temperature of the reaction mixture) | |                                    |
was investigated against Wistar rats which showed promising activity. It suggests that functionalization of Ag NPs with natural phytochemicals may protect the cell proteins from ROS production. Ag NPs have also been synthesized from aqueous leaf extract of Artocarpus altillis. They are moderately antimicrobial and antioxidant. Thalictrum foliolosum root extract mediated Ag NPs synthesis has been confirmed on the basis of the appearance of a sharp peak at 420 nm in UV–vis region of the spectrum [239]. The monodispersed spherical nanoparticle of 15–30 nm had face centered cubic geometry. Shape and size dependent controlled synthesis of Ag NPs from Aloe vera plant extract and their antimicrobial efficiency has been reported by Logaranjan et al. [35]. The UV–vis peak at 420 nm confirmed the formation of silver nanoparticles. After microwave irradiation of the sample, Ag NPs of 5–50 nm with octahedral geometry was obtained. Nearly two to fourfold antibacterial activity of Ag NPs was observed compared to commonly available antibiotic drugs. Biosynthesis of Ag NPs from the aqueous extract of Piper longum fruit extract has been also achieved [240]. The nanoparticles were spherical in shape with an average particle size of 46 nm determined by SEM and dynamic light scattering (DLS) analyser. The polyphenols present in the extract are believed to act as a stabilizer of silver nanoparticles. The fruit extract and the stabilized nanoparticles showed antioxidant properties in vitro. The nanoparticles were found to be more potent against pathogenic bacteria than the flower extract of P. longum. Ag NPs have been fabricated from leaf extract of Ceropedia thwaitesii and formation was confirmed from absorption of SPR at 430 nm. The nanoparticles of nearly 100 nm diameter were crystalline in nature [139]. Plant extract of Ocimum tenuiflorum, Solanum tricobatum, Syzygium cumini, Centella asiatica and Citrus sinensis have been used to synthesize Ag NPs of different sizes in colloidal form [249]. The size of all nanoparticles was found to be 22–65 nm. They were all stable and well dispersed in solution. Niraimath and co-workers [140] have reported biosynthesis of Ag NPs from aqueous extract of Alternanthera sessilis and showed that the extract contains alkaloids, tannins, ascorbic acid, carbohydrates and proteins which serve as reducing as well as capping agents. Biomolecules in the extract also acted as stabilizers for silver nanoparticles. Ag NPs from seed powder extract of Artocarpus heterophyllus have been synthesized [138]. The morphology and crystalline phase of the nanoparticles were determined by SEM, TEM and SAED, EDAX and IR spectroscopy. They were found to be irregular in shape. The extract was found to contain amino acids, amides etc. which acted as reducing agents for AgNO₃ to produce silver nanoparticles. The quantity of phenols, anthocyanins and benzoic acid were determined in the berry juices and were responsible for the transformation of silver ions to Ag NPs [241]. UV–vis spectra displayed an absorbance peak at 486 nm for lingonberry and 520 nm for cranberry containing silver nanoparticles. Since the two absorption peaks are different they cannot be assigned only to Ag NPs but also partly to different quantities of the reducing chemicals present in the juices. However, the spectra indicated the presence of polydispersed silver nanoparticles. Puiso et al. [241] have proposed that due to irradiation of water by UV rays, strong oxidants and reductants as photolysis products are formed. They reduce silver ions to Ag NPs or silver oxide. The photolysis products may produce oxidant and reductant but it depends upon the quantum of radiation and exposure time which may not be enough to produce a sufficient quantity of redox chemicals to reduce Ag⁺ to Ag NPs or Ag₂O. This hypothesis is conceptually incorrect because Ag₂O cannot be formed as it requires a very strong oxidizing agent. On the other hand, AgNO₃ itself is slowly reduced in water, but in the presence of reducing agents the reaction proceeds at a rapid rate. The SPR is dependent on the size, shape and agglomeration of Ag NPs which is reflected from the UV–vis spectra [242]. Mock et al. [243] have found different scattered colors in hyperspectral microscopic images which are mainly due to the different shape and size of silver nanoparticles in the colloidal solution. The blue, green, yellow and red colors have been attributed to spherical, pentagonal, round-triangle and triangle shapes, respectively.

Zaheer and Rafiuddin [12] have reported the synthesis of Ag NPs using oxalic acid as reducing agent and mistook it as green synthesis. Formation of nanoparticles was confirmed by a change in color of the solution which showed an absorption peak at 425 nm (Fig. 2a) in the UV–visible region. It was also noted that a scattered silver film was formed on the wall of the container that shines and reflects light (Fig. 2b) which is the characteristic of monodispersed spherical Ag NPs [244, 245]. Since the size of nanoparticles varies between 7 and 19 nm the silver film is not uniform. It is different from regular silver mirror due to irregular shape and size of nanoparticles (Fig. 2c). Actually, very small size nanoparticles can be obtained when AgNO₃ is exposed to a reducing agent for a longer duration of time [246]. The kinetics and mechanism proposed for the formation of Ag NPs by oxalic acid is not convincing [12] because oxalic acid in no case can produce CO₂ unless it reacts with any carbonate salt or heated at a very high temperature. The authors [12] have proposed following reactions to prove that the colour of Ag NPs in solution is due to Ag⁺⁺ formation that absorbs at 425 nm (Scheme 1). The formation of Ag⁺⁺ is highly improbable even if the above reaction is kinetically very fast. Also, the stabilization of Ag⁺⁺ is questionable.
This hypothesis of Ag$_{2}^{2+}$ formation is beyond imagination and does not carry any experimental evidence in its support. Absorbance of Ag NPs in solution varies between 400 and 445 nm depending on the nature of reducing agent used for their fabrication. The SPR band in UV–vis spectrum is due to electron oscillation around the surface of nanoparticles. The reduction process is instantaneous and no further spectral change occurs after 60 min. Indicating the completion of redox process. Ag NPs are circular, triangular, hexagonal and polydispersed at 70 °C. The EDAX and XRD spectra support each other.

Synthesis of Ag NPs from aqueous extract of Cleistanthus collinus and their characterization by UV–vis, FTIR, SEM, TEM and XRD has been reported by Kanipandian et al. [247]. The crystalline Ag NPs of 20–40 nm showed significant free radical scavenging capacity. Tippayawat et al. [27] have reported a green and facile synthesis of Ag...
NPs from *Aloe vera* plant extract. They were characterized by UV–vis, SEM, TEM and XRD. Fabrication of Ag NPs was confirmed on the basis of the appearance of a sharp peak at 420 nm in UV–vis region of the spectrum. In addition, they have reported that the reaction time and temperature markedly influence the fabrication of silver nanostructures. Ag NPs were spherical in shape and particle size ranged from 70.70 ± 22 to 192.02 ± 53 nm. Their size changes with time and temperature of the reaction mixture used during fabrication (Fig. 3).

Green synthesis of Ag NPs from *Boerhaavia diffusa* plant extract has been reported by Vijay Kumar et al. [136] where the extract acted as both the reducing as well as capping agent. The colloidal solution of Ag NPs showed an absorption maximum at 418 nm in the UV–vis spectrum. The XRD and TEM analyses revealed a face centered cubic structure with an average particle size of 25 nm. Ag NPs of 5–60 nm have been synthesized from *Dryopteris crassirhizoma* rhizome extract in presence of sunlight/LED in 30 min [235]. XRD studies showed face centered cubic structure of silver nanoparticles.

Green synthesis of Ag NPs using 1 mM aqueous AgNO₃ and the leaf extract of *Musa balbisiana* (banana), *Azadirachta indica* (neem) and *Ocimum tenuiflorum*...
(black tulsi) has been done [248]. They were characterized by UV–vis, SEM, TEM, DLS, EDS and FTIR spectroscopy. They were found to accelerate the germination rate of Vigna radiata (Moong Bean) and Cicer arrietinum (Chickpea). It is therefore, believed that Ag NPs are not toxic to such crops at germination level. Stable and capped Ag NPs from aqueous fruit extract of Syzygium alternifolium of 5–68 nm have been synthesized [92]. Nearly 12.7% of silver was detected from EDAX. The polydispersed spherical nanoparticles were capped and stabilized by the phenols and proteins present in the fruit extract. Biosynthesis of Ag NPs from methanolic leaf extract of Leptadenia reticulate has been done [142]. They were crystalline, face centred and spherical particles of 50–70 nm. They exhibited antibacterial activity and radical scavenging activity. Purple sweet potato (Ipomoea batatas L.) root extract has been exploited to synthesize Ag NPs [143]. Organic components in the act extract acted both as reducing and capping agents. Ag NPs have shown remarkable antibacterial activity against four clinical and four aquatic pathogens. Sweet potato root extract is known to contain glycoalkaloids, mucin, dioscin, choline, polyphenols and anthocyanins which function as antioxidant, free radical scavenger, antibacterial agent and reducing agents. In presence of Ag NPs these functions are further enhanced.

Cytotoxicity of silver nanoparticles
Cytotoxicity of nanomaterials depends on their size, shape, coating/capping agent and the type of pathogens against which their toxicity is investigated. Nanoparticles synthesized from green method are generally more toxic than those obtained from the non-green method. Some pathogens are more prone to nanomaterials, especially Ag NPs than others due to the presence of both the Ag ions released and Ag NPs. They slowly envelop the microbes and enter into the cell inhibiting their vital functions. It is clear that the fabrication and application of nanoparticles has resulted in public awareness of their toxicity and impact on the environment [249, 250]. Nanoparticles are relatively more toxic than bulk materials. They are toxic at cellular, subcellular and biomolecular levels [251]. Oxidative stress and severe lipid peroxidation have been noticed in fish brain tissue on exposure to nanomaterials [252]. The cytotoxicity by Ag NPs is believed to be produced through reactive oxygen species (ROS) as a consequence of which a reduction in glutathione level and an increase in ROS level occur. From in vitro studies on animal tissue and cultured cells, Kim and Ryu [253] have observed an increase in oxidative stress, apoptosis and genotoxicity when exposed to silver nanoparticles. Since such studies have been made with varying sizes of Ag NPs and coatings under different conditions a direct correlation cannot be made. Hackenberg and coworkers [254] reported reduced viability at a dose of 10 µg/mL of Ag NPs of over 50 nm size in human mesenchymal cells whereas some people reported no toxicity [255] even at a higher dose (100 µg/mL). Besides, stability and aging of the sample are also important factors as an increase in toxicity has been reported by aged Ag NPs stored in water for 6 months which is related to the release of silver ions [256]. It seems that the toxicity is a cumulative effect of Ag NPs and silver ions. Some workers have shown that the toxicity of Ag NPs is due to released Ag ions [257] while others have attributed the toxicity to Ag NPs [258].

Vijay Kumar et al. [136] obtained Ag NPs from B. dif fusus plant extract and tested them against three fish bacterial pathogens. It was found that Ag NPs were most effective against Flavobacterium branchiophilum. Ag NPs fabricated from P. longum fruit extract exhibited cytotoxic effect against MCF-7 breast cancer cell lines with an IC50 of 67 µg/mL/24 h [240]. They also exhibited antioxidant and antimicrobial effects. Ag NPs were produced by using P. endlicherianum plant extract; and have shown that the inhibitory activity was increased against gram positive and gram negative bacteria when they were exposed to Ag NPs at a very low dose of 7.81 to 6.25 ppm [137]. Latha et al. [89] have fabricated Ag NPs from leaf extract of Adathoda vasica and studied their antimicrobial activity against Vibrio parahaemolyticus in agar medium. The nanoparticles were found to be significantly active against V. parahaemolyticus but were nontoxic to Artemia nauplii. V. parahaemolyticus is a prevalent sea food borne enteropathogen which is closely associated with mortality in Siberian tooth carps, milk fish [259], abalone [260] and shrimps [251]. Vibrio infection in cultured fish and shrimps causes large scale mortality. Quite often, the whole population perishes. The use of antibiotic has made them resistant. Under such conditions, Ag NPs have appeared as an effective remedy which saves shrimps from perishing. Ag NPs from seed powder extract of A. heterophyllus have also exhibited antibacterial activity against gram positive and gram negative bacteria [138].

Ag NPs fabricated from leaf extract of C. thwaitesii have shown antibacterial efficacy against Salmonella typhi, Shigella flexneri and Kibsiella pneumoniae indicating them to be significant. Niraimathi and co-workers [140] have also fabricated Ag NPs from aqueous extract of A. sessilis and showed significant antibacterial and antioxidant activities. Ag NPs from Ocimum tenuiflorum, Solanum tricobatum, Syzygium cumini, Centella asiatica and Citrus sinensis have also shown antibacterial activity against S. aureus, P. aeruginosa, E. coli and K. pneumoniae. The highest activity of nanoparticles was observed
against *S. aureus* and *E. coli* [261]. Antimicrobial activity of colloidal Ag NPs was found to be higher than the plant extract alone. Lee et al. [141] synthesized Ag NPs from *Dryopteris crassirhizoma* and found them to be highly effective against *B. cereus* and *P. aeruginosa*. Similarly, Ag NPs obtained from leaf extract of banana, neem and black tulsi were also active against *E. coli* and *Bacillus sp.* [248]. Hazarika et al. [239] have performed antimicrobial screening of Ag NPs obtained from *T. foliolosum* root extract against six bacteria and three fungi which showed morphological changes in the bacterial cells. Fabricated of Ag NPs from *Millettia pinnata* flower extract and their characterization together with anti-cholinesterase, anti-bacterial and cytotoxic activities have been reported by Rajakumar et al. [145]. Spherical shaped Ag NPs ranging from 16 to 38 nm exhibited excellent inhibitory efficacy against acetyl cholinesterase and butyl cholinesterase. They also exhibited cytotoxic effects against brine shrimp.

Ag NPs obtained from *S. alternifolium* have also exhibited high toxicity towards bacterial and fungal isolates [92]. Ag NPs fabricated from *L. reticulate* [142] were found to be toxic to HCT15 cancer cell line. Kanipandian et al. [247] have reported that Ag NPs obtained from *C. collinus* aqueous extract exhibit dose dependent effects against human lung cancer cell (A549) and normal cell (HBL-100). The IC₅₀ for cancer cells was very low (30 µg/mL) but since Ag NPs synthesized from *C. collinus* were toxic to normal cells they cannot be used in vivo. However, if the plant extract contains some antioxidants, the whole mixture may exhibit this property but the nanoparticles alone are incapable to do so. Ag NPs from *Aloe vera* plant extract have shown varying degrees of antibacterial effects [36]. Ag NPs obtained at 100 °C for 6 h and 200 °C for 12 h (varying temperature and reaction time) exhibited change in bacterial cell membrane when contacted with the nanoparticles (Fig. 4). They were more effective for gram negative bacteria (*P. aeruginosa*, ATCC27803). In addition, they have also shown minimal cytotoxicity to human peripheral blood mononuclear cells.

The particle size, agglomeration and sedimentation are related to the cytotoxicity of silver nanoparticles. It has been demonstrated from Alamar Blue (AB) and Lactate dehydrogenase test (LDH) that Ag NPs of 10 nm coated with citrate and PVP separately, are toxic to human lung

---

**Fig. 4** SEM images of the bacterial strains. **a** *Staphylococcus epidermidis*, Gram-positive, **b** *Pseudomonas aeruginosa*, Gram-negative, **c** *S. epidermidis* treated with 100–6 h silver nanoparticles (0.04 mg/mL), **d** *P. aeruginosa* treated with 100–6 h silver nanoparticles (0.04 mg/mL) [36]
cells [262] when exposed for 24 h. AB test is a measure of cell proliferation and mitochondrial activity. However, the LDH measures the cytotoxicity of Ag NPs in terms of membrane damage from the cytoplasm. Both the citrate and PVP coated nanoparticles of 10 nm exhibited significant toxicity after 24 h at the highest dose of 50 µg/mL. Ag NPs of larger dimensions did not alter cell viability [263, 264]. Cytotoxicity is related to enzyme inhibition which is correlated to the release of Ag ions because they inhibit the catalytic activity of LDH.

It has been observed that Ag NPs damaged DNA but they did not increase ROS when cells were exposed to them for 24 h at a dose of 20 µg/mL [263]. Gliga et al. [262] have suggested that silver ions from AgCl are released in the biological fluid and complexed. The formation of AgCl is possible only if the fluid is contaminated with Cl⁻ ions, nevertheless it cannot ionize to Ag⁺ and Cl⁻ ions since AgCl is almost insoluble in aqueous medium [265]. The experiment with extracellularly released silver ions in cell medium did not exhibit toxicity, perhaps it would have reacted with Cl⁻ ions to yield insoluble AgCl.

Cytotoxicity is related to the size of Ag NPs irrespective of the coating agent. Carlson et al. [266] have shown an increase in ROS production for 15 nm hydrocarbon coated Ag NPs relative to 55 nm. It has been reported by Liu et al. [267] that 5 nm Ag-nanoparticles were more toxic than 20 and 50 nm nanoparticles to four cell lines, namely, A549, HePG2, MCF-7 and SGC-7901. Wang et al. [268] have also reported that smaller nanoparticles (10–20 nm) induce greater cytotoxicity than the larger ones (110 nm), and citrate coated 20 nm Ag NPs produced acute neutrophilic inflammation in the lungs of mice compared to those with larger ones. The cell viability and DNA damage may be explained by ROS generation [269] which may be contradictory to findings by others in in vitro studies [253].

It is hypothesized that irreparable DNA damage is due to the interaction of Ag NPs with repair pathways. Since this work has been done in vitro, the DNA once damaged may not have the ability to repair. However, in living systems the cells have the ability to undergo repair and multiply but such experiments have seldom been done. It is however, unanimously agreed that both Ag NPs and silver ions are present at the subcellular level. The transformation of Ag to Ag⁺ ions occurs due to their interaction with biomolecules in the cell membrane. The release of elemental silver is directly proportional to the size of nanoparticles in a non-linear fashion [270]. The size dependent toxicity is related to the intracellular release of silver ions. Although, agglomeration of nanoparticles reduces their release, the antibacterial effect was hindered under anaerobic condition, because in absence of oxygen, the oxidation process Ag → Ag⁺ ceases to continue. Ag NPs exhibited excellent activity against Y. enterocolitica, P. vulgaris, E. coli, S. aureus and S. faecalis. Since the nanoparticles are smaller than the bacterial cell they may stick to their cell walls disallowing permeation of essential nutrients leading to the death of microorganisms [236]. Smaller size is related to greater surface area of nanoparticles and their agglomeration around the cell wall inhibits the cell division of microbes.

Besides their application in diverse areas, Ag NPs are extensively used as antioxidant and antimicrobial agents regardless of the process of their synthesis [271, 272]. They are more toxic to microorganisms than human beings. Antibacterial and antifungal activities of Ag NPs were tested against B. cereus, S. aureus, C. koseri, P. aeruginosa bacteria and C. albicans fungus respectively. It has been proposed that Ag NPs penetrate into the bacterial cell and interact with the thiol, hydroxyl and carboxyl groups of the biomolecules present in them, eventually deactivating the vital functions by releasing Ag⁺ ions. The authors have, however, not explained how the Ag⁺ ions were produced. We firmly believe that silver ions must have been produced through a redox mechanism and subsequently complexed with electron donating thiol and phosphate groups inhibiting the cell replication of pathogens. It is well known that silver ions strongly bind with sulfur and oxygen containing electron donor groups in living system and arrest the functioning of vital organs that lead to the death of animal.

Ag NPs synthesized from lingonberry and cranberry juices [241] were tested for their activity against microbes commonly found in food and food products namely, S. aureus, S. typhi, L. monocytogenes, B. cereus, E. coli, B. subtillis and C. albicans. They observed that Ag NPs were more effective towards S. aureus, B. subtillis and B. cereus. Antibacterial activity was screened against B. cereus and S. aureus which produce toxins in food products [243]. A similar study has also been reported by Nanda and Saravanan [168] on other pathogens such as S. aureus, S. epidermidies and S. pyogens. The decrease in antimicrobial effect of Ag NPs against food borne bacteria has been ascribed to low pH or high NaCl content in food. The high concentration of NaCl may increase the toxicity towards bacteria because they may kill them. However, it is concluded that Ag NPs may be used in packaging to prevent infection in food products by microbes.

Zhao and Stevens [273] have studied antimicrobial effects of Ag salts on 12 species of bacteria and showed that they are highly effective against them. It has also been shown [274] that Ag NPs with amphiphilic hyper-branched macro molecules act as antimicrobial coating agents. Kim et al. [275] have thoroughly screened the antimicrobial effect of Ag NPs prepared from AgNO₃.
and NaBH₄ as reducing agent. They examined the efficacy of a wide range of concentrations of Ag NPs starting from 0.2 to 33 nM. At a concentration of 33 nM of Ag NPs the growth inhibition of *E. coli* and *E. aerogenes* was almost comparable with the positive control, although at 13.2 nM concentration a significant effect was observed. However, the inhibitory effect of 1.6–6.6 nM of Ag NPs is nearly the same (~ 55% relative to control). It was observed that silver nanoparticle is most effective against *E. coli* and has a mild inhibitory effect on *S. aureus*. However, gold nanoparticles of the same concentration were ineffective against these microbes, although it also belongs to the same group of elements.

Ag NPs synthesized from fungus *Humicola* sp. were investigated for their cytotoxicity on NIH3T3 mouse embryonic fibroblast cell line and MDA-MB-231 human breast carcinoma cell line [224]. In both cell lines, the cell viability declined in a dose-dependent manner. Cytotoxicity of Ag NPs was recorded at a concentration of 250 µg/mL; the cell viability declined by 20.83% in the case of NIH3T3 and 42.18% for MDA-MB-231 cell line at 1000 µg/mL concentration. Very recently [269], it has been investigated that Ag NPs in conjugation with other metals such as TiO₂@Ag nanoparticles act against leishmaniasis. These nanoparticles along with other drugs for leishmaniasis, like neglumine antimoniate at nontoxic concentrations increase the efficacy of both drugs. This combination of drug led to the inhibition of *L. tropica* amastigotes at a very high rate of 80–95%. Also, it increased the metabolic activities 7–20-fold.

Owaid et al. [237] have produced Ag NPs from aqueous extract of *P. cornucopiae* var. *citrinopileatus* which served both as reducing and stabilizing agent. Their antimicrobial activity was investigated against four pathogenic *Candida* sp. namely *C. albicans*, *C. glabrata*, *C. krusei* and *C. pseudotropicalis*. Ag NPs at 60 µg/well showed a significant increase in inhibition of *candida* sp. However, pure extract was ineffective against all microbes at 20–40 µg/well. Mechanism of action has been ascribed to the interaction between the positive charge on silver ion and the negative charge on the cell membrane of microorganism [25, 35]. Due to electrostatic attraction between the two the silver ions penetrate into the microbial cell via diffusion leading to their death. Ag NPs synthesized using fungus *Trichoderma viride* were examined for their antimicrobial activity in combination with various antibiotics (ampicillin, kanamycin, erythromycin and chloramphenicol) against both gram positive and gram negative bacteria [234]. Antibacterial activities of antibiotics were increased in the presence of Ag NPs against the tested strains and *P. aeruginosa*. The original aqueous extract of *P. ostreatus* was found to be ineffective against all bacterial strains at 25–75 µg/mL.

Allahverdiyev et al. [276] have reported that the combination of Ag NPs with antibiotics decreases the toxicity toward human cells by reducing the required dosage. Furthermore, these combinations restore the ability of the drug to kill bacteria that have acquired resistance to them [175]. Hence, a separate approach of using Ag NPs synthesized from bacterial strains alone and in combination can act as effective novel antimicrobials to sensitize resistant pathogens. Nevertheless, a study with *E. coli* has demonstrated that the bacteria could become resistant to Ag NPs on its regular exposure for 225 generations through genetic mutations [277]. Thus, a precaution should be taken to avoid the constant exposure of microorganisms against such types of nanoparticles. In addition, treatment with bacterial Ag NPs has shown the cell viability reduction in a dose-dependent manner in HeLa cervical cancer [278, 279], MDA-MB-231 breast cancer [280], A549 adenocarcinoma lung cancer [281] and HEP2 [282] cell lines. Ag NPs produced from bacterial strains exhibited cytotoxicity to cancer cells but their impact on normal healthy cells cannot be ignored.

**Mechanism of antibacterial activity**

As discussed previously, several reports are available which have shown that Ag NPs are effective against pathogenic organisms namely *B. subtilis*, *Vibrio cholerae*, *E. coli*, *P. aeruginosa*, *S. aureus*, *Syphilis typhus* etc. [10, 11, 109, 145]. Ag NPs with larger surface area provide a better contact with microorganisms [283]. Thus, these particles are capable to penetrate the cell membrane or attach to the bacterial surface based on their size. In addition, they were reported to be highly toxic to the bacterial strains and their antibacterial efficiency is increased by lowering the particle size [284]. Many arguments have been given to explain the mechanism of growth inhibition of microbes by Ag NPs but most convincing is the formation of free radical which has also been supported by the appearance of a peak at 336.33 in the electron spin resonance (ESR) spectrum of Ag NPs [275]. The free radical generation is quite obvious because in a living system they can attack membrane lipids followed by their dissociation, damage and eventually inhibiting the growth of these microbes [285]. It is worth noting that the equal mass of silver Ag NPs and that of Ag ions exhibit identical growth inhibition of *E. coli* and *S. aureus*. In a study, the highly antibacterial activity has been ascribed to the release of silver cation from Ag NPs [173]. The Ag⁺ permeated into bacteria through the cell wall [286, 287] as a consequence of which the cell wall ruptures leading to denaturation of protein and death. Since Ag ions are positively charged and much smaller than neutral Ag NPs they can easily interact with electron rich biomolecules in the bacterial cell wall containing S or P and N. Some
researchers have reported that interaction between the positive charge on Ag NPs and negative charge on the cell membrane of the microorganisms is the key to growth inhibition of the microbes [286, 287]. On the other hand, Sondi et al. [288] have reported that antibacterial activity of Ag NPs toward gram negative bacteria depends on its concentration. The nanoparticles form pits in the cell wall of microbes, get accumulated, and penetrate into the bacterial cell leading to their death. It has been reported [289, 290] that Ag free radical formation and antimicrobial property are inter related which has been confirmed by ESR [275]. They claim that such an antimicrobial study included both the positively charged silver ions and negatively charged silver nanoparticles.

The absorption of Ag NPs at 391 nm is the signature of spherical nanoparticles due to their surface plasmon resonance [291]. This absorption spectrum does not undergo any change even when the suspension of Ag NPs is diluted ten times indicating that they are not agglomerated. Besides Ag NPs and silver compounds, there are other inorganic ions which also possess antibacterial properties [241, 287, 292]. It is known that silver ions bind to the protein of the microorganisms preventing their further replication but the organisms also avoid interacting with these ions and produce cysts to become resistant.

Ag NPs may be oxidized to Ag⁺ but cannot be reduced [287, 289]. Silver is known to have 4d¹⁰, 5s¹ outermost electronic configuration and it cannot hold an extra electron to become Ag⁺ anion. Silver salt of sulphathiazine is used in burn therapy to protect the skin from infection by pseudomonas species. Silver is released slowly from the salt which is sufficiently toxic to microorganisms. Since the salt is sparingly soluble the silver acts on the external cell structure. Silver salt and Ag NPs exhibit cytotoxicity against a broad range of microorganisms, although the toxicity depends on the quantum of silver ions released [275].

The monodispersed nanoparticles of uniform size are produced. Graphene oxide exhibits antibacterial activity against E. coli [293, 294] but Ag NPs functionalized graphene based material show enhanced antibacterial activity [295, 296]. Graphene oxide is nicely dispersed in polar solvents like water which allows the deposition of nanoparticle for its use in various fields. Antibacterial activity of both Ag NPs and Ag-graphene oxide composite has been tested in a wide range of concentration between 6.25 and 100 µg/mL against both gram positive and gram negative bacteria. It was noticed that both Ag NPs and Ag-graphene oxide composite were more effective against gram positive than gram negative bacterial strains. Ag-graphene oxide is a better growth inhibitor of S. Typhi, even at a very low concentration of 6.25 µg/mL, than Ag NPs of the same concentration. However, Ag NPs and Ag-graphene oxide do not show any inhibitory effect against gram positive bacteria, S. aureus and S. epidermis below 50 µg/mL. It was also noted that graphene oxide alone is ineffective against these bacteria even at a higher concentration of 100 µg/mL [293, 296].

Silver ions released from Ag NPs may penetrate into bacterial cell components such as peptidoglycan, DNA and protein preventing them from further replication [297, 298]. Release of Ag⁺ ions means the oxidation of elemental silver which requires an oxidizing agent.

Silver nanoparticle $\rightarrow$ Ag⁺ + e⁻

The organic groups like carbonyl and protein in the bacterial cell wall are electron donors rather than electron acceptors and hence they cannot produce Ag⁺ ions from Ag atoms, nevertheless the Ag⁺ ions are produced which confirms the presence of an oxidizing agent [296, 299]. Ag⁺ ions are thus bonded to the proteins of bacteria and inhibit their vital functions.

Tho et al. [300] have shown that spherical Ag NPs of 2.76–16.62 nm size fabricated from Nelumbo nucifera seed extract are highly toxic to Gram negative bacteria. The antibacterial property has been ascribed to the attachment of Ag NPs to the surface of cell membrane disallowing permeation and respiration of the cells.

The outer layer of gram negative bacteria is made up of a lipopolysaccharide layer and the inner layer is composed of a linear polysaccharide chain forming a three-dimensional network with peptides. Ag NPs get accumulated due to attraction between the negative charge on the polysaccharides and weak positive charge on the silver nanoparticles. It stops the cell replication of the microbes.

Toxicity by nanoparticles is generally triggered by the formation of free radicals, such as ROS [301, 302]. If the ROS is produced it may cause membrane disruption and disturb the permeability. The mechanism of growth inhibition follows electrostatic interaction, adsorption and penetration of nanoparticles into the bacterial cell wall. Toxicity of nanoparticles also depends on composition, surface modification, intrinsic properties and type of microorganisms [9, 303–306]. For instance, TiO₂-nanoparticles can increase peroxidation of the lipid membrane disrupting the cell respiration [307]. The biogenic Ag NPs in combination with antibiotics like erythromycin, chloramphenicol, ampicillin and kanamycin enhance the toxicity against gram positive and gram negative bacteria [308, 309]. A possible mechanism is presented in Fig. 5. Besides, Ag NPs are also toxic to nitrifying bacteria [310]. The ROS include superoxide (O₂⁻), hydroxyl (·OH), peroxy (RCOO·) and hydrogen peroxide (H₂O₂). RNS includes nitric oxide (NO⁻) and
nitrogen dioxide (NO\textsubscript{2}\textsuperscript{−}) [311, 312]. The cell replication and development of microbes in ROS containing atmosphere will cease to continue. However, this process may be delayed in presence of an antioxidant such as an enzyme or a non-enzymatic component which scavenges the free radicals [313].

**Conclusion**

Regardless of the method of fabrication, Ag NPs are used as an antimicrobial agent, electrochemical sensors, biosensors, in medicine, health care, agriculture and biotechnology. They have great bactericidal potential against both gram positive and gram negative pathogens. Since Ag NPs coupled with antibiotics are active against many drug resistant bacteria they can be used as easily accessible medicine for the treatment of several infections. Ag NPs in the drug delivery system, quite often increase the solubility, stability and bio-distribution enhancing their efficiency. In presence of nanoparticles the absorption of medicine increases several times therefore, Ag NPs may be used as a drug delivery system.

Although, the long-term effect of nanoparticles on human health and crops is not clear. A large number of nanoparticles are being explored in many areas of industry technology, biotechnology and agriculture. It is known that various forms of silver from laundry, paints, clothes etc. and biosolids reach the sewage and sludge. It has been reported that nano sized Ag\textsubscript{2}S are formed in the activated sludge as a consequence of the reaction between silver nanoparticles/Ag\textsuperscript{+} ions and the sulfide produced in sewage. It is not possible for Ag NPs in the elemental form to react with evolved H\textsubscript{2}S. Only Ag\textsuperscript{+} ions may react with H\textsubscript{2}S to yield Ag\textsubscript{2}S according to the reaction given below.

\[
2\text{AgNO}_3 + \text{H}_2\text{S} \rightarrow \text{Ag}_2\text{S} + 2\text{HNO}_3
\]

Ag\textsubscript{2}S or AgNO\textsubscript{3} may be ionized to give free Ag\textsuperscript{+} ions which inhibit the bacterial growth. Besides many advantages of Ag NPs there are some disadvantages too. They inhibit the growth of nitrifying bacteria, thereby inhibiting the biological nitrogen removal. As little as 1–20 ppm Ag NPs have been reported to be effective against microbes. It is anticipated that Ag NPs may be used as an inexpensive broad spectrum antimicrobial agent to protect plant crops and infections in human beings.

**Authors’ contributions**

AH, KSS and RAKR gathered the research data. AH and KSS analyzed these data and wrote this review paper. All the authors read and approved the final manuscript.

**Author details**

1 Department of Chemistry, Aligarh Muslim University, Aligarh, Uttar Pradesh 202002, India. 2 Department of Biology, College of Natural and Computational Sciences, University of Gondar, P.O. Box # 196, Gondar, Ethiopia. 3 Department of Applied Chemistry, Zakir Husain College of Engineering and Technology, Aligarh Muslim University, Aligarh, Uttar Pradesh 202002, India.

**Acknowledgements**

Authors are thankful to publishers for permission to adopt figures in this review.

**Competing interests**

The authors declare that they have no competing interests.
References

1. Husen A, Siddiqi KS. Phytosynthesis of nanoparticles: concept, controversy and application. Nano Res Lett. 2014;9:229.
2. Husen A, Siddiqi KS. Plants and microbes assisted selenium nanoparticles: characterization and application. J Nanobiotechnol. 2014;12:28.
3. Siddiqi KS, Husen A. Green synthesis, characterization and uses of palladium/platinum nanoparticles. Nano Res Lett. 2016;11:482.
4. Husen A, Siddiqi KS. Carbon and fullerenes nanomaterials in plant system. J Nanobiotechnol. 2014;12:16.
5. Siddiqi KS, Rahman A, Tajuddin Husen A. Biogenic fabrication of iron/iron oxide nanoparticles and their application. Nano Res Lett. 2016;11:498.
6. Siddiqi KS, Husen A. Recent advances in plant-mediated engineered gold nanoparticles and their application in biological system. J Trace Elements Med Biol. 2017;40:10–23.
7. Siddiqi and Husen. Engineered gold nanoparticles and plant adaptation potential. Nano Res Lett. 2016;11:400.
8. Wei L, Lu J, Xu H, Patel A, Chen ZS, Chen G. Silver nanoparticles: synthesis, properties, and therapeutic applications. Drug Discov Today. 2015;20:595–601.
9. Lara HH, Garza-Trevino EN, Itxepan-Turrent L, Singh DK. Silver nanoparticles are broad-spectrum bactericidal and virucidal compounds. J Nanobiotechnol. 2011;9:390.
10. Siddiqi KS, Husen A. Fabrication of metal nanoparticles from fungi and metal salts: scope and application. Nano Res Lett. 2016;11:98.
11. Siddiqi KS, Husen A. Fabrication of metal and metal oxide nanoparticles by algae and their toxic effects. Nano Res Lett. 2016;11:363.
12. Zareer Z, Rahuddin. Silver nanoparticles to self-assembled films: Green synthesis and characterization. Colloids Surf B Biointerfaces. 2012;90:48–52.
13. Lokina S, Stephen A, Kaviyarasan V, Arulvasu C, Narayanan V. Cytotoxicity and antimicrobial activities of green synthesized silver nanoparticles. Euro J Med Chem. 2014;76:256–63.
14. Saifuddin N, Wong CW, Yasumira AAN. Rapid biosynthesis of silver nanoparticles using culture supernatant of bacteria with microwave irradiation. e-J Chem. 2009;6:61–70.
15. Shahverdi AR, Miaesian S, Shahverdi HR, Jamalifar H, Noori AA. Rapid synthesis of silver nanoparticles using culture supernatant of Enterobacteria: a novel biological approach. Process Biochem. 2007;42:919–23.
16. Ahamed M, AlSaali MS, Siddiqui MKJ. Silver nanoparticle applications and human health. Clin Chim Acta. 2010;411:1841–8.
17. Chen X, Schluesener HJ. Nanosilver: a nanoproduct in medical application. Toxicol Lett. 2008;176:1–12.
18. Jones SA, Bowler PG, Walker M, Parsons D. Controlling wound bioburden with a novel silver-containing Hydrofiber dressing. Wound Repair Regen. 2004;12:288–94.
19. Silver S, Phung LT. Bacterial heavy metal resistance: new surprises. Annu Rev Microbiol. 1996;50:753–89.
20. Catauro M, Raucci MG, De Gaetano FD, Marotta A. Antibacterial and bioactive silver-containing Na2O x CaO x 25SiO2 glass prepared by sol-gel method. J Mater Sci Mater Med. 2004;15:831–7.
21. Crabtree JH, Burchette RJ, Siddiqi RA, Huen IT, Handott LL, Fishman A. The efficacy of silver-ion implanted catheters in reducing peritoneal dialysis-related infections. Perit Dial Int. 2003;23:368–74.
22. Das R, Gang S, Nath SS. Preparation and antibacterial activity of silver nanoparticles. J Biomater Nanobiotechnol. 2011;2:472–5.
23. Aramwit P, Bang N, Ratanavaraporn J, Ekgarit JS. Green synthesis of silk sericin-capped silver nanoparticles and their potent anti-bacterial activity. Nano Res Lett. 2014;9:79.
24. Vigneshwaran N, Nachane RP, Balasubramanya RH, Varadarajan PV. A novel one-pot ‘green’ synthesis of stable silver nanoparticles using soluble starch. Carbohydr Res. 2006;341:2012–8.
25. Shin Y, Bae IT, Exarhos GJ. Green approach for self-assembly of platinum nanoparticles into nanowires in aqueous glucose solutions. Colloids Surf A. 2009;348:191–5.
26. Zhang Q, Li N, Goebl J, Lu Z, Yin Y. A systematic study of the synthesis of silver nanoplates: is citrate a ‘magic’ reagent? J Am Chem Soc. 2011;133:18931–9.
27. Roldán MV, Pellegrin N, de Sanctis O. Electrochemical method for Ag-PEG nanoparticles synthesis. J Nanopart. 2013;13:524150.
28. Sotiriou GA, Pratsinis SE. Antibacterial activity of nanosilver ions and particles. Environ Sci Technol. 2010;44:5649–54.
29. Sotiriou GA, Teleki A, Camenzind A, Krumiech F, Meyer A, Panke S, Pratsinis SE. Nanosilver on nanostructured silica: antibacterial activity and Ag surface area. Chem Eng J. 2011;170:547–54.
30. Abou El-Neur KM, Eftaia A, Al-Waithan A, Ammar BAA. Synthesis and applications of silver nanoparticles. Arab J Chem. 2010;3:35–40.
31. Tien DC, Tseng KH, Liao CY, Huang JC, Tsung TT. Discovery of ionic silver in silver nanoparticle suspension fabricated by arc discharge method. J Alloys Compd. 2008;463:408–11.
32. Asanithi P, Chayakun S, Limsupwan P. Growth of silver nanoparticles by DC magnetron sputtering. J Nanomater. 2012;2012:63609.
33. Zhang W, Qiao X, Chen J. Synthesis of silver nanoparticles—effects of concerned parameters in water/oil microemulsion. Mater Sci Eng B. 2007;142:1–15.
34. Wright R, Zhang Q, Kirby P. Synthesis of silver nanoparticle and fabrication of aqueous Ag inks for inkjet printing. Mater Chem Phys. 2011;129:1075–80.
35. Logarasan K, Raiza AJ, Gopinath SCB, Chen Y, Pandian K. Shape- and size-controlled synthesis of silver nanoparticles using Aloe vera plant extract and their antimicrobial activity. Nano Res Lett. 2016;11:520.
36. Tippayawat P, Phromviyo N, Boueroy P, Chompoosor A. Green synthesis of silver nanoparticles in aloe vera plant extract prepared by a hydrothermal method and their synergistic antibacterial activity. Peer J. 2016;4:e2589.
37. Moosa AA, Ridha AM, Al-Kaser M. Process parameters for green synthesis of silver nanoparticles using leaves extract of Aloe vera plant. Int J Mult Curr Res. 2015;3:966–75.
38. Sreekanth TVM, RaviKumar S, Lee YR. Good use of fruit wastes: eco-friendly synthesis of silver nanoparticles, characterization BSA protein binding studies. J Mol Recgn. 2015;29:253–9.
39. Kumar V, Singh DK, Mohan S, Hasan SH. Photo induced biosynthesis of silver nanoparticles using aqueous extract of Eriogonum bonariensis and its catalytic activity against Acridine orange. J Photochem Photobio B. 2015;129:39–50.
40. Jelin FJ, Kumar SS, Malini M, Vanaja M, Annadurai G. Environment-assisted green approach AgNPs by nutmeg (Myristica fragans): inhibition potential accustomed to pharmaceuticals. Euro J Biomed Pharm Sci. 2015;2:258–74.
41. Ajitha B, Reddy YAK, Reddy PS. Biosynthesis of silver nanoparticles using Mamordica charantia leaf broth: evaluation of their innate antimicrobial and catalytic activities. J Photoch Photobiol B. 2015;146:1–9.
42. Chowdhury IH, Ghash S, Roy M, Naskar MK. Green synthesis of water-dispersible silver nanoparticles at room temperature using green carambola (star fruit) extract. J SolGel Sci Technol. 2015;73:199–207.
43. Kumar B, Smita K, Cumbal L, Debut A. Green synthesis of silver nano-
particles using Andean blackberry fruit extract. Saudi J Biol Sci.
2017;2:45–50.

44. Kumar B, Angulo Y, Smita K, Cumbal L, Debut A. Capuli cherry-mediated
green synthesis of silver nanoparticles under white solar and blue LED
light. Particulometry. 2016;24:123–8.

45. Mohapatra B, Kuriakose S, Mohapatra S. Rapid green synthesis of silver
nanoparticles and nanorods using Piper nigrum extract. J Alloys Compd.
2015;637:119–26.

46. Amooaghaie R, Saeri MR, Azizi M. Synthesis, characterization and bio-
compatibility of silver nanoparticles synthesized from Nigella sativa leaf
extract in comparison with chemical silver nanoparticles. Ecotoxicol
Environ Saf. 2015;120:400–4.

47. Pavani KV, Gayathramma K. Synthesis of silver nanoparticles using
extracts of Calotropis gigantean flowers. Int J Res Pharm Nano Sci.
2015;4:236–40.

48. Raj DR, Prasanth S, Vineeshkumar TV, Sundarsanakumar C. Surface
plasmon resonance based fiber optic dopamine sensor using green
synthesized silver nanoparticles. Sens Act B Chem. 2016;246:600–6.

49. Kamachandran K, Kalpana D, Sathishkumar Y, Lee YS, Ravichandran K,
Kumar GG. A facile green synthesis of silver nanoparticles using Piper
betle biomass and its catalytic activity toward sensitive and selective
nitrite detection. J Ind Eng Chem. 2015;35:29–35.

50. Vennila M, Prabha N. Plant mediated green synthesis of silver nano-
particles from the plant extract of Manisa tinctoria and its application in
effluent water treatment. Int J ChemTech Res. 2015;7:2993–9.

51. Meena RK, Chouhan N. Biosynthesis of silver nanoparticles from plant
(fenugreek seeds) reducing method and their optical properties. Res J
Rec Sci. 2015;4:47–52.

52. Sreekanth TW, Jang M, Eom I. Green synthesis of silver nanoparticles,
decorated on graphene oxide nanosheets and their catalytic activity.
Appl Surf Sci. 2015;351:102–6.

53. Suarez-Cerda J, Alonso-Nunez G, Espinoza-Gomez H, Flores-Lopez LZ.
Synthesis, kinetics and photocatalytic study of “ultra-small” AgNPs
obtained by a green chemistry method using an extract of Rosa ‘Andell’
double delicate petals. J Colloid Interface Sci. 2015;458:169–77.

54. Tahir K, Nazir S, Li B, Khan AU, Khan ZUH, Ahmad A, Khan FU. An
efficient photo catalytic activity of green synthesized silver nano-
particles using Salvadora persica stem extract. Separ Pur Technol.
2015;150:316–24.

55. Ali M, Kim B, Belfield KD, Norman D, Brennan M, Ali GS. Green synthesis
and characterization of silver nanoparticles using Artemisia absin-
thium aqueous extract—a comprehensive study. Mat Sci Eng C.
2016;58:359–65.

56. Barbinta-Parasce ME, Badea N, Ungureanu C, Constantin M, Pirvu C,
Rau I. Silver-based biohybrid “birds” “green” synthesized from Chelidonium
majus L. Opt Mater. 2016;56:94–9.

57. Babu SA, Prabu HG. Synthesis of AgNPs using the extract of Calotropis
procera flower at room temperature. Mat Lett. 2011;65:1675–7.

58. Bogieddy NKR, Kumar HAK, Mandal BK. Biofabricated silver nano-
particles as green catalyst in the degradation of different textiles dyes.
J Environ Chem Eng. 2016;4:56–64.

59. Edison TNJI, Lee YR, Sethuraman MG. Green synthesis of silver nano-
particles using Terminalia chebula and its catalytic action in reduction
of direct yellow-12 dye. Spectrochim Acta Mol Biomol Spectrosc.
2016;143:1–6.

60. Khan ZUH, Khan A, Shah A, Wan P, Chen Y, Khan GM, Khan AU, Tahir K,
Muhammad N, Khan HU. Enhanced photocatalytic and electrocatalytic
applications of green synthesized silver nanoparticles. J Mol Liq.
2016;220:248–57.

61. Ahmad A, Wei Y, Syed F, Khan S, Khan GM, Tahir K, Khan ALU, Raza M,
Khan FU, Yuan Q. Isatis tinctoria mediated synthesis of amphotericin
B-bound silver nanoparticles with enhanced photo induced antileish-
manial activity: a novel green approach. J Photochem Photobiol B Biol.
2016;161:17–24.

62. Velmurugan P, Shimi J, Kim HW, Lim J, Kim SA, Seo Y, Kim J, Kim K, Oh B.
Bio-functionalization of cotton, silk, and leather using different in situ
silver nanoparticle synthesis modifiers, and their antibacterial properties.
Res Chem Intermed. 2016. https://doi.org/10.1007/s11164-016-2481-3.

63. Chouhan N, Meena RK. Biosynthesis of silver nanoparticles using Trachyspermum ammi and evaluation of their antibacterial activities. Int J Pharma Sci. 2015;6:1077–86.

64. Ali K, Ahmed B, Dwivedi S, Saqib Q, Al-khedhairea AA, Musarrat J. Micro-
wave accelerated green synthesis of stable silver nanoparticles with
Eucalyptus globulus leaf extract and their antibacterial and antibiofilm
activity on clinical isolates. PLoS ONE. 2015;10:e0131178.

65. Zia F, Ghafoor N, Iqbal M, Mehboob S. Green synthesis and characteri-
zation of silver nanoparticles using Cynedia oblong seed extract. Appl
Nanosci. 2016;6:1023.

66. Devi TA, Ananthi N, Amaladas TP. Photobiological synthesis of noble
metal nanoparticles using Hydrocortylo antisica and application as cata-
lyst for the photodegradation of cationic dyes. J Nanostrut Chem.
2016;6:75–92.

67. Manjamadka VP, Muthukumar K. Ultrasound assisted synthesis of
silver nanoparticles using weed plant. Bioprocess Biosyst Eng. 2016;39:401–11.

68. Busu S, Maji P, Ganguly J. Rapid green synthesis of silver nanoparticles
by aqueous extract of seeds of Nyctanthes arbor-tristis. Appl nanosci.
2016;6:1–5.

69. Sedaghat S, Agbolag AE, Bagheriyani S. Biosynthesis of silver nanoparti-
cles using pennroyal water extract as a green route. J Nanostrut Chem.
2016;6:25–7.

70. Paruru S, Nagari V, Bhanocci M. Green synthesis of silver nanoparticles
using leaf extract of medicinally potent plant Saraca indica: a novel study.
Appl Nanosci. 2016;6:747–53.

71. Edison TNJI, Apchudan R, Lee YR. Optical sensor for dissolved ammonia
through the green synthesis of silver nanoparticles by fruit extract of
Terminalia chebula. J Clust Sci. 2016;27:583–90.

72. Cicek S, Gungor AA, Adiguzel A, Nadaoglu H. Biochemical evaluation
and green synthesis of nano silver using peroxidea from Euphorbi-
a (Euphorbia amygdaloides) and its antibacterial activity. J Chem.
2015;486948:7.

73. Anandakalshmi K, Venugodk J, Ramasamy V. Characterization of silver
nanoparticles by green synthesis method using Pedalium murex leaf
extract and their antibacterial activity. Appl Nanosci. 2016;6:399–408.

74. Alishah H, Seyedi SP, Ebrahimpour SY, Esmaeli-Mahani S. A green
approach for silver nanoparticles using root extract of Chelidonium
majus: characterization and Antibacterial evaluation. J Cluster Sci.
2016;27:421–9.

75. Jadhav K, Dhamecha D, Dalvi B, Patil M. Green synthesis of silver nano-
particles using Solasia chirensis: characterization and its antibacterial
activity. Part Sci Technol. 2015;33:445–55.

76. Ramamurthi V, Geetha S, Prabhu S. Synthesis, characterization and antibacterial activity of silver nanoparticles from Tammarindus indica (L) seed coat extract. J Chem Pharm Res. 2015;7:1022–32.

77. Paul B, Bhyun B, Purkayastha DD, Dhar SS. Photocatalytic and antibacte-
rial activities of gold and silver nanoparticles synthesized using biomass
of Parkia roxburghi leaf. J Photochem Photobiol B. 2016;154:1–7.

78. Shannumagam C, Sivasubramanian C, Parthasarathi BK, Baskaran K,
Balachander R, Parmeswaran VR. Antimicrobial, free radical scaveng-
ing activities and catalytic oxidation of benzyl alcohol by nano-silver
synthesized from the leaf extract of Aristolochia indica L.: a promenade
towards sustainability. Appl Nanosci. 2016;6:711.

79. Karthik R, Hau Y, Chen S, Blangovan A, Ganesan M. Eco-friendly
synthesis of Ag-NPs using Cuzus semulato plant extract—its catalytic,
electrochemical reduction of 4-NPh and antibacterial activity. J Ind Eng
Chem. 2016;37:330–9.

80. Parlinska-Wojtan M, Kus-Lisiewicz M, Depciuch J, Sadik O. Green syn-
thesis and antibacterial effects of aqueous colloidal solutions of silver
nanoparticles using camomile terpenoids as a combined reducing and
capping agent. Bioprocess Biosyst Eng. 2016;39:1213–23.

81. Ocsoy I, Temiz M, Celik C, Altnsosy B, Yilmaz V, Duman F. A green
approach for formation of silver nanoparticles on magnetic graphene
oxide and highly effective antimicrobial activity and reusability. J Mol
Liq. 2017;227:147–52.

82. Swamy MK, Akhtar MS, Mohanty SK, Sinniah UR. Synthesis and char-
acterization of silver nano particles using fruit extract of Momordica
cymbalaria and assessment of their in vitro antimicrobial, antioxidant
and cytotoxicity activities. Spectrochim Acta A Mol Biomol Spectrosc.
2015;151:939–44.
83. Pugazhenthid S, Kirubha E, Palanisami PK, Gopalakrishnan R. Synthesis and characterization of silver nanoparticles from Alpinia calcarata by green approach and its applications in bactericidal and nonlinear optics. Appl Surf Sci. 2015;357:1801–8.

84. Verma DK, Harshiny M, Matheswaran M, Arthanareeswaran G, Kumaran S, Rajasree S. Enhancement of antibacterial properties of silver nanoparticles—cetyltrimethylammonium bromide conjugate through Mucor mucedo/pesnantula leaf extract mediated synthesis. Ecotoxicol Environ Saf. 2015;121:135–41.

85. Nayak D, Ashe S, Rauta PR, Kumar M, Nayak B. Bark extract mediated green synthesis of silver nanoparticles: evaluation of antimicrobial activity and antiproliferative response against osteosarcoma. Mater Sci Eng, C. 2015;58:54–62.

86. Ahmed S, Saffullah Ahmad M, Swami BL, Ikram S. Green synthesis of silver nanoparticles using Azadirachta indica aqueous leaf extract. J Radi Res Appl Sci. 2016;9:1–7.

87. Latha M, Priyanka M, Rajasekar P, Manikanand P, Prabhu NM. Biocompatibility and antibacterial activity of the Adhatoda vasica leaf extract mediated silver nanoparticles. Microbiop. 2016;93:88–94.

88. Kolya H, Mati P, Pandey A, Tripathy T. Green synthesis of silver nanoparticles with antimicrobial and azo dye (Congo red) degradation properties using Amaranthus gangeticus Linn leaf extract. J Anal Sci Technol. 2015;6:33.

89. Allafchian AR, Mirahmadi-Zare SZ, Jalali SAH, Hashemi SS, Vahabi M. Green synthesis of silver nanoparticles using Phlomis leaf extract and investigation of their antibacterial activity. J Nanostruct Chem. 2016;6:129–35.

90. Yugandhar P, Haribabu R, Savithramma N. Synthesis, characterization and antimicrobial properties of green-synthesised silver nanoparticles from stem bark extract of Syzygium alternifolium (W1) Wālp. Z. Biotech. 2015;5:1031–9.

91. Moyo M, Gomba M, Nharungo T. Afzelia quanzensis bark extract for green synthesis of silver nanoparticles and study of their antibacterial activity. Int J Ind Chem. 2015;6:329–38.

92. Karunakaran G, Jagathambal M, Gusev A, Kolesnikov E, Mandal AR, Kuznetsova D. Allamanda cathartica flower’s aqueous extract—mediated green synthesis of silver nanoparticles with excellent antioxidant and antibacterial potential for biomedical application. Mat Res Soc Comm. 2016;6:41–6.

93. Kokila T, Ramesh PS, Geetha D. Biosynthesis of AgNPs using Carica papaya peel extract and evaluation of its antioxidant and antimicrobial activities. Ecotoxicol Environ Saf. 2015;93:467–73.

94. El-Sherbiny IM, El-Shibiny A, Salli E. Photo-induced green synthesized and anti-microbial activity of poly (P-caprolactone)/cucurmin/grape leaf extract- silver hybrid nanoparticles. J Photochem Photobiol B. 2015;160:355–63.

95. Sengottayal A, Myrthily R, Selvankumar T, Aravindhan A, Kamala-Kannan S, Manoharan K, Thyagarajan P, Govarthanan M, Kim J. Green synthesis of silver nanoparticles using Solanum indicum L. and their antibacterial, spirocycly cytotoxic potentials. Res Chem Intermed. 2016;42:3095–103.

96. Devadiga A, Shetty KV, Saidutta MB, Timber industries waste-teak (Lyrbius grandis) leaves and investigation of their anti-microbial activity. J Nanobiotechnol. 2015;9:288–93.

97. Singha S, Bhattacharyya D, Patil M. Green and ecofriendly synthesis of silver nanoparticles using methanolic root extracts of Diospyros paniculata and their antimicrobial activities. Mater Sci Eng C Mater Biol Appl. 2016;62:553–7.

98. Verma DK, Harshiny M, Matheswaran M, Arthanareeswaran G, Kumaran S, Rajasree S. Enhancement of antibacterial properties of silver nanoparticles using herbal extract of Salvinia molesta and its antimicrobial efficacy. J Photochem Photobiol B. 2016;155:51–9.

99. Nalvolthula R, Murugan K, Thiyagarajan P, Govarthanan M, Kim J. Green synthesis of silver nanoparticles using methanolic root extracts of Cassia roxburghii and its antimicrobial activity against Pseudomonas aeruginosa. Appl Nanosci. 2016;6:895.

100. Balamankandan T, Balaji S, Pandirajan J. Biological Synthesis of silver nanoparticles using using onion (Allium cepa) extract and their antibacterial and antifungal activity. World App Sci J. 2015;33:939–43.

101. El-Sherbiny IM, El-Shibiny A, Salih E. Photo-induced green synthesized silver nanoparticles using Salvia miltiorrhiza and its antimicrobial activity. J Photochem Photobiol B. 2016;155:109–15.

102. Nalvolthula R, Murugan K, Thiyagarajan P, Govarthanan M, Kim J. Green synthesis of silver nanoparticles using methanolic root extracts of Sida acuta and its antimicrobial activity. J Photochem Photobiol B. 2016;155:51–9.

103. Singh D, Rawat D, Isha B. Microwave-assisted synthesis of silver nanoparticles using stem bark extract of Diospyros paniculata and its antimicrobial activity. J Photochem Photobiol B. 2016;155:109–15.

104. Krishna IM, Reddy GB, Veerabhadram G, Madhusudhan A. Eco-friendly green synthesis of silver nanoparticles using Salmalia malabarensis—synthesis, characterization, antimicrobial, and catalytic activity studies. Appl Nanosci. 2016;6:681.

105. Sowmyyan T, Lakshmi GV. Green synthesis and characterization of silver nanoparticles using Syzygium alternifolium from stem bark extract of Syzygium alternifolium (W1) Wālp. Z. Biotech. 2015;5:1031–9.

106. Bose D, Chatterjee S. Biogenic synthesis of silver nanoparticles using guava (Psidium guajava) leaf extract and its antibacterial activity against Pseudomonas aeruginosa. Appl Nanosci. 2016;6:895.

107. Murugan K, Thiyagarajan P, Govarthanan M, Kim J. Green synthesis of silver nanoparticles using methanolic root extracts of Cassia roxburghii and its antimicrobial activity. World App Sci J. 2015;33:939–43.

108. Awad MA, Mehmanker WK, Menghian NM, Hendi AA, Ortashi QMO, Al-Abbas F, Eisa NE. Green synthesis, characterization and Anti-bacterial activity of silver/polystyrene nanocomposite. J Nanomater. 2015;943821:6.

109. Ahmed MJ, Murzagaz, Mehmood A, Bhatti TM, Mehmood A. Green synthesis of silver nanoparticles using leaves extract of Skimmia laureola characterization and anti-bacterial activity. Mater Lett. 2015;153:10–9.

110. Elangovan K, Elumalai D, Anupriya S, Shenbhagaraman R, Kaleena PK, Murugesan K. Phytosynthesis and biogenic synthesis of silver nanoparticles using leaf extract of Andrographis echioides and its bio-efficacy on antitumor and antibacterial activities. J Photochem Photobiol. 2015;151:118–24.

111. Ali SG, Khan H, Jala I, Mansi MA, Mahdi AA, Ahmad MK. Green synthesis of silver nanoparticles using the leaf extract of Putranja roxburghii wall. and their antimicrobial activity. Asian J Pharma Clin Res. 2015;8:335–8.

112. Balasubramaniam T, Sridharan M, Krishnan P, Anandaraj P, Govarnan P. Synthesis, characterization and antibacterial activity of silver nanoparticles using flower extracts of Ikora cocinea. Inter J Chem Tech Res. 2015;7:2374–80.

113. Ramesh PS, Kokila T, Geetha D. Plant mediated green synthesis and antibacterial activity of silver nanoparticles using Emblica officinalis fruit extract. Spectrochim Acta Mol Biomol Spectrosc. 2015;142:339–43.

114. Nayak D, Ashe S, Rauta PR, Nayak B. Biosynthesis, characterization and antimicrobial activity of silver nanoparticles using Hibiscus rosasinensis petals extracts. IET Nanobiotechnol. 2015;9:288–93.

115. Govindarajan M, Rajeswary M, Veerakumar K, Muthukumarun I, Hoti SL, Mehhom H, Barnard DR, Benelli G. Novel synthesis of silver nanoparticles using Bauhinia variegata: a recent eco-friendly approach for mosquito control. Parasitol Res. 2016;115:723–33.

116. Panneerselvam C, Murugan K, Roni M, Aziz AT, Suresh U, Rajaganes R, Madhiyazhagan P, Subramaniam J, Dinesh N, Nicoletti M, Higuchi A, Alaraj AA, Munusamy MA, Kumar S, Deaneux N, Benelli G. Fern-synthesized nanoparticles in the fight against malaria: LC/MS analysis of Pteridium aquilinum leaf extract and biosynthesis of silver nanoparticles with high mosquitocidal and antiplasmodial activity. Parasitol Res. 2016;115:997–1013.

117. Murugan K, Labeeba MA, Panneerselvam C, Dinesh D, Suresh U, Subramaniam J, Madhiyazhagan P, Hwang J, Wang L, Nicoletti M, Benelli G. Anisomeles indica green synthesized silver nanoparticles: a sustainable control tool against the malaria vector Anopheles stephensi. Res Vet Sci. 2015;102:127–35.

118. Muthukumarun U, Govindarajan M, Rajeswary M. Green synthesis of silver nanoparticles from Cassia roxburghii—a most potent power for mosquito control. Parasitol Res. 2014;114:4385–95.

119. Govindarajan M, Rajeshwary M, Veerakumar K, Muthukumarun K, Hoti SL, Benelli G. Green synthesis and characterization of silver nanoparticles fabricated using Anisomeles indica mosquitocidal potential against malaria, dengue and Japanese encephalitis vectors. Exp Parasitol. 2016;161:40–7.

120. Suman TY, Rajaseen SR, Jayaseelan C, Mary R, Gayathiri S, Aranganathan L, Remya BR. GC–MS analysis of bioactive components and biosynthesis of silver nanoparticles using Hybanthus enneaspermus at room
temperature evaluation of their stability and its larvicidal activity. Environ Sci Pollut Res. 2016;23:705–14.

121. Sigamoney M, Shaik S, Govender P, Krishna SBN, Sershen. African leafy vegetables as bio-factories for silver nanoparticles: a case study on Amaranthus dubius C. Mart. Ex Thell S Afr J Bot. 2016;103:239–40.

122. Seekeanth JVM, Pandurangan M, Jung M, Lee YR, Iom E. Eco-friendly decoration of graphene oxide with green synthesized silver nanoparticles: cytotoxic activity. Res chem Intermediat. 2016;62:5665–76.

123. Varghese A, Anandhi P, Arunadevi R, Boovisha A, Sounthari P, Saranya R, Nakkala JR, Sadras SR. Catalytic and biological activities of green Nalavothula R, Alwala J, Nagati VB, Manthurpadigya PR. Biosynthesis of silver nanoparticles using Impatien balsamina leaf extracts and its characterization and cytotoxic studies using human cell lines. Inter J Chem Res. 2015;7:2460–8.

125. Rajakumar G, Gomathi T, Thiruvengadam M, Rajeswari VD, Kalpana VN, Chung JH. Evaluation of anti-cholinesterase, antibacterial and cytotoxic activities of green synthesized silver nanoparticles using Millelita pinnata flower extract. Micro Pathol. 2017;103:123–8.

126. Ahmad A, Wei Y, Syed F, Tahir K, Rehman AU, Khan A, Ullah S, Yuan Q. The effects of bacteria-nanoparticles interface on the antibacterial activity of green synthesized silver nanoparticles. Microb Pathol. 2017;102:133–42.

127. Dong C, Cao J, Zhang X, Zhan Y, Wang X, Yang X, Zou K, Xiao X, Yuan B. Wolfberry fruit (Lycium barbarum) extract mediated novel route for the green synthesis of silver nanoparticles. Optik. 2017;130:162–70.

128. Dhyalan M, Denison MJ, Jegadeeshwari AL, Krishnan K, Gandhi NN. In vitro antioxidant, antimicrobial, cytotoxic potential of gold and silver nanoparticles prepared using Embelia ribes. Nat Prod Res. 2017;31:465–8.

129. Maria BS, Devadiga A, Kodalbal VS, Saidutta MB. Synthesis of silver nanoparticles using medicinal Zizyphus xylopyrus bark extract. Appl Nanosci. 2015;5:755–62.

130. Kumar CG, Mamidyala SK, Das B, Srividya B, Devi GS, Karuna MS. Synthesis of biosurfactant-based silver nanoparticles with purified rhamnolipids isolated from Pseudomonas aeruginosa BS-161R. J Microbiol Biotechnol. 2010;20:1061–8.

131. Kiran GS, Sabu A, Selvin J. Synthesis of silver nanoparticles by glycolipid biosurfactant produced from marine Brevibacterium casei MSA19. J Biotechnol. 2010;148:221–5.

132. Deepak V, Limmaheshwaran PS, Guhan K, Nanthini RA, Krishiga B, Jaitoon NMH, Gurunathan S. Synthesis of gold and silver nanoparticles using purified rUKR. Coll Surf B Biointerface. 2011;86:353–8.

133. Liu C, Yang D, Wang Y, Shi J, Jiang Z. Fabrication of antimicrobial bacteria cellulose—Ag/AgCl nanocomposite using bacteria as versatile biofactory. J Nanopart Res. 2012;14:1084–9.

134. Manikpatubhi D, Lingappa K. Antibacterial activity of silver nanoparticles against methicillin-resistant Staphylococcus aureus synthesized using model Streptomyces sp. pigment by photo-irradiation method. J Pharm Res. 2013;6:255–60.

135. Sathiyanarayanan G, Kiran GS, Selvin J. Synthesis of silver nanoparticles by polycyclic biosurfactant produced from marine Bacillus subtilis MSBN17. Coll Surf B Biointerface. 2013;102:13–20.

136. Gopinathan P, Ashok AM, Selvakumar R. Bacterial flagella as biotemplate for the synthesis of silver nanoparticle impregnated biomaterial. Appl Surf Sci. 2013;276:717–22.

137. Hosseini-Abari A, Emtiazi G, Ghaseemi SM. Development of an eco-friendly approach for biogenesis of silver nanoparticles using spores of Bacillus anthracis. World J Microbiol Biotechnol. 2013;29:2359–64.

138. Kanmani P, Lim ST. Synthesis and structural characterization of silver nanoparticles using bacterial exopolysaccharide and its antimicrobial activity against food and multidrug resistant pathogens. Process Biochem. 2013;48:1099–106.

139. Morsy FM, Nafady NA, Abd-Alla MH, Elhady DA. Green synthesis of silver nanoparticles by water soluble fraction of the extracellular polysaccharides/matrix of the cyanobacterium Nostoc commune and its application as a potent fungal surface sterilizing agent of seed crops. Univ J Microbiol Res. 2014;2:36–43.
160. Farias CBB, Silva AF, Rufino RD, Luna JM, Souza JEG, Sarubbo LA. Synthesis of silver nanoparticles using a biosurfactant produced in low-cost medium as a stabilizing agent. Electro J Biotechnol. 2014;17:122–5.

161. Galhawat G, Shiffa S, Chaddha BS, Chaudhuri SR, Maylaj S, Choudhury AR. Microbial glycopolyprotein-capped silver nanoparticles as emerging antibacterial agents against choler. Micro Cell Fact. 2016;15:25.

162. Sowani M, Mohite P, Munot H, Shoouche Y, Bapat T, Kumar AR, Kulkarni M, Zinjarde S. Green synthesis of gold and silver nanoparticles by an actinomycete Gordonia amicalis HS-11: mechanistic aspects and biological application. Process Biochem. 2016;51:374–83.

163. Mendrek B, Chojnick J, Libera M, Trzebicka B, Bernart P, Pasiaszkiewicz K, Plaza G. Silver nanoparticles formed in bio- and chemical syntheses with biosurfactant as the stabilizing agent. J Disp Sci Technol. 2017;38:1647–55.

164. Durán N, Priscyla D, Marcaro PD, Alves O, De Souza G, Esposito E. Mechanistic aspects of biosynthesis of silver nanoparticles by several Fusarium oxysporum strains. J Nanobiotechnol. 2005;3:1–7.

165. Ganesh Babu MM, Gunasekaran P. Production and structural characterization of crystalline silver nanoparticles from Bacillus cereus isolate. Coll Surf B. 2009;74:191–5.

166. Kalimuthu K, Babu RS, Venkatakanam D, Bilal M, Guranathan S. Biosynthesis of silver nanocrystals by Bacillus licheniformis. Coll Surf B. 2008;65:150–3.

167. Klauss T, Joerger R, Olsson E, Granqvist CG. Silver-based crystalloidal nanoparticles synthesized by Bacillus subtilis. J Nanosci Nanotechnol. 2010;10:13611–4.

168. Nanda A, Saravanan M. Biosynthesis of silver nanoparticles from Staphylococcus aureus and its antimicrobial activity against MRSA and MRSE. Nanomedicine. 2009;5:452–6.

169. Reddy AS, Chen CC, Chen CC, Juan JS, Chen HS, Tseng MJ, Fan CW, Wang JC. Biological synthesis of gold and silver nanoparticles mediated by the bacteria Bacillus subtilis. J Nanosci Nanotechnol. 2010;10:6567–74.

170. Shivaji S, Madhu S, Singh S. Extracellular synthesis of antibacterial silver nanoparticles using psychrophilic bacteria. Process Biochem. 2011;46:930–7.

171. Wei X, Luo M, Li W, Yang L, Liang X, Xu L, Kong P, Liu H. Synthesis of silver nanoparticles by solar irradiation of cell-free Bacillus amyloliquefaciens extracts and AgNO3. Bioresour Technol. 2012;103:273–8.

172. Saravanan M, Vemuguri AK, Bandkar SK. Rapid biosynthesis of silver nanoparticles from Bacillus megaterium (NCIM 2326) and their antibacterial activity on multi drug resistant clinical pathogens. Coll Surf B. 2011;88:325–31.

173. Priyadarshini S, Gopinath V, Meera Priyadharssini N, Mubarak Ali D, Velusamy P. Synthesis of anisotropic silver nanoparticles using novel strain, Bacillus flexus and its biomedical application. Coll Surf B Biointerface. 2009;74:328–35.

174. Thomas R, Jasim B, Mathew J, Radhakrishnan EK. Extracellular synthesis of silver nanoparticles by the endophytic phylotype Kandhornas oryzae pv. oryzae strain BCOR. J Microbiol Biotechnol. 2013;23:1287–92.

175. Pourali P, Baserisalehi M, Afsharnezhad S, Behravan J, Alavi H, Hosseini A. Bacterial synthesis of silver sulfide nanoparticles. Nanotechnol China. 2010;37:1798–804.

176. Rajeshkumar S, Malarkodi C, Paulkumar K, Vanaja M, Gnanajobitha G. Intracellular and extracellular biosynthesis of silver nanoparticles by using marine bacterium Vibrio alginolyticus. Nanosci Nanotechnol. 2013;3:21–5.

177. Narayarana KB, Saktivel N. Biosynthesis of silver nanoparticles by phytotoxopohgen Kandhornas oryzae pv. oryzae strain BCOR. J Microbiol Biotechnol. 2013;23:1287–92.

178. Pourali P, Baseriashlieh M, Afsharnezhad S, Behravan J, Alavi H, Hosseini A. Biological synthesis of silver and gold nanoparticles by bacteria in different temperatures (37 °C and 50 °C). J Pure Appl Microbiol. 2012;6:757–63.

179. Pugazhenthiran N, Anandandan S, Kathiresan G, Prakash NKU, Crawford S, Pugazhenthiran N, Anandandan S, Kathiresan G, Prakash NKU, Crawford S. Antibacterial synthesis of silver nanoparticles using Photorhabdus luminescens strain of Stenotrophomonas maltophilia. PLoS ONE. 2013;8:e59140.

180. Karthick C, Radha KV. Biosynthesis and characterization of silver nanoparticles using Enterobacter aerogenes: a kinetic approach. Dig J Nanomater Biostroct. 2012;7:1007–14.

181. Guranathan S, Kalaiviswan K, Vaidyanathan R, Deepak V, Pandian SRN, Muniyandi J, Haripriya N, Gomathi SH. Biosynthesis, purification, and characterization of silver nanoparticles using Escherichia coli. Coll Surf B Biointerface. 2009;74:328–35.

182. Law N, Ansari S, Livenes FR, Renshaw JC, Lloyd JR. The formation of nanoscale elemental silver particles via enzymatic reduction by Geobacter sulfurreducens. Appl Environ Microbiol. 2008;74:7900–9.

183. Krishnaraj RV, Berchmans S. In vitro antiplatelet activity of silver nanoparticles synthesized using the microorganism Glucosobacter roseus: an AFM-based study. RSC Adv. 2013;3:8953–9.

184. Seshadi S, Prakash A, Kovshik M. Biosynthesis of silver nanoparticles by marine bacterium, Idiomarina sp. p R58–8. Bull Mater Sci. 2012;35:1201–5.

185. Durasmamy K, Yang SL. Synthesis and characterization of bactericidal silver nanoparticles using cultural filtrate of simulated microgravity grown Klebsiella pneumoniae. Enzyme Microb Technol. 2013;52:151–6.

186. Parikh RV, Singh S, Prasad BLV, Patole MS, Saxtry M, Shoouche YS. Extracellular synthesis of crystalline silver nanoparticles and molecular evidence of silver resistance from Marginella sp.: towards understanding biochemical synthesis mechanism. Chem Bio Chem. 2008;9:1415–22.

187. Samadi N, Gokalan D, Balamurali A, Jamalifar H, Fazeli MR, Mohseni FA. Intra/extracellular biosynthesis of silver nanoparticles by an autotrophic strain of Proteus mirabilis isolated from photographic waste. J Biomed Nanotechnol. 2009;5:247–53.

188. Srivastava SK, Constanti M. Room temperature biogenic synthesis of multiple nanoparticles (Ag, Pd, Fe, Rh, Ni, Ru, Pt Co, and Li) by Pseudomonas aeruginosa: a kinetic approach. Dig J Nanomater Nanotechnol. 2012;6:757–63.

189. Bai HJ, Yang BS, Chai CJ, Yang GE, Jia WL, Yi ZB. Green synthesis of silver nanoparticles using Rhodobacter sphaeroides. World J Microbiol Biotechnol. 2011;27:2723–8.

190. Chun-Jing C, Hong-Juan B. Biosynthesis of silver nanoparticles using the phototrophic bacteria Rhodopseudomonas palustris and its antimicrobrial activity against Escherichia coli and Staphylococcus aureus. Microbiol Res. 2010;165:79–85.

191. Debabov VG, Voelickova TA, Shebanova AS, Shaitan KV, Emel'yanova LV, Novikova LM, Kirpichnov MP. Bacterial synthesis of silver sulfide nanoparticles. Nanotechnol Russ. 2012;7:1481–40.

192. Debabov VG, Voelickova TA, Shebanova AS, Shaitan KV, Emel'yanova LV, Novikova LM, Kirpichnov MP. Bacterial synthesis of silver sulfide nanoparticles. Nanotechnol Russ. 2012;7:1481–40.

193. Oves M, Khan MS, Zaidi A, Ahmed AS, Ahmad E, Sherwani A, Owais M. Room temperature biogenic synthesis of multiple nanoparticles Ag, Pd, Fe, Rh, Ni, Ru, Pt Co, and Li by Pseudomonas aeruginosa SM1. J Nanopart Res. 2012;14:831–40.

194. Pugazhenthiran N, Anandandan S, Kathiresan G, Prakash NKC, Crawford S, Pugazhenthiran N, Anandandan S, Kathiresan G, Prakash NKC, Crawford S. Antibacterial synthesis of silver nanoparticles using the phototrophic bacteria Vibrio alginolyticus. Nanosci Nanotechnol. 2013;3:21–5.
201. Wang C, Kim YJ, Singh P, Mathiyalagan R, Jin Y, Yang DC. Green synthesis of silver nanoparticles by Bacillus methylotrophicus, and their antimicrobial activity. Artif Cell Nanomed Biotechnol. 2016;44:1127–32.

202. Kannan N, Mukunthan KS, Balaji S. A comparative study of morphology, reactivity and stability of synthesized silver nanoparticles using Bacillus subtilis and Catharanthus roseus (L.) G. Don. Coll Surf B Biointerface. 2011;86:378–83.

203. Paulkumar K, Rajeshkumar S, Gnanajobitha G, Vanaja M, Malarakodi C, Annadurai G. Biosynthesis of silver chloride nanoparticles using Bacillus subtilis MTCC 3053 and assessment of its antifungal activity. ISRN Nano-materials. 2013;3:17963.8.

204. Baru AN, Balasubramanian C, Moorthi PV. Biosynthesis of silver nanoparticles using Bacillus thuringiensis against dengue vector, Aedes aegypti (Diptera: Culicidae). Parasitol Res. 2014;113:311–6.

205. Kalishwaralal K, Deepak V, Pandian SRK, Kottaisamy M, BarathManikanth S, Kartikeyan B, Gurunathan S. Biosynthesis of silver and gold nanoparticles using Brevibacterium casei. Coll Surf B Biointerface. 2010;77:257–62.

206. Zhang H, Li Q, Lu Y, Sun D, Lin X, Deng X, He N, Zheng S. Biosorption of Cu (II) G. Don. Coll Surf B Biointerface.

207. Tamboli DP, Lee DS. Mechanistic antimicrobial approach of extracellularly synthesized silver nanoparticles against gram positive and gram negative bacteria. J Hazard Mater. 2013;260:878–84.

208. Fayaz MM, Girindra Rahman M, Venkatesan R, Kalachivel PT. Biosynthesis of silver and gold nanoparticles using thermophilic bacterium Geobacillus stearothermophilus. Process Biochem. 2011;46:1958–62.

209. Dhoondia ZH, Chakraborty H. Antimicrobial activity of Ingle A, Gade A, Pierrat S, Sönnichsen C, Rai M. Mycosynthesis of silver nanoparticles using Geobacillus stearothermophilus. Process Biochem. 2011;46:1958–62.

210. Otari SV, Patil RM, Nadaf NH, Ghosh SJ, Pawar SH. Green synthesis of silver nanoparticles by microorganism using organic pollutant: its antimicrobial and catalytic application. Environ Sci Pollut Res. 2014;21:1503–13.

211. Deepa S, Kanimozi K, Panneerselvam A. Antimicrobial activity of Deepa S, Kanimozhi K, Panneerselvam A. Antimicrobial activity of extracellularly synthesized silver nanoparticles from marine derived actinomycetes. Int J Curr Microbiol Appl Sci. 2013;2:223–30.

212. Juibari MM, Abbasalsadzeh S, Jouzani GS, Noruzi M. Intensified biosynthesis of silver nanoparticles using a native extrermophic Aerobicellus thermophaga strain. Mater Lett. 2011;65:1014–7.

213. Ingle A, Gade A, Perrat S, Sonnichsen C, Rai M. Mycosynthesis of silver nanoparticles using the fungus Fusarium culmorum and its activity against some human pathogenic bacteria. Curr Nanosci. 2008;4:141–4.

214. Ingle A, Rai M, Gade A, Bawaskar M. Fusarium solani: a novel biological agent for the extracellular synthesis of silver nanoparticles. J Nanopart Res. 2009;11:2079–85.

215. Kathiresan K, Manivannan S, Nabeal MA, Dhivya B. Studies on silver nanoparticles synthesized from a marine derived actinomycetes. Int J Curr Microbiol Appl Sci. 2013;2:223–30.

216. Duran N, Marcera PD, De Souza GH, Alves OL, Esposito E. Antibacterial effect of silver nanoparticles produced by fungal process on textile fabrics and their effluent treatment. J Biomed Nanotechnol. 2007;3:203–8.

217. Vigneshwaran N, Ashtaputre NM, Varadarajan PV, Nachane RP, Paralkar KM, Balasubramanya RH. Biological synthesis of silver nanoparticles. J Nanopart Res. 2009;11:2079–85.

218. Katheresin K, Manivannan S, Nabeal MA, Dhivya B. Studies on silver nanoparticles synthesized from a marine fungus, Penicillium fellanum isolated from coastal mangrove sediment. Coll Surf B Biointerface. 2009;71:133–7.

219. Duran N, Marcera PD, De Souza GH, Alves OL, Esposito E. Antibacterial effect of silver nanoparticles produced by fungal process on textile fabrics and their effluent treatment. J Biomed Nanotechnol. 2007;3:203–8.

220. Vigneshwaran N, Ashtaputre NM, Varadarajan PV, Nachane RP, Paralkar KM, Balasubramanya RH. Biological synthesis of silver nanoparticles. J Nanopart Res. 2009;11:2079–85.

221. Bhainsa KC, D’Souza SF. Extracellular biosynthesis of silver nanoparticles using the fungus Aspergillus flavus. Mater Lett. 2007;61:1413–8.

222. Chwalibog A, Sawosz E, Hotowy A, Szeliga J, Mitura S, Mitura K, Grodzik M, Orlowski P, Sokolowska A. Visualization of interaction and its inhibitory effects against Candida albicans. Microb Pathog. 2011;50:1065–94.

223. Nair MN, Rajan J, Lakshmanan H, Hassan AA, Sabaratnam V. Green synthesis of silver nanoparticles using tree oyster mushroom Pleurotus ostreatus and its inhibitory action against pathogenic bacteria. Mat Lett. 2017;186:21–5.

224. Vigneshwaran N, Khale A, Silver-protein (core-shell) nanoparticle production using spent mushroom substrate. Langmuir. 2007;23:1113–7.

225. Mukherjee P, Roy M, Mandal BP, Dey GK, Mukherjee PK, Ghatak J, Tyagi AK, Kale SP. Green synthesis of highly stabilized nanocrystalline silver nanoparticles by a non-pathogenic and agriculturally important fungus T. asperellum. Nanotechnology. 2008;19:1–7.

226. Vahabi K, Mansoori GA, Kimi S. Biosynthesis of silver nanoparticles by fungus Trichoderma reesei (a route for large-scale production of AgNPs). Insci J. 2011;1:65–79.

227. Rayaz M, Tiwary CS, Kalaichelvan PT, Venkatesan R. Blue orange light mediated synthesis of silver nanoparticles produced by fungal process on textile fabrics and their effluent treatment. J Biomed Nanotechnol. 2010;5:1085–94.

228. Chwalibog A, Sawosz E, Hotowy A, Szeliga J, Mitura S, Mitura K, Grodzik M, Orloski P, Sokolowska A. Visualization of interaction between inorganic nanoparticles and bacteria or fungi. Int J Nanomed. 2010;5:1065–94.

229. Reddy ND, Vali DN, Rani M, Rani SS. Evaluation of antioxidant, antibacterial and cytotoxic effects of green synthesized silver nanoparticles. J Biomed Nanotechnol. 2014;105:346–55.

230. Husen A. Gold nanoparticles from plant system synthesis, characterization and their application. In: Ghorbanpour M, Manika K, Varma A, editors. Nanoscience and plant–soil systems, vol. 48. Cham: Springer International Publication; 2017. p. 455–70.

231. Hatziakou SP, Gupta K, Shafique KN, Bhawajy P, Borah R, Yadav KK, Naglot A, Deb P, Mandal D, Doley R, Verre V, Barua I, Namsa ND. One-pot facile green synthesis of biocidal silver nanoparticles. Mat Res Exp. 2016;3:075401. https://doi.org/10.1088/2053-1591/3/7/075401.

232. Reddy ND, Vali DN, Rani M, Rani SS. Evaluation of antioxidant, antibacterial and cytotoxic effects of green synthesized silver nanoparticles. J Biomed Nanotechnol. 2014;105:346–55.

233. Pujio J, Jonkuviene D, Macioniene I, Salomskiene J, Jusutiene I, Kondrotas R. Biosynthesis of silver nanoparticles using lingenonberry and cranberry juices and their antimicrobial activity. Coll Surf B Biointerface. 2014;121:214–21.

234. Silver Nanoparticle Properties, Cytodiagnostics Inc. (2017) http://www.cytodiagnostics.com/store/pc/Silver-Nanoparticle-Properties-d11.htm. Accessed 8 Aug 2017.
Mock JJ, Barbic M, Smith DR, Shultz DA, Shultz S. Shape effects in plasmon resonance of individual colloidal silver nanoparticles. J Chem Phys. 2002;116:6755–9.

Henglein A. Physicochemical properties of small metal particles in solution: “microwave” reactions, chemisorption, composite metal particles, and the atom-to-metal transition. J Phys Chem. 1993;97:5457–71.

Henglein A. Colloidal silver nanoparticles: photochemical preparation and interaction with O2, CC4, and some metal ions. Chem Mater. 1993;10:4440–50.

Bakshi MS, Possmayer F, Petersen NO. Role of different phospholipids in the synthesis of pearl-necklace-type Gold–Silver bimetallic nanoparticles as bioconjugate materials. J Phys Chem. 2007;11:14113–24.

Kim S, Ryu DY. Silver nanoparticle-induced oxidative stress, genotoxicity and apoptosis in cultured cells and animal tissues. J Appl Toxicol. 2002;22:6755–9.

Hackenberg S, Scherzed A, Kessler M, Hummel S, Technau A, Froelich K, Ginzkey C, Koehler C, Hagen R, Kleinsasser N. Silver nanoparticles: evaluation and bioavailability to cell and lung toxicological potential. Small. 2014;10:385–98.

Beck C, Foldbjerg R, Hayashi Y, Sutherland DS, Autrup H. Toxicity of silver nanoparticles at the air-liquid interface. Biomed Res Int. 2013;2012:109635:8.

Brayner R. The toxicological impact of nanoparticles. Nanotoday. 2008;3:48–53.

Panda KK, Achary VMM, Krishnaveni R, Padhi BK, Sarangi SN, Sahu SN, Panda BB. In vitro biosynthesis and genotoxicity bioassay of a silver nanoparticles using plants. Toxicol Vitro. 2011;25:1097–105.

Jayasree L, Janakiram P, Madhavi R. Characterization of Vibrio spp. associated with dead shrimp from culture ponds of Andhra Pradesh (India). J World Aquacult Soc. 2006;37:523–32.

Oberdorster E. Manufactured nanomaterials (fullerenes, C60) induce oxidative stress in the brain of juvenile largemouth bass. Environ Health Perspect. 2004;112:1058–62.

Kim S, Ryu DY. Silver nanoparticle-induced oxidative stress, genotoxicity and apoptosis in cultured cells and animal tissues. J Appl Toxicol. 2013;33:78–89.

Hackenberg S, Scherzed A, Kessler M, Hummel S, Techau A, Froelich K, Ginzkey C, Koehler C, Hagen R, Kleinsasser N. Silver nanoparticles: evaluation of DNA damage, toxicity and functional impairment in human mesenchymal stem cells. Toxicol Lett. 2011;201:27–33.

Samberg ME, Loboa EG, Oldenburg SJ, Montero-Riviere NA. Silver nanoparticles do not influence stem cell differentiation but cause minimal toxicity. Nanomedicine. 2012;7:1997–209.

Kittler S, Greulich C, Diendorf J, Koller M, Eppler M. Toxicity of silver nanoparticles increases during storage because of slow dissolution under release of silver ions. Chem Mater. 2010;22:4548–54.

Beer C, Foldbjerg R, Hayashi Y, Sutherland DS, Atrup H. Toxicity of silver nanoparticles-nanoparticle or silver ion? Toxicol Lett. 2012;208:286–92.

Cronholm P, Karlsson HL, Hedberg J, Lowe TA, Winberg L, Ehn K, Wallinder IO, Moller L. Intracellular uptake and toxicity of Ag and CuO nanoparticles: a comparison between nanoparticles and their corresponding metal ions. Small. 2013;9:1970–82.

Austín B, Austin DA. Bacterial fish pathogens. Diseases of farmed and wild fish. Chichester: Springer-Praxis Publishing Ltd; 1999.

Cai JP, Li J, Thompson KD, Li CX, Han HC. Isolation and characterization of pearl-necklace-type Gold–Silver bimetallic nanoparticles using Neem (Azadirachta indica) leaf broth. J Coll Interface Sci. 2004;275:496–502.

Zhao G, Stevens SE Jr. Multiple parameters for the comprehensive evaluation of the susceptibility of Escherichia coli to the silver ion. Biomaterials. 1998;19:27–32.

Aymoner C, Schlottbeck-U, Antonielli L, Zacharias P, Thomann R, Tiller JC, Mecking S. Hybrids of silver nanoparticles with amphiphilic hyperbranched macromolecules exhibiting antimicrobial properties. Chem Commun (Camb). 2002;24:3018–9.

Kim JS, Kuk E, Yu KN, Kim JH, Park SJ, Lee HJ, Kim SH, Park YK, Park YH, Hwang CY, Kim YK, Lee YS, Jeong DH, Cho MH. Antimicrobial effects of silver nanoparticles. Nanomed Nanotechnol Bio Med. 2007;3:95–101.

Allahverdiiyev AM, Kon KV, Abamor ES, Bagirlo M, Rafalovich M. Coping with antibiotic resistance: combining nanoparticles with antibiotics and other antimicrobial agents. Expert Rev Anti Infect Ther. 2011;9:1035–52.

Graves JS, Tolkarimi M, Cunningham Q, Campbell A, Nonga H, Harrison SH, Barrick JE. Rapid evolution of silver nanoparticle resistance in Escherichia coli. Front Genet. 2015;6:42.

Manivasagan P, Venkatesan J, Senthilkumar K, Sivakumar K, Kim SK. Biosynthesis, antimicrobial and cytotoxic effect of silver nanoparticles using a novel Nocardiosis sp. MBRC-1. Biomed Res. 2013. https://doi.org/10.1155/2013/286768.

Shanmugasundaram T, Radhakrishnan M, Gopikrishnan V, Pazhamimurugan R, Balagurunathan R. A study of the bactericidal, anti-biofouling, cytotoxic and antioxidant properties of actinobacterially synthesised silver nanoparticles. Colloids Surf B Biointerfaces. 2013;11:680–7.

Gurunathan S, Han JW, Eppakalyala V, Jeyaraj M, Kim J-H. Cytotoxicity of biologically synthesized silver nanoparticles in MDMA-MB-231 human breast cancer cells. Biomed Res Int. 2013;2013:876389:9.

Kumar SP, Balachandran C, Duraiappandian V, Ramasamy D, Ignacimuthu S, Al-Dhabi NA. Extracellular biosynthesis of silver nanoparticle using Streptomyces sp. 09 PBT 005 and its antibacterial and cytotoxic properties. Appl Nanosci. 2015;5:169–80.

Rai M, Yadav A, Gade A. Silver nanoparticles as a new generation of antimicrobials. Biotechnol Adv. 2009;27:76–83.

Agnihotri S, Mukherji S, Mukherji S. Size-controlled silver nanoparticles synthesized by Lactobacillus acidophilus against HEp2. J Pharm Res. 2011;4:1651–3.

Namasivayam SKR, Prakash P, Kumar G. Anti tumor activity of biologically synthesized silver nanoparticles produced by Lactobacillus acidophilus against HEp2. J Pharm Res. 2011;4:1651–3.

Shankar SS, Ahmad A, Asrty M, Geranium leaf assisted biosynthesis of silver nanoparticles. Biotechnol Prog. 2003;19:1627–31.

Shankar SS, Rai A, Ahmad A, Asrty M. Rapid synthesis of Au, Ag, and bimetallic Au core–Ag shell nanoparticles using Neem (Azadirachta indica) leaf broth. J Coll Interface Sci. 2004;275:496–502.
antimicrobial activity against bacteria, enveloped viruses and fungi. Microbiol Res. 2000;156:1–7.

288. Sondi I, Salopek-Sondi B. Silver nanoparticles as antimicrobial agent: a case study on E. coli as a model for Gram-negative bacteria. J Coll Interface Sci. 2004;275:177–82.

289. Amro NA, Kotra LP, Wadu-Mesthrige K, Bulychev A, Mobashery S, Liu G. High-resolution atomic force microscopy studies of the Escherichia coli outer membrane: structural basis for permeability. Langmuir. 2000;16:2789–96.

290. Danilczuk M, Lund A, Saldo J, Yamada H, Michalik J. Conduction electron spin resonance of small silver particles. Spectro Acta Part A. 2006;63:189–91.

291. Creighton JA, Blatchford CG, Albrecht MG. Plasma resonance enhancement of Raman scattering by pyridine adsorbed on silver or gold sol particles of size comparable to the excitation wavelength. J Chem Soc Faraday Trans II. 1979;75:790–8.

292. Funo F, Morley KS, Wong B, Sharp BL, Arnold PL, Howdle SM, Roger JF, Akhavan O, Ghaderi E. Toxicity of graphene and graphene oxide nanomaterials: implications for wastewater treatment plants. J Environ Monit. 2011;13:1164–83.

293. Allahverdiyev AM, Abamor ES, Bagirov M, Rafalovich M. Antimicrobial effects of TiO2 and Ag2O nanoparticles against drug-resistant bacteria and leishmania parasites. Fut Microb. 2011;6:933–40.

294. Guzman M, Dille J, Godet S. Synthesis and antibacterial activity of silver nanoparticles against gram-positive and gram-negative bacteria. Nano-technology. 2012;8:37–45.

295. Wang Y, Zhang D, Wang Y, Qi P, Wu J, Hou B. Vancomycin-functionalised Ag@TiO2 phototoxicity for bacteria. J Hazard Mater. 2011;186:306–12.

296. Devi LS, Joshi SR. Antimicrobial and synergistic effects of silver nanoparticles synthesized using soil fungi of high altitudes of Eastern Himalaya. Mycobiol. 2012;40:27–34.

297. Juan L, Zhimin Z, Anchun M, Lei L, Jingchao Z. Deposition of silver nanoparticles on titanium surface for antibacterial effect. Int J Nanomed. 2010;5:261–7.

298. You J, Zhang Y, Hu Z. Bacteria and bacteriophage inactivation by silver and zinc oxide nanoparticles. Colloids Surf B Biointerfaces. 2011;85:161–7.

299. Gulcin I. Antioxidant activity of food constituents: an overview. Arch Toxicol. 2012;86:345–91.

300. Gulcin I, Topal F, Cakmakci R, Bilgel M, Goren AC, Erdogan U. Pomegranate juice: nutritional quality, polyphenol content analysis, and antioxidant properties of domesticated and wild ecotype forms of pomegranate (Rubus idaeus L.). J Food Sci. 2011;76:CS58–93.

301. Rice-Evan CA, Miller N. Antioxidant property of phenolic compounds. Trends Plant Sci. 1997;2:152–9.