Biogenic Synthesis of Gold Nanoparticles and Their Potential Application in Agriculture

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Abstract

Nanotechnology is a new approach for the production of particles with unique features at the nanoscale dimensions. Among the various routes available for the synthesis of these nanoparticles, biogenic synthesis is a simple, low-cost, and eco-friendly method. The biosynthesis of gold nanoparticles is provided by various natural sources including plants, fungi, bacteria, actinomycetes, yeasts, and algae. Gold nanoparticles of various shapes and sizes are synthesized using biomass and/or extract of the organism. Enzymes secreted by microorganisms and metabolites of plants act as reducing, stabilizing, and capping agents for the production of the nanoparticles. The gold nanoparticles have antibacterial/antifungal properties that can be used to protect plants against pathogens. In addition, they can be applied for pesticide identification and water purification. This chapter focuses on the biosynthesis of gold nanoparticles, their characterization, and application in agriculture.

Keywords

Agriculture · Biogenic synthesis · Biosynthesis · Extracellular · Gold nanoparticle · Intracellular · Nanotechnology

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11.1 Introduction

In recent years, nanotechnology has development as an effective field in biology and material science. Nanotechnology is a technology at nanometer scale (1–100 nm) that controls the shape and size of particles. The nanoparticles have unique properties that are related to the very small size of particles and the increase of the surface to volume ratio (Ochekpe et al. 2009; Khadem Moghadam et al. 2019; Maghsoodi et al. 2019).

Nanoparticles are produced by different approaches, including physical, chemical, and biological methods. Biogenic synthesis of nanoparticles is a process that utilizes the biological agents such as plants, bacteria, fungi, etc. to produce nanoparticles (Fig. 11.1). The biological synthesis of nanoparticles is important because of its environment-friendly approach.

In recent years, the biosynthesis of noble metal nanoparticles (gold, silver, palladium, and platinum) has been considered due to the development of eco-friendly technologies in material synthesis (Chandran et al. 2006; Aromal and Philip 2012; Jia et al. 2009; Song et al. 2010). Among metal nanoparticles, gold is a very popular element due to being chemically inert and non-toxic (Connor et al. 2005). The gold nanoparticles are most stable and resistant to oxidation (Daniel and Astruc 2004). They are used in a variety of fields, including catalysis, gene expression, nonlinear optics, and delivery systems. The biosynthesis of metal nanoparticles is carried out using the "bottom-up" approach of nanotechnology (Golinska et al. 2014). In this method, the nanoparticles are formed through the growth or assembly of atoms or molecules that are the building units.

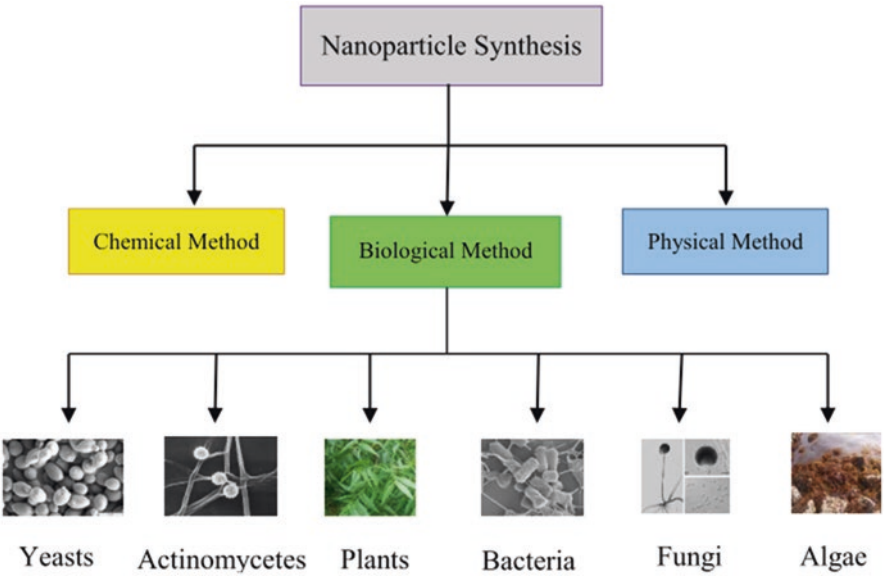

Fig. 11.1 Synthesis of nanoparticles using biological method

Biosynthesis of nanoparticles is formed through reduction/oxidation reactions of metal. In biogenic synthesis of metal nanoparticles, enzymes secreted by microbial agents and metabolites of plants are responsible for the occurrence of these reactions (Prabhu and Poulose 2012).

11.2 Biosynthesis of Nanoparticles

11.2.1 Synthesis of Gold Nanoparticles Using Plant

The use of plant extracts is preferred to produce metal nanoparticles compared with the use of microorganisms. The synthesis rate of nanoparticles using plants is faster than microbial agents, and nanoparticles obtained are more stable (Iravani 2011). In addition, plants are known as an important source of various metabolites, and they have the potential for synthesis of metal nanoparticles in large scale (Jha et al. 2009). However, reaction time required for biogenic synthesis methods is longer than chemical methods for the production of nanoparticles (Song and Kim 2009). Biomass and extract of different parts of plants such as leaf, root, flower, seed, stem, and fruit are used for the biosynthesis of gold nanoparticles. Extract of plants can act as a stabilizing, reducing, and capping agent for the synthesis of nanoparticles (Sharma et al. 2015).

11.2.1.1 Plant Biomass

The presence of metal elements, especially in drinking water, is a serious concern for global health. The use of plant biomass for the removal of heavy metals from aqueous solutions can be valuable as an eco-friendly method and also because of their potential application in removing contaminants from industrial wastewater in the future.

For this reason, many researchers have studied the role of plants in the absorption and accumulation of metal nanoparticles. The formation of gold nanoparticles from living plants was first reported by Gardea-Torresdey et al. (2002). The gold nanoparticles are synthesized inside live alfalfa plants (*Medicago sativa*) by gold ion uptake from the $AuCl_4$-rich agar solid media. The absorption and formation of gold nanoparticles within the plant were confirmed by X-ray absorption spectroscopy (XAS) and transmission electron microscopy (TEM). TEM images showed that gold nanoparticles were in crystalline state, but also twinned crystal structures and icosahedral nanoparticles were found.

In another study, Armendariz et al. (2004a) reported the synthesis of gold nanoparticles using oat (*Avena sativa*) biomass. The binding trend of Au(III) to oat and the possible formation of gold nanoparticles were studied at different pH values (pH 2–6). The size of the nanoparticles produced by oat biomass was dependent on the pH of the solution, while the shape of the nanoparticles was not significantly affected by the different pH values. Similar results have been reported for gold nanoparticles formed by wheat biomass (Armendariz et al. 2004b).

11.2.1.2 Plant Extracts

The synthesis of gold nanoparticles using plant leaf extracts has been demonstrated by many researchers (Table 11.1). Dubey et al. (2010a) reported the rapid synthesis of gold nanoparticles using leaf extract of *Rosa rugosa* within 10 min. In addition, they evaluated the effect of leaf extract quantity and concentration of metal solution (auric acid) in order to optimize the synthesis route of the metal nanoparticles. The formation and stability of the biosynthesized gold nanoparticles was confirmed using spectroscopic characterizations of UV-Vis, TEM, FTIR (Fourier transform infrared spectroscopy), and zeta potential. The sharpness, shape, size, and rate of formation of gold nanoparticles depend on the concentrations of leaf extract and metal ion. Sharp and symmetrical nanoparticles were formed at higher concentrations of leaf extract. Comparatively larger size of gold nanoparticles (50–250 nm) was found at higher gold ion concentration, and the rate of formation of the nanoparticles was slower at lowest concentration.

Gold nanoparticles were formed when the leaves of *Pelargonium graveolens* were exposed to aqueous chloroaurate ions. The rapid bioreduction of metal ions led to the formation of stable gold nanoparticles of different sizes. The size of the nanoparticles was in the range of 20–40 nm, and their shape was mainly decahedral and icosahedral (Shankar et al. 2003).

Shankar et al. (2004) reported the synthesis of pure metallic silver and gold nanoparticles and bimetallic Au core-Ag shell nanoparticles using the broth of neem leaves (*Azadirachta indica*). They proposed that the presence of reducing sugars and/or terpenoids in the broth can possibly facilitate the reduction of metal ions. The time of reduction of Au^{+} ion (2 h) by neem leaf extract was faster than that observed for Ag^{+} ion (4 h).

The biological synthesis of gold nanoparticles using olive leaf extracts has been reported (Khalil et al. 2012). The characterization of gold nanoparticles exhibited that the morphology of the gold nanoparticles depends on the extract concentration and the solution pH. The nanoparticles formed at lower concentrations of leaf broth were mainly triangular in shape, while spherical shaped nanoparticles were obtained at higher concentrations of leaf broth. The increase of pH also results in the production of smaller nanoparticles.

Green synthesis of gold nanoparticles using fruit extracts has been demonstrated by some researchers. For instance, Ankamwar et al. (2005) used *Emblica officinalis* (amla) fruit extract to produce gold nanoparticles. Chloroauric acid solution was treated with amla fruit extract (as the reducing agent), which results in the formation of highly stable gold nanoparticles. The size of the nanoparticles produced was in the range of 15–25 nm.

The effect of pH on the morphology of gold nanoparticles prepared from pear fruit extract has been investigated (Ghodake et al. 2010). According to the results of the investigation, gold nanostructures produced in an alkaline condition were very efficient and provide an optimal quantity of pure nanomaterial (Fig. 11.2b). The triangular and hexagonal nanoplates were formed in the range of 200–500 nm in size, depending on the shape (Fig. 11.2c, d). It was suggested that the mechanism of induction of these nanostructures is alkaline-responsive phytochemicals, such as

Table 11.1 Biological synthesis of gold nanoparticles using plants

No.	Name of the plants	Biomass/plant extract	Morphology	Size	References
01	*Medicago sativa*	Biomass	Twinned crystal structures and icosahedral nanoparticles	4 nm, 6–10 nm	Gardea-Torresdey et al. (2002)
02	*Avena sativa*	Biomass	Tetrahedral, decahedral, hexagonal, icosahedral multitwinned, irregular, and rod shaped	5–20 nm (pH 3 & 4), 25–85 nm (pH 2)	Armendariz et al. (2004a)
03	*Triticum aestivum*	Biomass	Tetrahedral, decahedral, hexagonal, icosahedral multitwinned, irregular, and rod shaped	10–30 nm	Armendariz et al. (2004b)
04	*Pelargonium graveolens*	Leaf extract	Decahedral and icosahedral	20–40 nm	Shankar et al. (2003)
05	*Rosa rugosa*	Leaf extract	Triangular and hexagonal	11 nm	Dubey et al. (2010a)
06	*Azadirachta indica*	Leaf extract	Spherical, triangular, hexagonal	50–100 nm (au/ag)	Shankar et al. (2004)
07	Olive leaf broth	Leaf extract	Triangular, hexagonal, and spherical	50–100 nm	Khalil et al. (2012)
08	*Emblica officinalis*	Fruit extract	Polyhedron, extracellular	15–25 nm	Ankamwar et al. (2005)
09	Pear fruit extract	Fruit extract	Triangular, hexagonal	200–500 nm	Ghodake et al. (2010)
10	*Tanacetum vulgare*	Fruit extract	Spherical, triangular	11 nm	Dubey et al. (2010b)
11	*Prunus domestica*	Fruit extract	Spherical	20 ± 6 nm	Dauthal and Mukhopadhyay (2012)
12	*Nyctanthes arbor-tristis*	Flower extract	Triangular, pentagonal, rod shaped, and spherical	19.8 ± 5.0 nm	Das et al. (2011)
13	*Cuminum cyminum*	Seed powder extract	Triangular, octahedral, and spherical	5–400 nm	Sneha et al. (2011)
14	*Morinda citrifolia*	Root extract	Cubic	12.17–38.26 nm	Suman et al. (2014)
15	*Eucalyptus globulus*	Bark extract	Spherical	20.1–100.9 nm	Pinto et al. (2017)

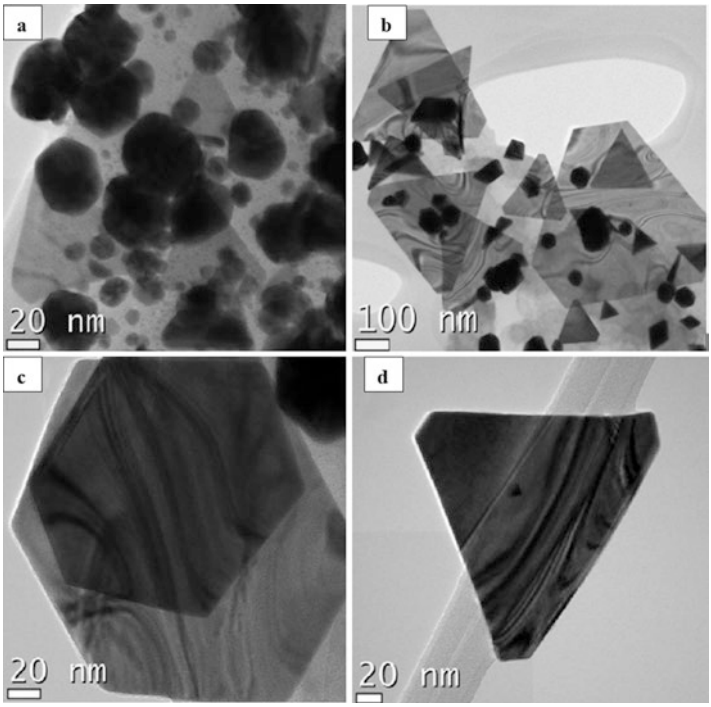

Fig. 11.2 HR-TEM micrographs of the gold nanoparticles formed from pear fruit extract under the normal (**a**) and alkaline (**b**) conditions and HR-TEM micrographs of a gold nanohexagon and nanotriangle formed under alkaline conditions (**c** and **d**) (Ghodake et al. 2010)

organic acids, amino acids, peptides, and/or proteins. Gold nanoparticles obtained under the normal conditions showed plate-like morphologies with low production efficiency (Fig. 11.2a).

Biosynthesis of gold nanoparticles using tansy fruit extract (*Tanacetum vulgare*) has also been reported (Dubey et al. 2010b). Zeta potential is an index of surface charge of the nanoparticles that is used to predict the stability of colloidal particles (Heurtault et al. 2003). The effect of pH on zeta potential of the nanoparticles produced by tansy fruit extract indicates that the zeta potential value of nanoparticles depends on the pH of the solution. The zeta potential value of gold nanoparticles in alkaline pH was slightly higher than that of acidic pH. Furthermore, size of the particles produced was increased by decreasing the pH.

In another study, gold nanoparticles have been fabricated by treatment of the $HAuCl_4$ solution with *Prunus domestica* (plum) fruit extracts (Dauthal and Mukhopadhyay 2012). The catalytic activity of gold nanoparticles dispersed in the fruit extract was studied for 4-nitrophenol reduction to 4-aminophenol. FTIR analysis suggested that the water-soluble polyols like flavanols, glycosides, and phenols were responsible for the reduction of Au^{3+} ions. Biosynthesized gold nanoparticles

showed dose-dependent catalytic activity for 4-NP reduction. The catalytic activity of 4-nitrophenol increased with increasing dosage of colloidal gold nanoparticles.

Flower extract of the plant *Nyctanthes arbor-tristis* has been used as the reducing and capping agent for the synthesis of gold nanoparticles (Das et al. 2011). TEM images of the nanoparticles showed a mixture of different shapes (triangular, pentagonal, rod shaped, and spherical) with an average size of 19.8 ± 5.0 nm. Sneha et al. (2011) also reported the formation of gold nanoparticles using cumin seeds (*Cuminum cyminum*). They stated that the particles were predominately monodispersed at higher pH and polydispersed particles formed at lower pH. Table 11.1 summarizes the important examples of gold nanoparticles synthesized by plants.

11.2.2 Synthesis of Gold Nanoparticles Using Bacteria

Many microorganisms can produce various biomolecules either intracellularly or extracellularly. In synthesis of nanoparticles outside the cell, extracellularly, the enzymes secreted by microorganism play an important role in the bioreduction of metal ions. In synthesis of nanoparticles inside the cell, intracellularly, the enzymes present in the cell wall of the microorganisms involve in the reduction of metal ions to metal nanoparticles (Hulkoti and Taranath 2014). The nanoparticles produced inside the organism can have a smaller size than extracellularly formed nanoparticles (Narayanan and Sakthivel 2010).

Beveridge and Murray (1980) synthesized the gold nanoparticles using the cell wall of *Bacillus subtilis*. They were chemically modified amine and carboxyl groups of the cell wall of *B. subtilis* to determine their contribution to the metal uptake values. Their results indicated that chemical modifications of amine functions did not decrease the metal uptake values, whereas alteration of carboxyl groups was severely restricted metal deposition of most of the metals tested.

Deplanche and Macaskie (2008) demonstrated microbial reduction of gold using *Escherichia coli* and *Desulfovibrio desulfuricans* and determined the location and size of the formed gold particles. According to their report, hydrogenases are responsible in the bacteria-mediated reduction of the gold ions. The size and shape of the gold nanoparticles produced depend on the solution pH and the location of the formation of the nanoparticles. The nanoparticles ranged from 5 to 50 nm and located in the periplasmic space and on the cell surface as well as intracellularly.

The extracellular synthesis of gold nanoparticles using the gram-negative soil bacterium *Pseudomonas fluorescens* has been proven (Rajasree and Suman 2012). In a recent study, a human pathogenic bacterium *Salmonella enterica* subsp. *enterica* serovar Typhi isolated from blood and stool specimens of patients provided the biogenic synthesis of gold nanoparticles (Mortazavi et al. 2017). Characterizations of some gold nanoparticles synthesized by bacteria are enlisted in Table 11.2.

Table 11.2 Biological synthesis of gold nanoparticles using bacteria, actinomycetes, algae, and yeast

No.	Name of microorganism	Extracellular/ intracellular	Morphology	Size	References
Bacteria					
01	*Escherichia coli*, *Desulfovibrio desulfuricans*	Intracellular	Spherical, triangles, hexagons, and rods	5–50 nm	Deplanche and Macaskie (2008)
02	*Pseudomonas fluorescens*	Extracellular	Spherical	50–70 nm	Rajasree and Suman (2012)
03	*Salmonella enterica* subsp. *enterica* serovar Typhi	Extracellular	–	42 ± 2 nm	Mortazavi et al. (2017)
Actinomycetes					
01	*Thermomonospora* sp.	Extracellular	Spherical	8 nm	Ahmad et al. (2003a)
02	*Rhodococcus* sp.	Intracellular	Spherical	5–15 nm	Ahmad et al. (2003b)
03	*Streptomyces fulvissimus*	Extracellular	Spherical	20–50 nm	Soltani Nejad et al. (2015)
Algae					
01	*Plectonema boryanum*	Extracellular/ intracellular	Cubic	< 10–25	Lengke et al. (2006)
02	*Sargassum wightii* Greville	Extracellular	Thin planar structures	8–12 nm	Singaravelu et al. (2007)
03	*Galaxaura elongata*	–	Spherical	3.85–77.13 nm	Abdel-Raouf et al. (2017)
Yeast					
01	*Yarrowia lipolytica NCIM 3589*	Intracellular	Hexagonal, triangular	15 nm	Agnihotri et al. (2009)
02	*Magnusiomyces ingens LH-F1*	–	Sphere, triangle, and hexagon	80.1 ± 9.8 nm	Zhang et al. (2016)

11.2.3 Synthesis of Gold Nanoparticles Using Actinomycetes, Algae and Yeast

Actinomycetes are a group of gram-positive bacteria that have the characteristics of fungi. They produce various biomolecules including proteins, enzymes, antibiotics, and vitamins. Actinomycetes can be used as stabilizing and capping agents for the synthesis of metal nanoparticles, including gold. Among the bioactive agents secreted by actinomycetes, proteins play an important role in the synthesis of the nanoparticles. It is proven that free amine groups or cysteine residues in the proteins can bind to gold nanoparticles (Gole et al. 2001).

The alkalothermophilic actinomycete *Thermomonospora* sp. has been explored for extracellular synthesis of stable gold nanoparticles (Ahmad et al. 2003a).

Intracellular synthesis of gold nanoparticles has been provided by *Rhodococcus* sp. actinomycetes (Ahmad et al. 2003b). Spherical nanoparticles with size range of 5–15 nm were achieved.

Algae are photosynthetic eukaryotic microorganisms used for synthesis of gold nanoparticles. Cell walls of algae contain biomolecules, including polysaccharides, proteins, and enzymes which act as reducing agents for the reduction of gold ions (Sharma et al. 2015).

The powder and the ethanolic extract of marine red alga *Galaxaura elongate* have been used for synthesis of gold nanoparticles. The formation of gold nanoparticles by powder (3 h) was faster than alcoholic extract (2–5 min) (Abdel-Raouf et al. 2017).

Yeasts are single-cell eukaryotic microorganisms that are classified in the fungus kingdom. The biogenic synthesis of gold nanoparticles by the non-conventional yeasts *Yarrowia lipolytica* and *Magnusiomyces ingens* is described (Agnihotri et al. 2009; Zhang et al. 2016). X-ray diffraction (XRD) data and TEM images of *Y. lipolytica* showed that the nanoparticles are synthesized with a size of 15 nm and located on the wall of the cells (Agnihotri et al. 2009). TEM images and dynamic light scattering (DLS) data of *M. ingens* indicated that the average size of gold nanoparticles was 80.1 ± 9.8 and 137.8 ± 4.6 nm, respectively. According to the results of the investigation, some biomolecules were absorbed on the surface of the nanoparticles, which can act as organic ligands in the formation of gold nanoparticles (Zhang et al. 2016). Important examples of biosynthesis of gold nanoparticles by actinomycetes, algae, and yeasts are summarized in Table 11.2.

11.2.4 Synthesis of Gold Nanoparticles Using Fungi

The biosynthesis of gold nanoparticles using fungi has been demonstrated (Table 11.3). Among the microorganisms used for the synthesis of metal nanoparticles, fungi are a suitable candidate for the production of different enzymes, which have high growth capacity and are easy to handle.

The exact mechanism of synthesis of nanoparticles using biological agents is still unknown, but it has been demonstrated that different biomolecules have a significant role in the synthesis of nanoparticles. It has been revealed that the enzyme nitrate reductase is involved in biosynthesis of nanoparticles by fungi (Kumar et al. 2007a, b). The mechanisms for intracellular and extracellular synthesis of nanoparticles are different. Moreover, the shape and size of nanoparticles produced can be affected by enzymes and mechanisms involved in the synthesis of nanoparticles.

Mukherjee et al. (2001) reported intracellular synthesis of gold nanoparticles by bioreduction of aqueous $AuCl_4^-$ ions using the fungus *Verticillium* sp. TEM image of a single cell showed that the gold nanoparticles were formed on both the cell wall (outer boundary) and the cytoplasmic membrane (inner boundary). The number of gold nanoparticles on the cytoplasmic membrane was more than on the cell wall. The shape of gold nanoparticles was mostly spherical, although a few triangular and hexagonal particles were observed.

Table 11.3 Biological synthesis of gold nanoparticles using fungi

No.	Name of the fungi	Extracellular/ intracellular	Morphology	Size	References
01	*Verticillium* sp.	Intracellular	Spherical, triangular, and hexagonal	20 ± 8 nm	Mukherjee et al. (2001)
02	*Fusarium oxysporum*	Extracellular	Spherical, triangular	20–40 nm	Mukherjee et al. (2002)
03	*Rhizopus oryzae*	–	–	10 nm	Das et al. (2009)
04	*F. oxysporum* f. sp. *cubense*	Extracellular	–	22 nm	Thakker et al., (2013)
05	*Penicillium aurantiogriseum*, *P. citrinum*, and *P. waksmanii*	–	Spherical	153.3, 172, and 160.1 nm (90 = 300 nm)	Honary et al. (2013)
06	*Aspergillus sydowii*	Extracellular/ intracellular	Spherical	8.7–15.6 nm	Vala (2015)
07	*Alternaria* sp.	Extracellular	Quasi-spherical, spherical, and anisotropic nanoparticles	7–13, 15–18, and 69–93 nm	Dhanasekar et al. (2015)
08	*Pleurotus ostreatus*	Extracellular	–	22–39 nm	El-Batal et al. (2015)
09	*Penicillium aculeatum*	Extracellular	Spherical	60 nm	Barabadi et al. (2017)
10	*Aspergillus* sp. WL-Au	Extracellular	Spherical	2.5–6.7 nm	Shen et al. (2017)
11	Thermophilic fungi	Intracellular/ extracellular	Spherical, hexagonal, and amorphous	6–40 nm	Molnar et al. (2018)

In addition, they reported extracellular synthesis of gold nanoparticles by a eukaryotic system such as fungi for the first time (Mukherjee et al. 2002). The nanoparticles were synthesized by treatment of the fungus *Fusarium oxysporum* with $AuCl_4^-$ solution. TEM pictures showed that gold particles have spherical and triangular morphology with a size range of 20–40 nm. Indeed, the gold nanoparticle formed by reaction of gold ions with extracellular secreted enzymes by the fungus. Thakker et al. (2013) synthesized gold nanoparticles using a plant pathogenic fungus *F. oxysporum* f. sp. *cubense* and reported their antibacterial activity against *Pseudomonas* sp.

The microbial synthesis of gold nanoparticles has been investigated using the fungus *Rhizopus oryzae* to remove different organophosphorus pesticides (model) from water along with some microorganisms (Das et al. 2009). The gold nanoparticles were formed on the surface of *R. oryzae* and were stable even up to 6 months. FTIR spectra after treatment of *R. oryzae* with $HAuCl_4^-$ revealed the presence of amide I, II, and III groups and the disappearance of carboxyl groups present in mycelia. Based on the FTIR results, it was suggested that polypeptides/proteins are involved in the reduction of gold ions. Indeed, the gold nanoparticles are formed by surface-bound protein molecules that act as both reducing and stabilizing agents.

In another study, the use of a marine-derived fungus *Aspergillus sydowii* resulted in the formation of spherical gold nanoparticles with an average size of 10 nm. The fungus could synthesize gold nanoparticles extra-/intracellularly depending on the applied gold ion concentration (Vala 2015). Fungus-mediated synthesis of gold nanoparticles by *Penicillium aurantiogriseum*, *P. citrinum*, and *P. waksmanii* has been demonstrated (Honary et al. 2013).

11.3 Characterization of Gold Nanoparticles

The characteristics of gold nanoparticles are determined using various techniques such as scanning electron microscopy (SEM), atomic force microscopy (AFM), TEM, DLS, FTIR, XRD, and UV-Vis spectroscopy. The shape and size of nanoparticles are determined by TEM, SEM, and AFM. DLS is also used for determination of size, dispersity, and zeta potential of nanoparticles. Furthermore, FTIR and XRD are applied for the determination of structural characteristics and crystallinity of formed particles.

In the biogenic synthesis of gold nanoparticles, the change of color of the reaction mixture from pale yellow to dark purple/deep red reflects the formation of gold particles. The different colors of gold nanoparticle solution are due to their surface plasmon resonance properties (He et al. 2007). Generally, UV-visible spectroscopy is utilized to confirm formation of metal nanoparticles including gold. The UV-visible spectrum of the reaction mixtures (organism-gold ions) represents the formation of a gold surface plasmon resonance (detection of gold nanoparticles) that ranged from 500 to 600 nm (Deplanche and Macaskie 2008).

11.4 Applications of Gold Nanoparticles in Agriculture

In recent years, the use of nanotechnology in various fields, including pharmaceuticals, engineering, and agriculture, has been developed. The application of nanotechnology in the agricultural sector has improved, especially in the area of food industry and plant protection. Gold nanoparticles have many potential applications in agriculture due to their antimicrobial activity and unique optical property.

Gold nanoparticles can be applied as a sensor in a series of colorimetric assays. In this assay, the interaction between the analyte and the gold nanoparticles can induce the aggregation of gold nanoparticles and consequently solution color changes from red to purple. This feature can be used to identify different molecules, including pesticides. For instance, Bai et al. (2010) have studied gold nanoparticles as colorimetric probes for screening insecticide pymetrozine. It has been demonstrated that compounds containing nitrogen heterocycles and amine groups can be bound to the surface of metal nanoparticles and induce the accumulation of the nanoparticles (Gittins and Caruso 2001; Ai et al. 2009). Chemical structure of pymetrozine contains multiple binding sites including one exocyclic secondary amine and four-nitrogen hybrid ring. Indeed, the color change and aggregation of gold nanoparticles can be attributed to the specific interactions between the functional groups of gold nanoparticle and pymetrozine.

In addition, gold nanoparticle-based sensors can be utilized to determine the residue of different pesticides in plants and food products. For example, Bai and his colleagues (2010) determined the concentration of pymetrozine with the low detection limit (1×10^{-6} M) and reported the high sensitivity of this method for pymetrozine compared with other 11 pesticides. The detection sensitivity of this system could be increased by adding salt and reducing the pH. The use of bacterial-derived gold nanoparticles to detect organophosphorus pesticide residues in fruits and vegetables has been proven (Malarkodi et al. 2017).

Gold nanoparticles can also be useful in water purification. For instance, Zhang et al. (2014) fabricated imidazole ionic liquid functionalized gold nanoparticles for the recognition of imidacloprid. The researchers suggested that the detection system could be used to determine and remove imidacloprid in different water samples based on the aggregation phenomena of gold nanoparticles. The application of fungus-mediated synthesized gold nanoparticles to remove pesticides and pathogens from water has been reported (Das et al. 2009).

Gold nanoparticles have antibacterial and antifungal properties that can be used in plant disease management, food safety, and medical applications. Jayaseelan et al. (2013) synthesized gold nanoparticles using seed aqueous extract of *Abelmoschus esculentus* and posed antifungal activity of the nanoparticles against *Candida albicans*, *Aspergillus niger*, *Aspergillus flavus*, and *Puccinia graminis tritci*. The antibacterial activity of the biosynthesized gold nanoparticles against *Klebsiella pneumoniae*, *Bacillus subtilis*, *Pseudomonas aeruginosa*, and *Escherichia coli* has been reported (Annamalai et al. 2013; Muthuvel et al. 2014).

The mycelial growth inhibition of *Phomopsis theae* by *Trichoderma atroviride*-mediated biosynthesized gold nanoparticles has been demonstrated (Ponmurugan

2016). Field experiments conducted with soil application and wound dressing of the nanoparticles confirmed the efficacy of the nanoparticles for control of *Phomopsis* canker disease in tea plants.

It has been revealed that biosynthesized gold nanoparticles can be useful to control pests in agriculture and public health (Thakur et al. 2018; Sundararajan and Kumari 2017). Thakur et al. (2018) studied the effect of biosynthesized gold nanoparticles on root-knot nematodes (*Meloidogyne incognita*) in tomato crop. The nanoparticles showed suitable nematicidal effect and had no negative impact on plant growth. All articles on the insecticidal activity of gold nanoparticles focused on mosquito species of medical and veterinary importance.

Many researchers have demonstrated that gold nanoparticles induce cell division, seed and pollen germination, and plant growth (Arora et al. 2012; Gopinath et al. 2013; Mahakham et al. 2016; Thakur et al. 2018). Therefore, application of gold nanoparticles in agriculture and plant sciences could be beneficial to increase the plant growth and crop yield like several types of engineered nanomaterials (Baiazidi-Aghdam et al. 2016; Ghorbanpour and Hadian 2015; Hatami et al. 2013, 2016, 2017, 2019; Ghorbanpour et al. 2015, 2018; Ghorbanpour and Hatami 2014, 2015; Ghorbanpour 2015; Ghorbanpour and Hadian 2017; Ghorbanpour and Fahimirad 2017; Hatami et al. 2014; Hatami and Ghorbanpour 2013, 2014; Hatami 2017; Chegini et al. 2017; Mohammadi et al. 2018; Tian et al. 2018; Ahmadi et al. 2018).

11.5 Conclusions

The main goal of most nanotechnology research is to design and produce nanoparticles with new features. Compared with the chemical method, the biological synthesis of gold nanoparticles by organisms is an environmentally friendly and reliable method. The gold nanoparticles of a variety of shapes and sizes can be easily synthesized from different types of plants and microbes. The synthesis of gold nanoparticles depends on various factors including the concentration of plant extract/biomass and metal salt, pH of the solution, temperature, reaction time, and the location of nanoparticle formation (extracellular/intracellular). Applications of such eco-friendly nanoparticles in agriculture to purify rivers and lakes from pesticides can reduce the harmful impacts on nontarget organisms. Biosynthesized gold nanoparticles can be effective to protect the various crop plants against plant pathogens and can be a suitable alternative to chemical pesticides that are toxic to human and the environment.

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