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REVIEW

Microorganisms as efficient biosystem for the synthesis of metal nanoparticles: current scenario and future possibilities

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Abstract Nanoparticles, the elementary structures of nanotechnology, are important materials for fundamental studies and variety of applications. The different sizes and shapes of these materials exhibit unique physical and chemical properties than their bulk materials. There is a great interest in obtaining well-dispersed, ultrafine, and uniform nanoparticles to delineate and utilize their distinct properties. Nanoparticle synthesis can be achieved through a wide range of materials utilizing a number of methods including physical, chemical, and biological processes with various precursors from liquids and solids. There is a growing need to prepare environmentally friendly nanoparticles that do not produce toxic wastes in their process synthesis protocol. This kind of synthesis can be achieved by green environment benign processes, which happen to be mostly of a biological nature. Microorganisms are one of the most attractive and simple sources for the synthesis of different types of nanoparticles. This review is an attempt to provide the up-to-date information on current status of nanoparticle synthesis by different types of microorganisms such as fungi, yeast, bacteria, cyanobacteria, actinomycete, and algae. The probable biosynthesis mechanism and conditions for size/shape control are described. Various applications of microbially synthesized nanoparticles are summarized. They include antibacterial, antifungal, anticancer, larvicidal, medical imaging, biosensor, and catalytic applications. Finally, limitations and future prospects for specific research are discussed.

Keywords Biosynthesis · Nanoparticles · Microorganisms · Mechanism · Applications

Introduction

Nanotechnology, a multidimensional science devoted to study fundamental properties of nanomaterials, has attracted interest in recent years. Nanotechnology is defined as the manipulation of matter with at least one dimension sized from 1 to 100 nm. There is increasing research activity in the field of nanotechnology, which has influenced many areas such as energy, medicine, electronics, and space industries. Different types of nanomaterials such as nanoparticles, nanotubes, and nanowires are useful in different applications. Nanoparticles (NPs) have attracted considerable scientific interest in recent years (Wang et al. 2014; Polte 2015). Nanoparticles usually referred as particles between 1 and 100 nm in size. They are constituted of several tens or hundreds of atoms or molecules. Nanoparticles can have a variety of sizes and morphologies such as amorphous, crystalline, spherical, needles, etc. Nanoparticles display distinctive physical, chemical, and biological properties than their bulk materials (Lee et al. 2014). Depending on size and shape, nanoparticles show different useful properties. Nanoparticles have been used for applications in medicine, healthcare, electronics, and agriculture (Sun et al. 2000; Vilchis-Nestor et al. 2008; Mohanpuria et al. 2008; Lee et al. 2014; Borase et al. 2014).

Different methods like physical, chemical and biological processes are being used for the synthesis of nanoparticles. Some chemical molecules such as anionic polysaccharides

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like polyglucuronic acid, oligosaccharide derivatives, and chitosan have been investigated for their bioactivities and their abilities to be functionalized as interesting nano or film materials (Tavernier et al. 2008; Elboutachfaiti et al. 2011; Mati-Baouche et al. 2014; Delattre et al. 2015; Elchinger et al. 2015). However, nanomaterial synthesis protocols of some chemical and physical methods involve use of toxic chemicals (Azim et al. 2009; Tapan and Andrey 2009; Borase et al. 2014). Green processes for nanoparticle synthesis are therefore needed. Synthesis of nanoparticles by biological methods using microorganisms or plant extracts offers a reliable, eco-friendly alternative to chemical and physical methods. Biological approach of nanoparticle synthesis is advantageous than physical and chemical methods because of simplicity of synthesis method without requirement of high temperature, pressure, and energy besides eco-friendly, cost-effective, scalable processes (Borase et al. 2014). Many microorganisms have resistance against toxic metals and have abilities of remediation of toxic metals through reduction of metal ions. This property makes them useful for nanoparticle synthesis. Microorganisms with their enzymes can select metal ions from the precursor solutions and accumulate them in elemental form of reduced metal thereby synthesizing nanoparticles.

As per the location of nanoparticle synthesis, the microbial mediated synthesis is generally categorized into intracellular and extracellular synthesis (Simkiss and Wilbur 1989; Mann 1996). The nanoparticles in intracellular approach are synthesized in the presence of enzymes where ions are transported inside the microbial cell for the formation of nanoparticles. Whereas in extracellular synthesis, metal ions are trapped on the surface of the cells and are reduced to form nanoparticles with the help of enzymes. Different types of microorganisms have been used for the synthesis of mineral nanocrystals and metallic nanoparticles. The microorganisms include fungi (Ahmad et al. 2003a; Bruins et al. 2000; Salunkhe et al. 2011a, b), yeast (Mithila et al. 2009; Salunke et al. 2015), S-layer bacteria (Pum and Sleytr 1999), magnetotactic bacteria (Blackmore 1982), algae (Castro et al. 2013; Aziz et al. 2015), diatoms (Mann 2001), actinomycete (Ahmad et al. 2003b, c), and lichen (Mie et al. 2014). The control of the size, shape, composition, and monodispersity of particles has also been studied.

The present review summarizes the current status on the use of microbes for nanoparticle biosynthesis, possible biosynthesis mechanism, control of size/shape, limitations, future prospects, and diverse applications of nanoparticles.

Types of microorganisms in nanoparticle synthesis

Many microbes including fungi, yeast, bacteria, and actinomycetes have been found to be capable of intracellularly or extracellularly synthesizing mineral crystals and metallic nanoparticles. The general scheme of nanoparticle synthesis is displayed in Fig. 1. Different species of microorganisms such as fungi (Table 1), yeast (Table 2), bacteria (Table 3) cyanobacteria, actinomycete, and algae (Table 4) have been used for the synthesis of diverse types of nanoparticles. The type of nanoparticles includes Ag, Au, lead, Ag_2O, zirconia, CdS, barium titanate, CdSe quantum dots, silica, titanium, nickel oxide, iron, iron oxide (Fe_2O_3), copper, MnO_2, ZnO,

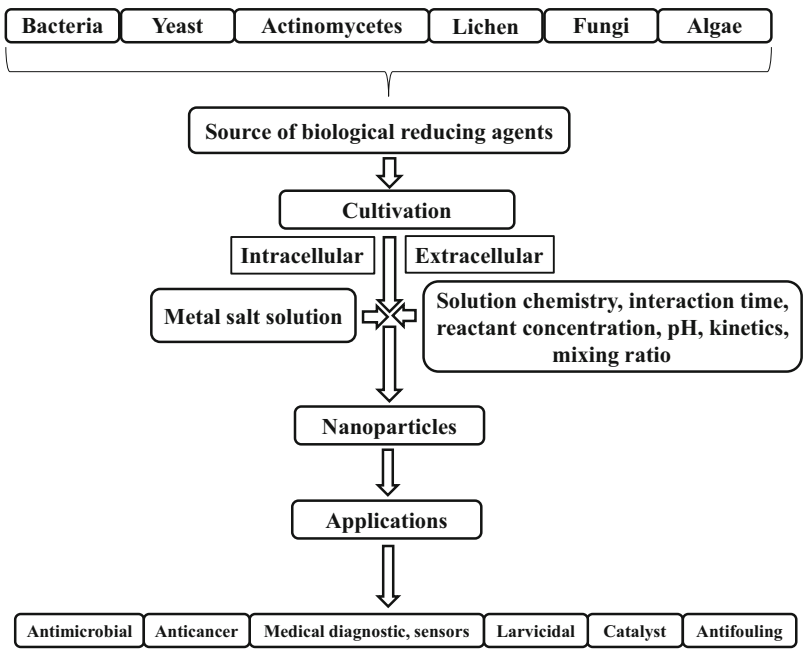

Fig. 1 General scheme of synthesis of nanoparticles by microorganisms

Table 1 Synthesis of different nanoparticles by fungi

Microbial species	Nanoparticle type	Size (nm)	Shape	Way of synthesis	Application	Reference
Fungi						
Alternaria solani	Ag	25	Spherical	Extracellular	–	Ghazwani (2015)
Alternaria sp.	Au	7–18	Spherical, rod, square, pentagonal, and hexagonal morphologies	Extracellular	–	Dhanasekar et al. (2015)
Aspergillus fumigatus	Ag	5–25		Extracellular	–	Bhainsa and D'souza (2006)
Aspergillus niger	Ag	20	Spherical	Extracellular	–	Ghazwani et al. (2015)
Aspergillus niger	Ag	43–63	Spherical	Intracellular and Extracellular	Antibacterial activity	Vanaja et al. (2015)
Aspergillus niger PFR6	Ag	8.7 ± 6	Spherical	Extracellular	–	Devi and Joshi (2015)
Aspergillus oryzae	Ag	6–37	Spherical	Extracellular	–	Bhimba et al. (2015)
Aspergillus oryzae	Ag	76.14	Spherical	Extracellular	Antifungal activity	Pereira et al. (2014)
Aspergillus sp.	Ag	–	–	Extracellular	Antimicrobial activity	Prabavathy et al. (2015)
Aspergillus sp.	Lead	5–20	Spherical	Extracellular	–	Pavani et al. (2012)
Aspergillus tamarii PFL2	Ag	3.5 ± 3	Spherical	Extracellular	–	Devi and Joshi (2015)
Aspergillus terreus VIT 2013	Ag_2O	–	–	Extracellular	Antibacterial	Sangappa, and Thiagarajan (2015)
Cochliobolus lunatus	Ag	14	Spherical	Intracellular and Extracellular		Salunkhe et al. (2011a)
Cochliobolus lunatus	Ag	3–21	Spherical	Intracellular and Extracellular	Mosquito larvicidal	Salunkhe et al. (2011b)
Colletotrichum sp.	Au	20–40		Extracellular		Shankar et al. (2003)
Fusarium oxysporum	Magnetite	20–50		Extracellular		Bharde et al. (2006)
Fusarium oxysporum	Ag	5–15	Spherical	Extracellular		Ahmad et al. (2003a, b, c)
Fusarium oxysporum	Au	20–40		Extracellular		Mukherjee et al. (2002)
Fusarium oxysporum	Zirconia	3–11		Extracellular		Bansal et al. (2004)
Fusarium oxysporum	CdS	5–20		Extracellular		Ahmad et al. (2002)
Fusarium oxysporum	Barium titanate	4–5		Extracellular		Bansal et al. (2006)
Fusarium oxysporum	CdSe quantum dots	–		Extracellular		Kumar et al. (2007b)
Fusarium oxysporum	Silica and Titanium particles (SiF_6^{2-} and TiF_6^{2-})	5–15		Extracellular		Bansal et al. (2005)
Fusarium oxysporum	Ag	5	Spherical	Extracellular	–	Ghazwani et al. (2015)
Fusarium oxysporum Nitrate reductases	Ag	10–25		Extracellular		Kumar et al. (2007a)

Table 1 continued

Microbial species	Nanoparticle type	Size (nm)	Shape	Way of synthesis	Application	Reference
Humicola sp.	Ag	5–25	Spherical	Extracellular	Cytoxicity	Syed et al. (2013)
Hypocrea lixii	Nickel oxide	1.25–3.8	Spherical	Intracellular and Extracellular	–	Salvadori et al. (2015)
Penicillium chrysogenum	Ag	100.6	Spherical	Extracellular	Antifungal activity	Pereira et al. (2014)
Penicllium ochrochloron PFR8	Ag	7.7 ± 4.3	Spherical	Extracellular	–	Devi and Joshi (2015)
Phanerochaete chrysosporium and enzyme	Au	10–100	Spherical	Intracellular and Extracellular	–	Sanghi et al. (2011)
Pleurotus sp.	Iron	–	–	Intracellular	–	Mazumdar and Haloi (2011)
Pycnoporus sanguineus	Au	10–500	Spherical, pseudo-spherical, triangular, truncated triangular, pentagonal, and hexagonal	Intracellular	Catalysis in degradation of 4-nitroaniline	Shi et al. (2015)
Rhizopus stolonier	Ag	5–50	Spherical	Extracellular	–	Banu and Rathod (2011)
Trichoderma Reesei	Ag	5–50	Spherical	Extracellular	–	Vahabi et al. (2011)
Trichothecium sp.	Au	–	–	Extracellular and Intracellular	–	Ahmad et al. (2005)
V. luteoalbum	Au	Few to 100	–	Intracellular	–	Gericke and Pinches (2006b)
Verticillium	Au	20	–	Intracellular	–	Mukherjee et al. (2001a)
Verticillium	Ag	25 ± 12	–	Intracellular	–	Mukherjee et al. (2001b), Senapati et al. (2004)
Verticillium sp.	Magnetite	20–50	–	Extracellular	–	Bharde et al. (2006)

Table 2 Synthesis of different nanoparticles by yeast

Microbial species	Nanoparticle type	Size (nm)	Shape	Way of synthesis	Biological activity	Reference
Yeast						
Baker's Yeast	Ag	5–25	Spherical	Extracellular		He et al. (2013)
Baker's Yeast	Ag	6–20	Spherical	Extracellular		Jha et al. (2008)
Baker's Yeast *Saccharomyces cerevisiae*	Ag	60–80	Spherical	Extracellular	Antimicrobial activity	Saravanan et al. (2013)
Candida albicans	Iron oxide (Fe_2O_3)	80	Spherical	Extracellular	Antimicrobial activity	Hassan et al. (2015)
Candida glabrata	CdS	2		Intracellular		Dameron et al. (1989)
Extremophilic yeast strain Portugal	Ag	20 nm		Extracellular	–	Mourato et al. (2011)
Extremophilic yeast strain Portugal	Au	30–100 nm		Extracellular	–	Mourato et al. (2011)
MKY3	Ag	2–5		Extracellular		Kowshik et al. (2002)
P. jadinii	Au	Few to 100		Intracellular		Gericke and Pinches (2006b)
Rhodotorula mucilaginosa	Copper	10.5	Spherical	Intracellular and Extracellular	–	Salvadori et al. (2014)
Saccharomyces cerevisiae	MnO_2	15–70	Hexagonal and spherical	Extracellular		Salunke et al. (2015)
Saccharomyces cerevisiae	ZnO	*52.72*	–	Extracellular		Pavani et al. (2015)
Saccharomyces cerevisiae	Au	–	–	–		Stegenga et al. (2011)
Saccharomyces cerevisiae	Ag	10	Spherical	Extracellular	Photocatalytic activity	Roy et al. (2014)
Schizosaccharomyces pombe	CdS	1–1.5		Intracellular		Kowshik et al. (2002)
Schizosaccharomyces pombe	CdS	2		Intracellular		Dameron et al. (1989)
Yarrowia lipolytica NCIM 3589	Au	9–27	Spherical hexagonal, triangular nanoplates	Intracellular and Extracellular	–	Pimprikar et al. (2009)
Yarrowia lipolytica NCIM 3589	Au	15	Hexagonal, triangular, Spherical	Intracellular and Extracellular	–	Agnihotri et al. (2009)
Yarrowia lipolytica NCYC 789	Au	–	–	Intracellular and Extracellular	Antibacterial and anti-biofilm activity	Nair et al. (2013)
Yarrowia lipolytica NCYC 789 and its melanin	Ag	15	–	Intracellular and Extracellular	Antibiofilm activity	Apte et al. (2013)
Yeast cells	Iron phosphate ($FePO_4$)	50–200	Spherical aggregations	Extracellular		He et al. (2009)

Table 3 Synthesis of different nanoparticles by bacteria

Microbial species	Nanoparticle type	Size	Shape	Way of synthesis	Biological activity	Reference
Bacteria						
Arthrobacter nitroguajacolicus	Au	40	Spherical	Extracellular		Dehnad et al. (2015)
Bacillus pumilus, B. persicus, and *Bacillus licheniformis*	Ag	77–92	Spherical	Extracellular	Antimicrobial and antiviral	Elbeshehy et al. (2015)
Bacillus subtilis	Ag	5–60	Spherical	Extracellular	–	Saifuddin et al. (2009)
Deinococcus radiodurans	Ag	4–50	Spherical	Extracellular	Antibacterial, Anti-biofouling, Anticancer	Kulkarni et al. (2015)
Desulfovibrio desulfuricans	Palladium	–		–		Yong et al. (2002)
E.coli	Ag	20–50	Spherical	Extracellular	Antibacterial	Kushwaha et al. (2015)
Geobacillus sp. strain ID17	Au	5–50	Quasi-hexagonal	Intracellular	–	Correa-Llantén et al. (2013)
Geobacter sp.	Iron sulfide (FeS) and siderite ($FeCO_3$)	40–60 and 10 nm −3 μm	–	–	–	Kim et al. (2015)
K. pneumonia	Ag	1–6	Spherical	Extracellular	–	Mokhtari et al. (2009)
Klebsiella aerogenes	Cadmium sulfide	20–200	Crystalline	Extracellular		Holmes et al. (1995)
Lactobacillus	TiO_2	8–35	Spherical and other shapes	Extracellular	–	Jha et al. (2009)
Lactobacillus sp.	Titanium	40–60	Spherical	Extracellular	–	Prasad et al. (2007)
Magnetotactic bacteria	Magnetic Fe3O4), reigite Fe3S4)	–	–	–		Roh et al. (2001)
Nocardiopsis sp. MBRC-1	Ag	45 ± 0.15	Spherical	Extracellular	Antimicrobial and Anticancer	Manivasagan et al. (2013)
Pseudomonas aeruginosa	Au	15–30		Extracellular		Husseiny et al. (2007)
Pseudomonas stutzeri	Ag	Up to 200				Joerger et al. (2000), Klaus et al. (2001)
Rhodobacter sphaeroides	Zinc sulfide	Average diameter of 8	Spherical	Extracellular	–	Bai et al. (2006)
Rhodopseudomonas palustris	Cadmium sulfide	8.01 ± 0.25	Crystalline, face-centered cubic	Intracellular	–	Bai et al. (2009)
Rhodopseudomonas capsulata	Au	10–20	Spherical and nanowires	Extracellular	–	He et al. (2008)
Serratia nematodiphila	Ag	10–31	Spherical	Extracellular	Antibacterial	Malarkodi et al. (2013)
Shewanella algae	Pt	Around 5	–	Intracellular and Extracellular	–	Konishi et al. (2007)
Shewanella putrefaciens (Gs-15)	Magnetite	10–50	Fine-grained crystal	Intracellular		Lovley et al. (1987)
Staphylococcus aureus	Ag	160–180	Spherical	Extracellular	Antibacterial	Nanda and Saravanan (2009)

Table 4 Synthesis of different nanoparticles by Cyanobacteria, Actinomycete, and Algae

Microbial species	Nanoparticle type	Size (nm)	Shape	Way of synthesis	Biological activity	Reference
Cyanobacteria						
Plectonema boryanum UTEX 485 (Cyanobacterium)	Au platlets	6–10	Octahedral	At the cell wall		Lengke et al. (2006a, b)
Plectonema boryanum (Cyanobacterium)	Palladium	≤30	Spherical and elongate	Intracellular and Extracellular	–	Lengke et al. (2007)
Actinomycete						
Rhodococcus sp.	Au	5–15		Intracellular		Ahmad et al. (2003a)
Streptomyces clavuligerus	Au	8.25 ± 0.64	Spherical	Extracellular	Anticancer	Kumar et al. (2015)
Streptomyces fulvissimus	Au	20–50	Spherical, Trinagular	Extracellular	–	Soltani et al. (2015)
Thermomonospora sp.	Au	8		Extracellular		Ahmad et al. (2003b)
Algae						
Aphanothece sp, Oscillatoria sp, Microcoleus sp, Aphanocapsa sp, Phormidium sp, Lyngbya sp, Gleocapsa sp, Synechococcus sp, Spirulina *sp*	Ag	40–80	Spherical	Extracellular	Antibacterial	Sudha et al. (2013)
Chlorella pyrenoidosa	Ag	5–30	Spherical	Extracellular	Antibacterial and Photocatalytic	Aziz et al. (2015)

iron phosphate ($FePO_4$), palladium, iron sulfide (FeS), siderite ($FeCO_3$), cadmium sulfide, TiO_2, titanium, magnetite (Fe_3O_4), greigite (Fe_3S_4), zinc sulfide, and Pt. AgNPs have been most studied due to their good antimicrobial and catalytic activities. The size of the synthesized nanoparticles ranges from 1 to 500 nm. The shape is predominantly spherical, but other shapes such as pseudo-spherical, rod, triangular, truncated triangular, square, pentagonal, hexagonal, nanoplate, fine-grained crystal, and nanowire morphologies have also been observed. The synthesized nanoparticles have been utilized for antimicrobial, antibacterial, anti-biofilm, anti-biofouling, antiviral, anticancer, and photocatalytic activities (Tables 1, 2, 3 and 4).

Mechanism of nanoparticle synthesis by microorganisms

Different studies have shown the role of cell wall, cell membrane, different enzymes, proteins, and other organic molecules in nanoparticle synthesis (Fig. 2). Salunke et al. (2015) suggested the role of *S. cerevisiae* cell wall components, alcoholic compounds, and proteins in MnO_2 nanoparticle synthesis and stabilization. *S. cerevisiae* cell walls are composed of chitin, glucan, and mannoprotein (Kollár et al. 1997; Lipke and Ovalle 1998). The components of the cell walls collectively may be responsible for the rapid synthesis of MnO_2 nanoparticles (Salunke et al. 2015). Proteins released by yeast cells have been reported to play an important role in the synthesis of AgNPs, whereas the cell wall was involved in the synthesis of AuNPs (Mourato et al. 2011). Proteins may have an active role in the synthesis of MnO_2 nanoparticles along with sugars and chitin. Priyabrata et al. (2001) observed majority of the particles were attached on the surface of the cytoplasmic membrane in their AgNP synthesis study. They suggested that electrostatic interaction on the cell surface traps the silver ions and further reduces it to form silver nuclei through action of unknown enzymes in the cell wall, which lead to the formation of nanoparticles on the mycelia after accumulation at nuclei. Reducing sugars formed by some

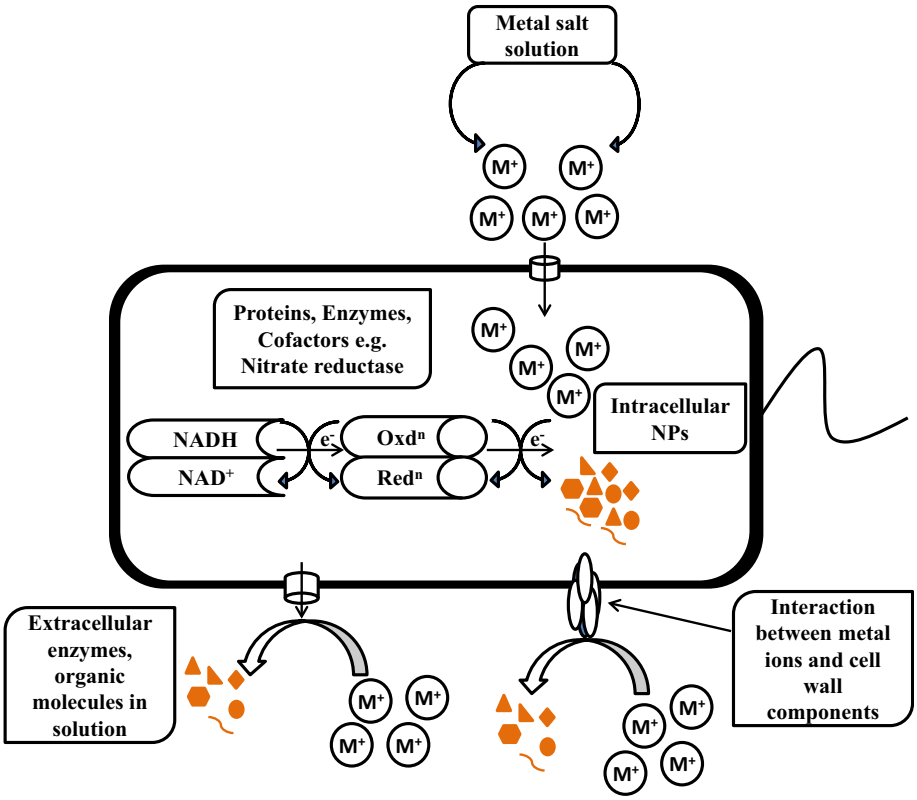

Fig. 2 Mechanism of nanoparticle synthesis by microorganisms

fungi were found responsible for synthesis of nanoparticles. Ahmad et al. (2003a) suggested the role of NADH-dependent reductase in nanoparticle synthesis. Nitrate reductase is apparently essential for metal ion reduction, but Salunkhe et al. (2011a) found that 72 h fungal culture of *Cochliobolus lunatus* was negative for nitrate reduction during silver resistance and AgNP formation. Their results indicated that other mechanisms for Ag reduction may be present. They suggested that the mechanism of AgNP synthesis was linked to cell wall polymer or electron shuttle quinones or both. The growth phase of microorganisms has an important role in nanoparticle biosynthesis. *Verticillium luteoalbum* cells harvested from different growth phase produced different numbers of particles (Gericke and Pinches 2006a, b). The cells obtained from the early exponential phase showed better ability to synthesize a number of nanoparticles than the cells from late exponential phase. Gericke and Pinches (2006a, b) gave a possible explanation for this phenomenon for gold nanoparticles that cells in early exponential phase of growth produce very high concentrations of enzymes and proteins that are actively involved in accumulation and reduction of the gold ions.

The synthesis mechanism of nanoparticles is not well understood yet. The provision of electrons is needed when the ions are converted to the corresponding elemental metals. The activities of microorganisms to reduce ions to their metallic particles may lead to generation of reducing agents. As heavy metallic ions are hazardous to microbes, the microbes will have to have protective mechanisms to resist toxicity of the metallic ions (Hallmann et al. 1997). The microbial cells need to trap the ions by some way. Electrostatic interaction and/or secretion of substances such as extracellular polymeric substances that can adhere to the ions are some of these mechanisms. Most of the bacteria have negative charge on cells (Albert et al. 1997; Manti et al. 2008). The electrostatic interactions are believed to happen between the positively charged ions and the negatively charged groups such as carboxylate groups on the cells. The secretion of adhesive materials as a result of their stickiness may possibly stabilize the ions in the cell. The ions are involved in the nutrient exchange and/or substance diffusion during the intracellular synthesis of nanoparticles. The microbial cells prevent damage by producing specific enzymes such as NADH-dependent reductase and electrons, which can reduce ions. The nuclei grow and thereby form nanoparticles intracellularly or extracellularly. Enzymes may be important in the whole process. The reduction reaction on the cell surface or inside the cells may be catalyzed by enzymes. Nanoparticle synthesis ability of most of the microorganisms has been correlated with a specific type of secreted enzyme(s), but the exact information about the different enzymes involved in nanoparticle synthesis is not fully established yet.

Size and shape control of nanoparticles

As compared to the bulk materials, their nanoforms possess some unique chemical, optical, and electronic properties. The properties of the nanoparticles change with size, shape, and monodispersity of the particles. Therefore, controlling these parameters is an important task during biosynthesis. The type of microorganism, growth medium, and synthesis conditions are important factors in controlled synthesis of nanoparticles (Holmes et al. 1995; Murali et al. 2003; Ahmad et al. 2003a; Gericke and Pinches 2006a, b; Husseiny et al. 2015). Fungi, yeast, and actinomycetes are found to be good for synthesis of uniform nanoparticles of controlled size (Murali et al. 2003; Ahmad et al. 2003b; Husseiny et al. 2015). After parametric optimization, Husseiny et al. (2015) found smallest particle size when *Fusarium oxysporum* was incubated for 72 h with 10^{-2} M silver nitrate (metal ion concentration) at 50 °C with 11 g wet biomass at pH 6 with fungal age 7 days. AgNPs produced were characterized by transmission electron microscopy (TEM) which revealed the formation of spherical, well-dispersed nanoparticles with size between 5 and 13 nm. Kathiresan et al. (2009) found that AgNP size increased with the increase of pH by *Penicillium fellutanum*. Change of Ag^{+} concentration was found to control the size and dispersion of particles using *Hormoconis resinae* (Varshney et al. 2009). The original precursor salt (e.g. silver nitrate or silver chloride) showed synthesis of different sized particles (Narges et al. 2009). Temperatures have effect on microbial activity and ion movement. The distinctive morphologies of AgNPs and size were found with change of temperature during synthesis using cyanobacteria (Maggy et al. 2007). Reaction time showed effect on particle sizes and monodispersity on nano-gold particle synthesis (Gericke and Pinches 2006b). Controlled particle size of AgNPs was achieved using irradiation of the mixture of *B. subtilis* cells and 1 mM silver ions (Narges et al. 2009). Precise controlling particle size and monodispersity using microbes are still not known. More extensive investigations on optimization of different parameters described are needed to achieve controlled synthesis. Extensive studies considering factors such as selection of specific strain of microbe, phase of growth, growth medium, synthesis conditions, pH, substrate concentrations, precursor salts, temperature, reaction time, irradiation, agitation, ultrasonication, and many different factors will need to be investigated and optimized to discover a reliable method of synthesizing particles with uniform shape and size.

Application of nanoparticles

Nanoparticles synthesized by different sources have been reported for various applications including antimicrobial, optics, biosensors, catalysis, and diagnosis (Sintubin et al. 2012; Borase et al. 2014). The applications of microbially synthesized nanoparticles are summarized below.

Antibacterial

Nanoparticles are coming up as new class of compounds as antibacterial. Microorganisms have developed resistance against many antibiotics. AgNPs are found to be good antiseptics in this regard. AgNPs have been investigated for activities against Gram-positive bacteria such as *Bacillus subtilis, Bacillus cereus, Enterococcus hirae, Staphylococcus aureus, Staphylococcus epidermidis*, and *Streptococcus pyogenes* (Nanda and Saravanan 2009; Saravanan et al. 2013; Manivasagan et al. 2013; Malarkodi et al. 2013; Sudha et al. 2013; Kulkarni et al. 2015; Kushwaha et al. 2015; Prabavathy et al. 2015; Vanaja et al. 2015; Sangappa and Thiagarajan 2015) and Gram-negative bacteria such as *Escherichia coli, Klebsiella planticola, Klebsiella pneumoniae, Proteus vulgaris, Pseudomonas aeruginosa, Pseudomonas* sp., *Salmonella typhi, Shigella flexneri*, and *Vibrio cholerae* (Nanda and Saravanan 2009; Saravanan et al. 2013; Manivasagan et al. 2013; Malarkodi et al. 2013; Sudha et al. 2013; Kulkarni et al. 2015; Kushwaha et al. 2015; Prabavathy et al. 2015; Vanaja et al. 2015). They are found to enhance antibacterial effect when used in combination with different antibiotics. *F. oxysporum* synthesized AgNPs integrated into textile fabrics were able to avoid or reduce survival of pathogenic bacteria like *Staphylococcus aureus* (Durán et al. 2007). Antibacterial activities of different nanoparticles have been shown in different studies by researchers (Nanda and Saravanan 2009; Nair et al. 2013; Malarkodi et al. 2013; Sudha et al. 2013; Vanaja et al. 2015; Sangappa and Thiagarajan 2015; Kulkarni et al. 2015; Kushwaha et al. 2015; Aziz et al. 2015). Vanaja et al. (2015) found that *E. coli* was most susceptible bacteria to the action of AgNPs with maximum zone of inhibition (11.53 ± 0.145 mm) compared to *K. planticola, Pseudomonas* sp, *B. subtilis*, and *B. cereus* (9.43 ± 0.219, 11.43 ± 0.067, 9.43 ± 0.219, and 11.47 ± 0.273 mm), respectively.

Antifungal activity

Antifungal activities of nanoparticles synthesized by microorganisms have been reported (Gajbhiye et al. 2009; Musarrat et al. 2010; Pereira et al. 2014). The biosynthesized nanoparticles were effective in combination with fluconazol (a triazole antifungal drug) with increase in diameter of inhibition zones and fold area against fungi *Phoma glomerata*, *P. herbarum*, *Fusarium semitectum*, *Trichoderma* sp., and *Candida albicans* (Gajbhiye et al. 2009). The antifungal activity of fluconazole increased significantly in presence of

AgNPs. The maximum antifungal activity was observed against *C. albicans* followed by *Trichoderma* sp. and *P. glomerata*. However, no enhancement of the antifungal activity was recorded in the cases of *F. semitectum* and *P. herbarum*. This was also shown through the assessment of increases in fold area of activity. It was observed that *C. albicans* had the highest increase in the fold area (3.69), while a much smaller increase in fold area (0.15) was observed for both *F. semitectum* and *P. herbarum*. *Amylomyces rouxii* synthesized AgNPs were active against fungi *F. oxysporum* and yeast *Candida albicans* (Musarrat et al. 2010). Antifungal susceptibility of the eight clinical strains of *T. rubrum* and the reference strain *T. rubrum* ATCC MYA-4438 were tested against three commercial antifungal drugs (terbinafine, itraconazole and fluconazole), and Chem-AgNPs and Bio-AgNPs produced by *P. chrysogenum* MUM 03.22 and *A. oryzae* MUM 97.19 (Pereira et al. 2014). The authors reported that the reference strain *T. rubrum* ATCC MYA-4438 was the most susceptible fungus against itraconazole, fluconazole, Chem-AgNPs, and Bio-AgNPs. In contrast, it was the less susceptible to terbinafine. Among the commercial antifungal drugs evaluated, terbinafine exhibited the lower minimum inhibitory concentration (MIC) values (0.063–0.25 μg/ml) for all clinical strains. Chem-AgNPs showed antifungal activity in the range from 0.25 to 2.5 μg/ml. Furthermore, Chem-AgNPs exhibited a stronger inhibitory effect against all *T. rubrum* strains evaluated, which MIC values were at least twofold higher than the MIC values of Bio-AgNPs. Bio-AgNPs produced by *P. chrysogenum* MUM 03.22 showed an antifungal activity in the range from 0.5 to 5.0 μg/ml. The Bio-AgNPs produced by that fungi exhibited higher antifungal activity than fluconazole, but lower activity than terbinafine, itraconazole, and Chem-AgNPs. In contrast, Bio-AgNPs produced by *A. oryzae* MUM 97.19 did not exhibit antifungal activity in concentrations up to 7.5 μg/ml. Regardless of the process used, Chem-AgNPs and Bio-AgNPs produced by *P. chrysogenum* MUM 03.22 (geometric mean of MIC values = 1.19 and 2.89 μg/ml, respectively) exhibited a stronger inhibiting activity than fluconazole (geometric mean of MIC values = 5.65 μg/ml).

Cytotoxicity

Cytotoxicity of different nanoparticles has been investigated in different studies (Syed et al. 2013; Kulkarni et al. 2015; Kumar et al. 2015). Monodispersed AuNPs produced by *Humicola* spp. were found to show cytotoxicity. The nanoparticles were conjugated with the anticancer drug doxorubicin for targeted drug delivery to liver (hepatic) cancer. Syed et al. (2013) assessed cytotoxicity of AgNPs against the cells (NIH3T3 mouse embryonic fibroblast cell line and MDA-MB-231 human breast carcinoma cell line) by treating with varying concentrations of AgNPs (50, 250, 500, and 1000 μg/ml) for 24 h. The authors did not find significant difference on cell viability at concentration of 50 μg/ml. The cell viability was reduced in a dose-dependent manner in both cell lines and the cytotoxicity of the nanoparticles was observed at concentrations of 250 μg/ml and higher in both cell lines. The cell viability was reduced by 20.83 % in the case of NIH3T3 and 42.18 % for MDA-MB-231 cell line at 1000 μg/ml concentration. Kulkarni et al. (2015) studied cell viability and metabolic activity using MTT assay by exposing MCF-7 cells to AgNPs at 0–30 μg concentrations for 24 h. The results of MTT assay showed a dose-dependent decrease in percent viability of the cells. The authors fitted cytotoxicity data to a sigmoidal curve, and used a four-parameter nonlinear logistic model to calculate the LD_{50} of nanomaterials that caused a 50 % inhibition in comparison to untreated controls, which was 7.9 μg/ml. Exposure to increasing concentrations of AgNPs showed a dose-dependent cytotoxicity on the cancer cell line. LD_{50} of AgNPs synthesized using *D. radiodurans* was reported to be 7–8 μg/ml, which suggests that these nanoparticles are effective at a lower concentration against MCF-7 human breast cancer cell line compared to AgNPs synthesized using other sources. The AgNPs in their studies were of small in size (average size of 16.82 nm). The cytotoxicity of nanoparticles is size dependent with smaller nanoparticles entering the cells more easily and thus are more efficient than larger ones. Therefore, AgNPs have promise for potential applications in cytotoxicity and anticancer activity.

Medical imaging

AgNPs synthesized by *Trichoderma viride* were demonstrated to be suitable for labeling and imaging (Sarkar et al. 2010). The cadmium telluride quantum dots associated with folic acid were utilized for in vitro imaging of cancer cells, and were recognized to have biocompatibility in a cytotoxicity assay (Bao et al. 2010a, b). The authors developed an efficient bacterial synthesis method to harvest cadmium telluride (CdTe) quantum dots (QDs) with tunable fluorescence emission using *E. coli* and yeast cells. Ultraviolet–visible, photoluminescence, X-ray diffraction, and TEM analysis confirmed the superior size-tunable optical properties, with fluorescence emission from 488 to 551 nm, and the good crystallinity of the as synthesized QDs. A surface protein capping layer was confirmed by hydrodynamic size, zeta potential, and Fourier transform infrared spectroscopy measurements, which could maintain the viability (92.9 %) of cells in an environment with a QD concentration as high as 2 μM. After functionalization with folic acid, the QDs were used to image cultured cervical cancer cells in vitro. Investigations of bacterial growth and

morphology and the biosynthesis of CdTe QDs in Luria–Bertani medium containing *E. coli*-secreted proteins showed that extracellular synthesis directly relied on the *E. coli*-secreted proteins. The authors suggested that the biosynthesized QDs may have great potential in broad bioimaging and bio-labeling applications.

Enhancing reaction rates

Shewanella oneidensis synthesized palladium nanoparticles were effective in dehalogenate polychlorinated biphenyl reduction (De Windt et al. 2005). The authors carried out microbial reduction of soluble Pd^{2+} by cells of *Shewanella oneidensis* MR-1 and of an autoaggregating mutant, which resulted in precipitation of palladium Pd^0 nanoparticles on the cell wall and inside the periplasmic space (bioPd). As a result of biosorption and subsequent bioreduction of Pd^{2+} with H_2, formate, lactate, pyruvate, or ethanol as electron donors, recoveries higher than 90 % of Pd^0 associated with biomass could be obtained. The bioPd nanoparticles thus obtained had the ability to reductively dehalogenate polychlorinated biphenyl (PCB) congeners in aqueous and sediment matrices. Bioreduction was observed in assays with concentrations up to 1000 mg Pd^{2+}/l with depletion of soluble Pd^{2+} of 77.4 % and higher. More than 90 % decrease of PCB 21 (2,3,4-chloro biphenyl) coupled to formation of its dechlorination products PCB 5 (2,3-chloro biphenyl) and PCB 1 (2-chloro biphenyl) was obtained at a concentration of 1 mg/l within 5 h at 28 °C. Bioreductive precipitation of bioPd by *S. oneidensis* cells mixed with sediment samples contaminated with a mixture of PCB congeners, resulted in dechlorination of both highly and lightly chlorinated PCB congeners adsorbed to the contaminated sediment matrix within 48 h at 28 °C. Fifty milligrams per litre of bioPd resulted in a catalytic activity that was comparable to 500 mg/l commercial Pd^0 powder. The high reactivity of 50 mg/l bioPd in the soil suspension was reflected in the reduction of the sum of seven most toxic PCBs to 27 % of their initial concentration. Magnetic Fe_3O_4 nanoparticle coated microbial cells of *Pseudomonas delafieldii* were good to accomplish desulfurization of dibenzothiophene (Shan et al. 2005). The authors coated microbial cells of *Pseudomonas delafieldii* with magnetic Fe_3O_4 nanoparticles and then immobilized by external application of a magnetic field. Magnetic Fe_3O_4 nanoparticles were synthesized by a co-precipitation method followed by modification with ammonium oleate. The surface-modified Fe_3O_4 nanoparticles were monodispersed in an aqueous solution and did not precipitate in over 18 months. Using TEM, the average size of the magnetic particles was found to be in the range from 10 to 15 nm. TEM cross section analysis of the cells showed further that the Fe_3O_4 nanoparticles were for the most part strongly absorbed by the surfaces of the cells and coated the cells. The coated cells had distinct superparamagnetic properties. The coated cells not only had the same desulfurizing activity as free cells but could also be reused more than five times. Compared to cells immobilized on Celite, the cells coated with Fe_3O_4 nanoparticles had greater desulfurizing activity and operational stability. Integrated nanosized zero-valent iron (NZVI) and microbial process demonstrated great advantage compared to solo NZVI and solo microbial process application on nitrate reduction (Choe et al. 2000). Nanoscale iron particles with a diameter in the range of 1–100 nm, which were characterized by the large BET specific surface area to mass ratio (31.4 m^2/g), removed mostly 50, 100, 200, and 400 mg/l of nitrate within a period of 30 min with little intermediates. Compared with microscale (75–150 μm) Fe^0, endproduct was not ammonia but N_2 gas. Kinetic analysis from batch studies revealed that the denitrification reaction with nanoscale Fe^0 appeared to be a pseudo first-order with respect to substrate and the observed reaction rate constant (k_{obs}) varied with iron content at a relatively low degree of application. The effects of mixing intensity (rpm) on the denitrification rate suggest that the denitrification appears to be coupled with oxidative dissolution of iron through a largely mass transport-limited surface reaction (<40 rpm).

Catalytic activity

Nanoparticles have been tested for catalytic activities (Shi et al. 2015; Roy et al. 2014; Aziz et al. 2015). Shi et al. (2015) synthesized of AuNPs using intracellular protein extract (IPE) of *Pycnoporus sanguineus*. The catalysis results showed that 0.019 mg of AuNPs with average size of 6.07 nm could catalyze the complete degradation of 12.5 μmol of 4-nitroaniline within 6 min and the degradation rate increased drastically with the addition of AuNPs. Roy et al. (2014) used AgNPs synthesized by yeast (*S. cerevisiae*) extract for photocatalytic activity under solar irradiation. These biosynthesized nanoparticles showed efficacy in degrading the organic dye, methylene blue within a few hours of exposure. Aziz et al. (2015) evaluated the photocatalytic activity by separately adding 10 mg of biosynthesized AgNPs, commercial AgNPs (8 nm diameter, Sigma-Aldrich), and bulk Ag powder (Sigma-Aldrich) to 100 ml of aqueous solution containing 5 mg/l of methylene blue (MB) dye. The solution was continuously stirred in the dark for 1 h to ensure adsorption/desorption equilibrium between the AgNPs and the MB solution. Subsequently, the suspension was irradiated using a 500 W xenon lamp. The suspensions were taken from the reactor and centrifuged at 10 min intervals, and their absorption spectra were recorded on a UV–vis spectrophotometer using deionized water as a reference. In the absence of AgNPs, the MB dye concentration remains almost unchanged after 30 min under visible

light irradiation, indicating that MB does not self-degrade under these conditions. The kinetics of MB degradation using different catalysts was found to follow a pseudo-first-order reaction and the biosynthesized AgNPs display superior photocatalytic activity toward the degradation of MB as compared to the commercially procured AgNPs and bulk silver powder. The authors reported that the superior activity may be due to their inherent porosity and therefore larger surface area.

Biosensor

Au–Ag alloy nanoparticles synthesized by yeast were effective for sensing vanillin (Zheng et al. 2010a). The authors biosynthesized Au–Ag alloy nanoparticles by yeast cells and applied to fabricate a sensitive electrochemical vanillin sensor. Fluorescence microscopic and TEM characterizations indicated that the Au–Ag alloy nanoparticles were mainly synthesized via an extracellular approach and generally existed in the form of irregular polygonal nanoparticles. Electrochemical investigations revealed that the vanillin sensor based on Au–Ag alloy nanoparticles modified glassy carbon electrode was able to enhance the electrochemical response of vanillin for at least five times. Under optimal working conditions, the oxidation peak current of vanillin at the sensor linearly increased with its concentration in the range of 0.2–50 μM with a low detection limit of 40 nM. This vanillin sensor was successfully applied to the determination of vanillin from vanilla bean and vanilla tea sample, suggesting that it may have practical applications in vanillin monitoring system. Biosensing of glucose oxidase was successful using AuNP-based biosensors (Zheng et al. 2010b). The authors used a facile green biosynthesis method to prepare AuNPs of various core sizes using a natural biomaterial, eggshell membrane (ESM) at ambient conditions. In situ synthesis of AuNPs-immobilized ESM was conducted in a simple manner by immersing ESM in a pH 6.0 aqueous solution of $HAuCl_4$ without adding any reductant. The formation of AuNPs on ESM protein fibers was attributed to the reduction of Au^{3+} ions to Au^0 by the aldehyde moieties of the natural ESM fibers. Energy dispersive X-ray spectroscopy, scanning electron microscopy, X-ray photoelectron spectroscopy, and X-ray powder diffraction unambiguously identified the presence of AuNPs on ESM. The effect of pH on the in situ synthesis of AuNPs on ESM was investigated in detail. The pH of the gold precursor ($HAuCl_4$) solution can influence the formation rate, dispersion and size of AuNPs on ESM. At pH $\leq$3.0 and $\geq$7.0, no AuNPs were observed on ESM while small AuNPs were homogeneously dispersed on ESM at pH 4.0–6.0. The optimal pH for AuNP formation on ESM was 6.0. AuNPs/ESMs were used to immobilize glucose oxidase for glucose biosensing. AuNPs on ESM can increase the enzyme activity of glucose oxidase. The linear response range of the glucose biosensor was 20 μM to 0.80 mM glucose with a detection limit of 17 μM. The biosensor was successfully applied to determine the glucose content in commercial glucose injections.

Mosquito larvicidal

Salunkhe et al. (2011b) used *Cochliobolus lunatus* mycosynthesized AgNPs against larvae of vectors *Aedes aegypti* and *Anopheles stephensi*. The efficacy of mycosynthesized AgNPs at all the tested concentrations (10, 5, 2.5, 1.25, 0.625, and 0.3125 ppm) against second, third, and fourth instar larvae of *A. aegypti* (LC_{50} 1.29, 1.48, and 1.58; LC_{90} 3.08, 3.33, and 3.41 ppm) and against *A. stephensi* (LC_{50} 1.17, 1.30, and 1.41; LC_{90} 2.99, 3.13, and 3.29 ppm) was observed, respectively. The mortality rates were positively correlated with the concentration of AgNPs. Significant ($P < 0.05$) changes in the larval mortality were also recorded between the period of exposure against fourth instar larvae of *A. aegypti* and *A. stephensi*. The possible larvicidal activity may be due to penetration of nanoparticles through membrane.

Current status and future prospects

There is great progress in microorganisms based synthesis of nanoparticles. Still, a lot of research needs to be done for improvement in processes of nanoparticle biosynthesis and applications. The process of nanoparticle synthesis by microorganisms is relatively slow as compared to physical and chemical approaches. Use of pathogenic microbes is not advisable for the nanoparticle synthesis as it can limit the use of produced particles for applications involving human or animal contacts. The produced nanoparticles should be non-toxic to living organisms and environment so investigation of toxicity using model organisms is vital. Stability of nanoparticles produced by microbes can be cause of concern. The investigation of microbes with ability to produce stable nanoparticles can be useful for developing reliable production processes. Some microbes can produce nanoparticles intracellularly with good features. However, obtaining such intracellular particles for applications may not be economical. The microbes with ability to synthesize nanoparticles extracellularly can be advantageous in this regard. The understanding on mechanism of microbial synthesis of nanoparticles can help to devise strategy for tailor made synthesis of nanoparticles according to desired shape and size. The rate of nanoparticle synthesis can differ with different species of microbes. Identification and characterization of microbial species with ability to synthesize nanoparticles at rapid rate are valuable. The growth medium,

synthesis conditions, substrate concentrations, pH, source compound of target nanoparticle, temperature, reaction time, irradiation, and agitation can have impact on rate of synthesis and control of size, shape, and uniformity of nanoparticles. Rapid synthesis of nanoparticles can be accomplished by choice of most suitable microbial strain and optimization of different conditions required for microbial synthesis. Scaling up of microbe based nanoparticle production processes from laboratory scale to large scale production processes can be important for increasing availability of nanoparticles for variety of applications. Therefore, a large scale screening of non-pathogenic microbes with ability to synthesize stable nanoparticles at rapid rate and development of large scale production processes are urgently needed.

Conclusion

In the present review, the synthesis of nanoparticles by microorganisms including probable biosynthesis mechanism, conditions for size/shape control, reaction rate enhancement, and various applications of nanoparticles, limitations and future prospects were briefly discussed. Different types of microorganisms such as fungi, yeast, bacteria, and actinomycetes have abilities to produce diverse nanoparticles such as Ag, Au, lead, Ag_2O, zirconia, CdS, barium titanate, CdSe quantum dots, silica, titanium, nickel oxide, iron, iron oxide (Fe_2O_3), copper, MnO_2, ZnO, iron phosphate ($FePO_4$), palladium, iron sulfide (FeS), siderite ($FeCO_3$), cadmium sulfide, TiO_2, titanium, magnetite (Fe_3O_4), greigite (Fe_3S_4), zinc sulfide, and Pt. The size of nanoparticles can range from 1 to 500 nm and shapes were mostly spherical, but other shapes such as pseudo-spherical, rod, triangular, truncated triangular, square, pentagonal, hexagonal, nanoplate, fine-grained crystal, and nanowires morphologies have also been observed. The microbially synthesized nanoparticles display antimicrobial, antibacterial, anti-biofilm, anti-biofouling, antiviral, anticancer, and photocatalytic properties. Considering the usefulness of nanoparticles for these various applications, they have promise to be used in food, cosmetic, or pharmaceutical field.

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References

Agnihotri M, Joshi S, Kumar AR, Zinjarde S, Kulkarni S (2009) Biosynthesis of gold nanoparticles by the tropical marine yeast *Yarrowia lipolytica* NCIM 3589. Mater Lett 63(15):1231–1234

Ahmad A, Mukherjee P, Mandal D, Senapati S, Khan MI, Kumar R, Sastry M (2002) Enzyme mediated extracellular synthesis of CdS nanoparticles by the fungus, *Fusarium oxysporum*. J Am Chem Soc 124(41):12108–12109

Ahmad A, Mukherjee P, Senapati S, Mandal D, Khan MI, Kumar R, Sastry M (2003a) Extracellular biosynthesis of silver nanoparticles using the fungus *Fusarium oxysporum*. Colloid Surface B 28:313–318

Ahmad A, Satyajyoti S, Khan MI, Rajiv K, Ramani R, Srinivas V, Murali S (2003b) Intracellular synthesis of gold nanoparticles by a novel alkalotolerant actinomycete, *Rhodococcus* species. Nanotechnology 14:824–828

Ahmad A, Senapati S, Khan MI, Kumar R, Sastry M (2003c) Extracellular biosynthesis of monodisperse gold nanoparticles by a novel extremophilic actinomycete, *Thermomonospora* sp. Langmuir 19:3550–3553

Albert VDW, Marcel M, Willem N, Alexander JBZ, Johannes L (1997) Electrokinetic potential of bacterial cells. Langmuir 13:165–171

Apte M, Sambre D, Gaikawad S, Joshi S, Bankar A, Kumar AR, Zinjarde S (2013) Psychrotrophic yeast *Yarrowia lipolytica* NCYC 789 mediates the synthesis of antimicrobial silver nanoparticles via cell-associated melanin. AMB Express 3(1):32

Azim A, Davood Z, Ali F, Mohammad RM, Dariush N, Shahram T, Majid M, Nasim B (2009) Synthesis and characterization of gold nanoparticles by tryptophane. Am J Appl Sci 6:691–695

Aziz N, Faraz M, Pandey R, Shakir M, Fatma T, Varma A, Prasad R et al (2015) Facile algae-derived route to biogenic silver nanoparticles: synthesis, antibacterial, and photocatalytic properties. Langmuir 31(42):11605–11612

Bai HJ, Zhang ZM, Gong J (2006) Biological synthesis of semiconductor zinc sulfide nanoparticles by immobilized *Rhodobacter sphaeroides*. Biotechnol Lett 28(14):1135–1139

Bai HJ, Zhang ZM, Guo Y, Yang GE (2009) Biosynthesis of cadmium sulfide nanoparticles by photosynthetic bacteria *Rhodopseudomonas palustris*. Colloid Surface B 70(1):142–146

Bansal V, Rautaray D, Ahmad A, Sastry M (2004) Biosynthesis of zirconia nanoparticles using the fungus *Fusarium oxysporum*. J Mater Chem 14(22):3303–3305

Bansal V, Rautaray D, Bharde A, Ahire K, Sanyal A, Ahmad A, Sastry M (2005) Fungus-mediated biosynthesis of silica and titania particles. J Mater Chem 15(26):2583–2589

Bansal V, Poddar P, Ahmad A, Sastry M (2006) Room-temperature biosynthesis of ferroelectric barium titanate nanoparticles. J Am Chem Soc 128:11958–11963

Banu A, Rathod V (2011) Synthesis and characterization of silver nanoparticles by *Rhizopus stolonier*. Int J Biomed Adv Res 2(5):148–158

Bao H, Hao N, Yang Y, Zhao D (2010a) Biosynthesis of biocompatible cadmium telluride quantum dots using yeast cells. Nano Res 3(7):481–489

Bao H, Lu Z, Cui X, Qiao Y, Guo J, Anderson JM, Li CM (2010b) Extracellular microbial synthesis of biocompatible CdTe quantum dots. Acta Biomater 6(9):3534–3541

Bhainsa KC, D'souza SF (2006) Extracellular biosynthesis of silver nanoparticles using the fungus *Aspergillus fumigatus*. Colloid Surface B 47(2):160–164

Bharde A, Rautaray D, Bansal V, Ahmad A, Sarkar I, Yusuf SM, Sastry M et al (2006) Extracellular biosynthesis of magnetite using fungi. Small 2(1):135–141

Bhimba BV, Gurung S, Nandhini SU (2015) Silver nanoparticles synthesized from marine fungi *Aspergillus oryzae*. Int J Chem Tech Res 7(1):68–72

Blackmore RP (1982) Magnetotactic bacteria. Annu Rev Microbiol 36:217–238

Borase HP, Salunke BK, Salunkhe RB, Patil CD, Hallsworth JE, Kim BS, Patil SV (2014) Plant extract: a promising biomatrix for ecofriendly, controlled synthesis of silver nanoparticles. Appl Biochem Biotech 173(1):1–29

Bruins RM, Kapil S, Oehme SW (2000) Microbial resistance to metals in the environment. Ecotox Environ Safe 45:198–207

Castro L, Blázquez ML, Muñoz JA, González F, Ballester A (2013) Biological synthesis of metallic nanoparticles using algae. IET Nanobiotechnol 7(3):109–116

Choe S, Chang YY, Hwang KY, Khim J (2000) Kinetics of reductive denitrification by nanoscale zero-valent iron. Chemosphere 41:1307–1311

Correa-Llantén DN, Muñoz-Ibacache SA, Castro ME, Muñoz PA, Blamey JM (2013) Gold nanoparticles synthesized by *Geobacillus* sp. strain ID17 a thermophilic bacterium isolated from Deception Island, Antarctica. Microb Cell Fact 12(1):1–6

Dameron CT, Reese RN, Mehra RK, Kortan AR, Carroll PJ, Steigerwald ML, Winge DR et al (1989) Biosynthesis of cadmium sulphide quantum semiconductor crystallites. Nature 338:596–597

De Windt W, Peter A, Willy V (2005) Bioreductive deposition of palladium (0) nanoparticles on *Shewanella oneidensis* with catalytic activity towards reductive dechlorination of polychlorinated biphenyls. Environ Microb 7:314–325

Dehnad A, Hamedi J, Derakhshan-Khadivi F, Abusov R (2015) Green synthesis of gold nanoparticles by a metal resistant isolated from gold mine. IEEE Trans Nanobiosci 14(4):393–396

Delattre C, Pierre G, Gardarin C, Traikia M, Elboutachfaiti R, Isogai A, Michaud P (2015) Antioxidant activities of a polyglucuronic acid sodium salt obtained from TEMPO-mediated oxidation of xanthan. Carbohyd Polym 116:34–41

Devi LS, Joshi SR (2015) Ultrastructures of silver nanoparticles biosynthesized using endophytic fungi. J Microsc Ultrastruct 3(1):29–37

Dhanasekar NN, Rahul G, Narayanan KB, Raman G, Sakthivel N (2015) Green chemistry approach for the synthesis of gold nanoparticles using the fungus *Alternaria* sp. J Microbiol Biotechnol 25(7):1129–1135

Durán N, Marcato PD, De Souza GI, Alves OL, Esposito E (2007) Antibacterial effect of silver nanoparticles produced by fungal process on textile fabrics and their effluent treatment. J Biomed Nanotechnol 3(2):203–208

Elbeshehy EK, Elazzazy AM, Aggelis G (2015) Silver nanoparticles synthesis mediated by new isolates of *Bacillus* spp., nanoparticle characterization and their activity against Bean Yellow Mosaic Virus and human pathogens. Front Microbiol 6:453

Elboutachfaiti R, Delattre C, Petit E, Michaud P (2011) Polyglucuronic acids: structures, functions and degrading enzymes. Carbohyd Polym 84(1):1–13

Elchinger PH, Delattre C, Faure S, Roy O, Badel S, Bernardi T, Taillefumier C, Michaud P (2015) Immobilization of proteases on chitosan for the development of films with anti-biofilm properties. Int J Biol Macromol 72:1063–1068

Gajbhiye M, Kesharwani J, Ingle A, Gade A, Rai M (2009) Fungus-mediated synthesis of silver nanoparticles and their activity against pathogenic fungi in combination with fluconazole. Nanomedicine 5(4):382–386

Gericke M, Pinches A (2006a) Biological synthesis of metal nanoparticles. Hydrometallurgy 83:132–140

Gericke M, Pinches A (2006b) Microbial production of gold nanoparticles. Gold Bull 39:22–28

Ghazwani AA (2015) Biosynthesis of silver nanoparticles by *Aspergillus niger, Fusarium oxysporum* and *Alternaria solani*. Afr J Biotechnol 14(26):2170–2174

Hallmann J, Quadt-Hallmann A, Mahaffee WF, Kloepper JW (1997) Bacterial endophytes in agricultural crops. Can J Microbiol 43:895–914

Hassan AA, Oraby NH, El-Dahshan EME, Ali MA (2015) Antimicrobial potential of iron oxide nanoparticles in control of some causes of microbial skin affection in cattle. Eur J Acad Essays 2(6):20–31

He S, Zhang Y, Guo Z, Gu N (2008) Biological synthesis of gold nanowires using extract of *Rhodopseudomonas capsulata*. Biotechnol Prog 24(2):476–480

He W, Zhou W, Wang Y, Zhang X, Zhao H, Li Z, Yan S (2009) Biomineralization of iron phosphate nanoparticles in yeast cells. Mat Sci Eng C 29(4):1348–1350

He FJ, Li ZH, Gao F, Yang Z (2013) Extracellular biosynthesis of Ag nanoparticles by commercial baker's yeast. Adv Mat Res 785:370–373

Holmes JD, Smith PR, Evans-Gowing R, Richardson DJ, Russell DA, Sodeau JR (1995) Energy-dispersive X-ray analysis of the extracellular cadmium sulfide crystallites of *Klebsiella aerogenes*. Arch Microbiol 163(2):143–147

Husseiny MI, El-Aziz MA, Badr Y, Mahmoud MA (2007) Biosynthesis of gold nanoparticles using *Pseudomonas aeruginosa*. Spectrochim Acta A 67:1003–1006

Husseiny SM, Salah TA, Anter HA (2015) Biosynthesis of size controlled silver nanoparticles by *Fusarium oxysporum*, their antibacterial and antitumor activities. Beni-Suef Univ J Basic Appl Sci 4(3):225–231

Jha AK, Prasad K, Kulkarni AR (2008) Yeast mediated synthesis of silver nanoparticles. Int J Nanosci Nanotechnol 4(1):17–22

Jha AK, Prasad K, Kulkarni AR (2009) Synthesis of TiO_2 nanoparticles using microorganisms. Colloid Surface B 71(2):226–229

Joerger R, Klaus T, Granqvist CG (2000) Biologically produced silver-carbon composite materials for optically functional thin film coatings. Adv Mater 12:407–409

Kathiresan K, Manivannan S, Nabeel MA, Dhivya B (2009) Studies on silver nanoparticles synthesized by a marine fungus, *Penicillium fellutanum* isolated from coastal mangrove sediment. Colloid Surface B 71:133–137

Kim Y, Lee Y, Roh Y (2015) Microbial synthesis of iron sulfide (FeS) and iron carbonate ($FeCO_3$) nanoparticles. J Nanosci Nanotechnol 15(8):5794–5797

Klaus T, Joerger R, Olsson E, Granqvist CG (2001) Bacteria as workers in the living factory: metal-accumulating bacteria and their potential for materials science. Trends Biotechnol 19:15–20

Kollár R, Reinhold BB, Petráková E, Yeh HJ, Ashwell G, Drgonová J, Kapteyn JC, Klis FM, Cabib E (1997) Architecture of the yeast cell wall $\beta(1 \rightarrow 6)$-glucan interconnects mannoprotein, $\beta(1 \rightarrow 3)$-glucan, and chitin. J Biol Chem 272:17762–17775

Konishi Y, Ohno K, Saitoh N, Nomura T, Nagamine S, Hishida H, Uruga T et al (2007) Bioreductive deposition of platinum nanoparticles on the bacterium *Shewanella algae*. J Biotechnol 128(3):648–653

Kowshik M, Deshmukh N, Vogel W, Urban J, Kulkarni SK, Paknikar KM (2002) Microbial synthesis of semiconductor CdS nanoparticles, their characterization, and their use in the fabrication of an ideal diode. Biotechnol Bioeng 78(5):583–588

Kulkarni RR, Shaiwale NS, Deobagkar DN, Deobagkar DD (2015) Synthesis and extracellular accumulation of silver nanoparticles by employing radiation-resistant *Deinococcus radiodurans*, their characterization, and determination of bioactivity. Int J Nanomed 10:963

Kumar SA, Abyaneh MK, Gosavi SW, Kulkarni SK, Pasricha R, Ahmad A, Khan MI (2007a) Nitrate reductase-mediated synthesis of silver nanoparticles from $AgNO_3$. Biotechnol Lett 29:439–445

Kumar SA, Ayoobul AA, Absar A, Khan MI (2007b) Extracellular biosynthesis of CdSe quantum dots by the fungus, *Fusarium oxysporum*. J Biomed Nanotechnol 3(2):190–194

Kumar SA, Peter YA, Nadeau JL (2008) Facile biosynthesis, separation and conjugation of gold nanoparticles to doxorubicin. Nanotechnology 19:495101

Kumar CG, Poornachandra Y, Chandrasekhar C (2015) Green synthesis of bacterial mediated anti-proliferative gold nanoparticles: inducing mitotic arrest (G2/M phase) and apoptosis (intrinsic pathway). Nanoscale 7(44):18738–18750

Kushwaha A, Singh VK, Bhartariya J, Singh P, Yasmeen K (2015) Isolation and identification of *E. coli* bacteria for the synthesis of silver nanoparticles: characterization of the particles and study of antibacterial activity. Eur J Exp Biol 5(1):65–70

Lee SH, Salunke BK, Kim BS (2014) Sucrose density gradient centrifugation separation of gold and silver nanoparticles synthesized using *Magnolia kobus* plant leaf extracts. Biotechnol Bioproc E 19(1):169–174

Lengke MF, Fleet ME, Southam G (2006a) Morphology of gold nanoparticles synthesized by filamentous cyanobacteria from gold (I)-thiosulfate and gold (III)-chloride complexes. Langmuir 22(6):2780–2787

Lengke MF, Ravel B, Fleet ME, Wanger G, Gordon RA, Southam G (2006b) Mechanisms of gold bioaccumulation by filamentous cyanobacteria from gold (III)-chloride complex. Environ Sci Technol 40(20):6304–6309

Lengke MF, Fleet ME, Southam G (2007) Synthesis of palladium nanoparticles by reaction of filamentous cyanobacterial biomass with a palladium (II) chloride complex. Langmuir 23(17):8982–8987

Lipke PN, Ovalle R (1998) Cell wall architecture in yeast: new structure and new challenges. J Bacteriol 180:3735–3740

Lovley DR, Stolz JF, Nord GL, Phillips EJ (1987) Anaerobic production of magnetite by a dissimilatory iron-reducing microorganism. Nature 330(6145):252–254

Maggy FL, Michael EF, Gordon S (2007) Synthesis of palladium nanoparticles by reaction of Filamentous cyanobacterial biomass with a palladium(II) chloride complex. Langmuir 23:8982–8987

Malarkodi C, Rajeshkumar S, Paulkumar K, Vanaja M, Jobitha GDG, Annadurai G (2013) Bactericidal activity of bio mediated silver nanoparticles synthesized by *Serratia nematodiphila*. Drug Invention Today 5(2):119–125

Manivasagan P, Venkatesan J, Senthilkumar K, Sivakumar K, Kim SK (2013) Biosynthesis, antimicrobial and cytotoxic effect of silver nanoparticles using a novel *Nocardiopsis* sp. MBRC-1. BioMed Res Int 2013:287638

Mann S (1996) Biomimetic materials chemistry. Wiley-VCH, New York

Mann S (2001) Biomineralization: principles and concepts in bioinorganic materials chemistry. Oxford University Press, Oxford

Manti A, Boi P, Falcioni T, Canonico B, Ventura A, Sisti D, Pianetti A, Balsamo M, Papa S (2008) Bacterial cell monitoring in wastewater treatment plants by flow cytometry. Water Environ Res 80:346–354

Mati-Baouche N, Elchinger PH, de Baynast H, Pierre G, Delattre C, Michaud P (2014) Chitosan as an adhesive. Eur Polym J 60:198–212

Mazumdar H, Haloi N (2011) A study on biosynthesis of iron nanoparticles by *Pleurotus* sp. J Microbiol Biotechnol Res 1(3):39–49

Mie R, Samsudin MW, Din LB, Ahmad A, Ibrahim N, Adnan SNA (2014) Synthesis of silver nanoparticles with antibacterial activity using the lichen *Parmotrema praesorediosum*. Int J Nanomed 9:121–127

Mithila A, Swanand J, Ameeta RK, Smita Z, Sulabha K (2009) Biosynthesis of gold nanoparticles by the tropical marine yeast *Yarrowia lipolytica* NCIM 3589. Mater Lett 63:1231–1234

Mohanpuria P, Rana NK, Yadav SK (2008) Biosynthesis of nanoparticles: technological concepts and future applications. J Nanopart Res 10(3):507–517

Mokhtari N, Daneshpajouh S, Seyedbagheri S, Atashdehghan R, Abdi K, Sarkar S, Shahverdi AR et al (2009) Biological synthesis of very small silver nanoparticles by culture supernatant of *Klebsiella pneumonia*: the effects of visible-light irradiation and the liquid mixing process. Mat Res Bull 44(6):1415–1421

Mourato A, Gadanho M, Lino AR, Tenreiro R (2011) Biosynthesis of crystalline silver and gold nanoparticles by extremophilic yeasts. Bioinorg Chem Appl 2011:546074

Mukherjee P, Ahmad A, Mandal D, Senapati S, Sainkar SR, Khan MI, Sastry M et al (2001a) Bioreduction of $AuCl^{4-}$ ions by the fungus, *Verticillium* sp. and surface trapping of the gold nanoparticles formed. Angew Chem Inter Edit 40(19):3585–3588

Mukherjee P, Ahmad A, Mandal D, Senapati S, Sainkar SR, Khan MI, Sastry M et al (2001b) Fungus-mediated synthesis of silver nanoparticles and their immobilization in the mycelial matrix: a novel biological approach to nanoparticle synthesis. Nano Lett 1(10):515–519

Mukherjee P, Senapati S, Mandal D, Ahmad A, Khan MI, Kumar R, Sastry M (2002) Extracellular synthesis of gold nanoparticles by the fungus *Fusarium oxysporum*. ChemBioChem 3(5):461–463

Murali S, Ahmad A, Khan MI, Rajiv K (2003) Biosynthesis of metal nanoparticles using fungi and actinomycete. Curr Sci 85:162–170

Musarrat J, Dwivedi S, Singh BR, Al-Khedhairy AA, Azam A, Naqvi A (2010) Production of antimicrobial silver nanoparticles in water extracts of the fungus *Amylomyces rouxii* strain KSU-09. Bioresource Technol 101(22):8772–8776

Nair V, Sambre D, Joshi S, Bankar A, Ravi Kumar A, Zinjarde S (2013) Yeast-derived melanin mediated synthesis of gold nanoparticles. J Bionanoscience 7(2):159–168

Nanda A, Saravanan M (2009) Biosynthesis of silver nanoparticles from *Staphylococcus aureus* and its antimicrobial activity against MRSA and MRSE. Nanomed Nanotechnol Biol Med 5(4):452–456

Narges M, Shahram D, Seyedali S, Reza A, Khosro A, Saeed S, Sara M, Hamid RS, Ahmad RS (2009) Biological synthesis of very small silver nanoparticles by culture supernatant of *Klebsiella pneumonia*: the effects of visible-light irradiation and the liquid mixing process. Mater Res Bull 44:1415–1421

Pavani KV, Kumar NS, Sangameswaran BB (2012) Synthesis of lead nanoparticles by *Aspergillus* species. Pol J Microbiol 61(1):61–63

Pavani T, Rao KV, Chakra CS, Prabhu (2015) Microbial synthesis of ZnO nanoparticles by Yeast: *Sacchromyces cerevisiae*. J Nanosci Nanoeng Appl 5(2):1–5

Pereira L, Dias N, Carvalho J, Fernandes S, Santos C, Lima N (2014) Synthesis, characterization and antifungal activity of chemically and fungal-produced silver nanoparticles against Trichophyton rubrum. J Appl Microbiol 117(6):1601–1613

Pimprikar PS, Joshi SS, Kumar AR, Zinjarde SS, Kulkarni SK (2009) Influence of biomass and gold salt concentration on nanoparticle synthesis by the tropical marine yeast *Yarrowia lipolytica* NCIM 3589. Colloid Surface B 74(1):309–316

Polte J (2015) Fundamental growth principles of colloidal metal nanoparticles—a new perspective. CrystEngComm 17(36): 6809–6830

Prabavathy D, Niveditha R, Vaishnavie R (2015) Antimicrobial activity of silver nanoparticles synthesized by endophytic *Aspergillus* sp isolated from *Justicia beddomei*. J Chem Pharma Res 7(3):784–788

Prasad K, Jha AK, Kulkarni AR (2007) *Lactobacillus* assisted synthesis of titanium nanoparticles. Nanoscale Res Lett 2(5):248–250

Priyabrata M, Ahmad A, Deendayal M, Satyajyoti S, Sudhakar RS, Mohammad IK, Renu P, Ajaykumar PV, Mansoor A, Rajiv K, Murali S (2001) Fungus mediated synthesis of silver nanoparticles and their immobilization in the mycelial matrix: a novel biological approach to nanoparticle synthesis. Nano Lett 1:515–519

Pum D, Sleytr UB (1999) The application of bacterial S-layers in molecular nanotechnology. Trends Biotechnol 17:8–12

Roh Y, Lauf RJ, McMillan AD, Zhang C, Rawn CJ, Bai J, Phelps TJ (2001) Microbial synthesis and the characterization of metal-substituted magnetites. Solid State Commun 118:529–534

Roy K, Sarkar CK, Ghosh CK (2014) Photocatalytic activity of biogenic silver nanoparticles synthesized using yeast (*Saccharomyces cerevisiae*) extract. Appl Nanosci 5(8):953–959

Saifuddin N, Wong CW, Yasumira AA (2009) Rapid biosynthesis of silver nanoparticles using culture supernatant of bacteria with microwave irradiation. Eur J Chem 6(1):61–70

Salunke BK, Sawant SS, Lee SI, Kim BS (2015) Comparative study of MnO_2 nanoparticle synthesis by marine bacterium *Saccharophagus degradans* and yeast *Saccharomyces cerevisiae*. Appl Microbiol Biotechnol 99(13):5419–5427

Salunkhe RB, Patil SV, Patil CD, Salunke BK (2011a) Larvicidal potential of silver nanoparticles synthesized using fungus *Cochliobolus lunatus* against *Aedes aegypti* (Linnaeus, 1762) and *Anopheles stephensi* Liston (Diptera; Culicidae). Parasitol Res 109(3):823–831

Salunkhe RB, Patil SV, Salunke BK, Patil CD, Sonawane AM (2011b) Studies on silver accumulation and nanoparticle synthesis by *Cochliobolus lunatus*. Appl Biochem Biotechnol 165(1):221–234

Salvadori MR, Ando RA, do Nascimento CAO, Corrêa B (2014) Intracellular biosynthesis and removal of copper nanoparticles by dead biomass of yeast isolated from the wastewater of a mine in the Brazilian Amazonia. PLoS ONE 9(1):e87968

Salvadori MR, Ando RA, Nascimento CAO, Corrêa B (2015) Extra and intracellular synthesis of nickel oxide nanoparticles mediated by dead fungal biomass. PLoS ONE 10(6):e0129799

Sangappa M, Thiagarajan P (2015) Combating drug resistant pathogenic bacteria isolated from clinical infections, with silver oxide nanoparticles. Indian J Pharm Sci 77(2):151–155

Sanghi R, Verma P, Puri S (2011) Enzymatic formation of gold nanoparticles using *Phanerochaete chrysosporium*. Adv Chem Eng Sci 1(3):154–162

Saravanan M, Amelash T, Negash L, Gebreyesus A, Selvaraj A, Rayar V, Deekonda K (2013) Extracellular biosynthesis and biomedical application of silver nanoparticles synthesized from baker's yeast. Int J Res Pharm Biomed Sci 4:822–828

Sarkar R, Kumbhakar P, Mitra AK (2010) Green synthesis of silver nanoparticles and its optical properties. Dig J Nanomat Bios 5(2):491–496

Senapati S, Mandal D, Ahmad A, Khan MI, Sastry M, Kumar R (2004) Fungus mediated synthesis of silver nanoparticles: a novel biological approach. Indian J Phys 78A:101–105

Shan GB, Xing JM, Zhang HY, Liu HZ (2005) Biodesulfurization of dibenzothiophene by microbial cells coated with magnetite nanoparticles. Appl Environ Microbiol 71:4497–4502

Shankar SS, Ahmad A, Pasricha R, Sastry M (2003) Bioreduction of chloroaurate ions by geranium leaves and its endophytic fungus yields gold nanoparticles of different shapes. J Mater Chem 13(7):1822–1826

Shi C, Zhu N, Cao Y, Wu P (2015) Biosynthesis of gold nanoparticles assisted by the intracellular protein extract of *Pycnoporus sanguineus* and its catalysis in degradation of 4-nitroaniline. Nanoscale Res Lett 10(1):1–8

Simkiss K, Wilbur KM (1989) Biomineralization. Academic, New York

Sintubin L, Verstraete W, Boon N (2012) Biologically produced nanosilver: current state and future perspectives. Biotechnol Bioeng 109(10):2422–2436

Soltani NM, Shahidi BGH, Khaleghi N (2015) Biosynthesis of gold nanoparticles using *streptomyces fulvissimus* isolate. Nanomed J 2(2):153–159

Stegenga RW, Al-Azawi S, Bandyopadhyay D, Bandyopadhyay K (2011) Biosynthesis of gold nanoparticles by *Saccharomyces cerevisiae*. FASEB J 25:726–728

Sudha SS, Rajamanickam K, Rengaramanujam J (2013) Microalgae mediated synthesis of silver nanoparticles and their antibacterial activity against pathogenic bacteria. Indian J Exp Biol 51(5):393–399

Sun S, Murray CB, Weller D, Folks L, Moser A (2000) Monodisperse FePt nanoparticles and ferromagnetic FePt nanocrystal superlattices. Science 287(5460):1989–1992

Syed A, Saraswati S, Kundu GC, Ahmad A (2013) Biological synthesis of silver nanoparticles using the fungus *Humicola* sp. and evaluation of their cytoxicity using normal and cancer cell lines. Spectrochim Acta 114:144–147

Tapan KS, Andrey LR (2009) Nonspherical noble metal nanoparticles: colloid chemical synthesis and morphology control. Adv Mater 21:1–24

Tavernier ML, Petit E, Delattre C, Courtois B, Courtois J, Strancar A, Michaud P (2008) Production of oligoglucuronans using a monolithic enzymatic microreactor. Carbohyd Res 343(15):2687–2691

Vahabi K, Mansoori GA, Karimi S (2011) Biosynthesis of silver nanoparticles by fungus *Trichoderma reesei*. Insciences J 1(1):65–79

Vanaja M, Rajeshkumar S, Paulkumar K, Gnanajobitha G, Chitra K, Malarkodi C, Annadurai G (2015) Fungal assisted intracellular and enzyme based synthesis of silver nanoparticles and its bactericidal efficiency. Int Res J Pharm Biosci 2(3):8–19

Varshney R, Mishra AN, Bhadauria S, Gaur MS (2009) A novel microbial route to synthesize silver nanoparticles using fungus *Hormoconis resinae*. Dig J Nanomater Bios 4:349–355

Vilchis-Nestor AR, Sánchez-Mendieta V, Camacho-López MA, Gómez-Espinosa RM, Camacho-López MA, Arenas-Alatorre JA (2008) Solventless synthesis and optical properties of Au and Ag nanoparticles using *Camellia sinensis* extract. Mat Lett 62(17):3103–3105

Wang X, Low XC, Hou W, Abdullah LN, Toh TB, Mohd Abdul Rashid M, Chow EKH et al (2014) Epirubicin-adsorbed nanodiamonds kill chemoresistant hepatic cancer stem cells. ACS Nano 8(12):12151–12166

Yong P, Rowson NA, Farr JPG, Harris IR, Macaskie LE (2002) Bioaccumulation of palladium by *Desulfovibrio desulfuricans*. J Chem Technol Biotechnol 77(5):593–601

Zheng B, Qian L, Yuan H, Xiao D, Yang X, Paau MC, Choi MM (2010a) Preparation of gold nanoparticles on eggshell membrane and their biosensing application. Talanta 82(1):177–183

Zheng D, Hu C, Gan T, Dang X, Hu S (2010b) Preparation and application of a novel vanillin sensor based on biosynthesis of Au–Ag alloy nanoparticles. Sensor Actuat B Chem 148(1):247–252