

Chapter 19

Microbe-Based Metallic Nanoparticles Synthesis and Biomedical Applications: An Update

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19.1 Introduction

Nanotechnology has emerged as a new and promising discipline of modern science that encompasses interdisciplinary topics such as material science, physics, chemistry and biology. Thus, nanotechnology has become more fascinating field of study by several group of scientific community including physicists, chemists, material scientists, electronics and mechanical engineers, biomedical researchers, and biologists. The advancement of nanoparticle synthesis and characterization has witnessed novel applications of nanoparticles (NPs) in various fields and it is evolving very rapidly in recent times (Rudramurthy et al. 2016). Typically, NPs are structural materials that possess a specific dimension within the nanoscale range (1–100 nm) (Li et al. 2011; Kato 2011). NPs are composed of three layers namely, the surface layer, shell layer and the core. Mostly, the surface layer is fabricated with different macromolecules, surfactants, metal ions or polymers to impart novel and unique properties (Khan et al. 2017).

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These nanosized particles have greatly attracted because of their uncommon, but attractive physicochemical, electronic, dielectric, electrical, magnetic, mechanical, and biological properties (Narayanan and Sakthivel 2010). In general, NPs exhibit relatively a greater surface to volume ratio, higher Raman scattering and Rayleigh scattering effect in metallic nanomaterials that imparts diverse properties to NPs making them more advantageous as compared to their bulk material counterparts (Narayanan and Sakthivel 2010; Swamy et al. 2015a, b; Akthar et al. 2015). Overall, unique and enhanced properties of nanomaterial are mostly due to their altered shape, size, distribution pattern and other morphological features compared to their bulk particles from which they are synthesized (Swamy et al. 2015a; Raza et al. 2016; Khan et al. 2017). Therefore, a precise control over these factors will govern the characteristic features of NPs and their applications. The controlled synthesis of metallic nanostructures with a definite dimension and organized monodispersity is one of the greatest challenge in nanotechnology research (Maliszewska 2011). In addition, some of the other issues such as easy recovery and purification of the synthesized NPs for their effective uses are equally important. The synthesized nanomaterials with a definite shape, size, and composition are widely explored in numerous fields such as biomedicine, food, cosmetics, energy science, electronics, optoelectronics, agriculture, chemical industries, textiles, optical devices, electrochemical applications, and environment (Iravani et al. 2014; Rudramurthy et al. 2016).

NPs with a size ranging between 0.1 and 1000 nm are frequently synthesized via bottom-up and top-down approaches (Narayanan and Sakthivel 2010; Rudramurthy et al. 2016). In bottom-up approach of nanofabrication, the substrates are added with a building blocks to form nanostructure. Otherwise, molecular nanostructures are formed by the assembly of atoms or molecules that give rise to crystal planes which further stack onto each other to form nanostructures. Usually, bottom-up approach is employed for biological or chemical synthesis of nanostructures. On the other hand, top-down approach employs a gradual degradation or breakdown of larger bulk materials into nano-sized structures. In this method, the nanomaterials are produced by incising out crystals planes that are previously coexistent on the bulk substrate.

Various physical and chemical procedures are broadly utilized for the synthesis of unique monodispersed NPs. The major concern is that both employs toxic chemicals such as surfactants, strong reducing agents, polymer capping agents, organic solvents for the synthesis of nanostructures. Also, the nanomaterials synthesized from these methods are unstable for long time and the cost of the chemicals are very expensive. Hence, the adsorption of toxic chemicals on NPs surface and organic solvents used during the chemical synthesis greatly limit their uses in biomedical fields (Narayanan and Sakthivel 2010; Maliszewska 2011; Rudramurthy et al. 2016). Consequently, developing an ecofriendly, cost effective, clean, non-toxic and biologically compatible NPs synthesis procedures are more appreciated.

Accordingly, recent times have witnessed the development of biological approaches for nanoparticle synthesis. Biological or green synthesis approaches comprise mainly polysaccharides, mixed-valence polyoxometalates, biosynthetic and irradiation methods. A careful selection of an appropriate green route synthesis methods must be considered with two important facts such as the right selection of solvent system and toxic free reducing or stabilizing agents (Iravani et al. 2014).

Biosynthesis methods employs an eco-friendly unicellular and multicellular biological entities including plants, fungi, yeast, bacteria, actinomycetes and viruses (Kowshik et al. 2003; Kuber and Souza 2006; Merzlyak and Lee 2006; Swamy et al. 2015a, b; Chengzheng et al. 2018; Akhtar et al. 2015; Rudramurthy et al. 2016; Shah et al. 2015). Among these, plant based NPs synthesis approach is relatively more advantageous and can be converted into a resourceful bio factories (Thakkar et al. 2010; Iravani et al. 2014; Shah et al. 2015). Nevertheless, microbe based approaches have few disadvantages such as microbes isolation, culturing and maintenance that requires more time, difficulty in obtaining better control over NPs size, shape, dispersion, crystallinity, and slow production rate while, phytosynthesis of NPs is a straight forward process which do not require any complex or multi-step processes and is rapid. Phytosynthesis approaches are simpler, economical and can be easily scaled up for producing NPs in bulk quantities (Swamy et al. 2015a, b; Iravani et al. 2014; Shah et al. 2015). Nevertheless, the understandings on microbial strain selection, manipulation of culture conditions such as pH, temperature, time, and metal ions concentrations has given some hope on the possible implementation of microbe based approaches for large scale production of NPs. A possible use of genetically manipulated microbes to overproduce definite reducing agents can further simplify the process in obtaining NPs with a definite sizes and shapes (Narayanan and Sakthivel 2010; Musarrat et al. 2011a, b). In addition, the NPs synthesized through biogenic route possess specific surface area with a greater catalytic activity and an enhanced interaction between the enzymes and metal ions (Bhattacharya and Mukherjee 2008; Li et al. 2011; Shah et al. 2015).

It is well established fact that microorganisms adsorb and accumulate metals from their environment and thus, they are widely used in various biological applications such as biomineralization, bioremediation, and bioleaching. Also, microbes are effective in reducing environmental pollution (Darnall et al. 1986; Huang et al. 1990; Kapoor et al. 1999; Lloyd and Lovley 2000; Klaus-Joerger et al. 2001). Microbes has the potential to reduce metals to form metallic NPs and therefore, microbes including bacteria, yeast and fungi are considered as best suitable source for synthesizing environmental friendly, cost-effective nanomaterials in recent times (Ahmad et al. 2002; Musarrat et al. 2011a, b). Therefore, this chapter highlights the recent research outcomes on NPs synthesized through microbial routes and their possible applications in various biomedical fields.

19.2 Biosynthesis of Metallic NPs Using Bacteria

Among natural sources, bacteria are expansively utilized for the synthesis of various metallic NPs. This is due to the fact that bacterial cells can be easily manipulated and control over their culture conditions. At present, research focus is towards understanding microbes interacting with inorganic molecules. It is reported that microorganisms can secrete inorganic constituents having nanoscale dimensions either within or outside their cells. Microbes resist heavy metal compounds mainly due to several mechanisms. These include, permeability barrier exclusion, chemical detoxification using enzymes, intra- and extra-cellular sequestration, reduction reactions, and electrochemical potential change caused by metal ion efflux between the cell membrane mediated by membrane proteins or proton anti-transporter proteins (Bruins et al. 2000; Narayanan and Sakthivel 2010). Thus, bacteria can effectively detoxify heavy metal ions through reduction reactions or by precipitating soluble inorganic ions into insoluble and non-toxic metallic nanostructures. The bacterial detoxification process could be both extracellular or intracellular way and thus, biosynthesis of several metallic NPs could be achieved through both the ways i.e., intracellularly and extracellularly. In this section, biosynthesis of different metallic NPs using actinomycetes, cyanobacteria and bacteria are discussed.

19.2.1 Silver Nanoparticles (AgNPs)

The most common bacterial species that are utilized for the biosynthesis of metal NPs include *Bacillus cereus*, *Escherichia coli*, *Klebsiella pneumonia*, *Actinobacter* sp., *Corynebacterium* sp., *Lactobacillus* sp., and *Pseudomonas* sp. (Tollamadugu et al. 2011; Iravani et al. 2014; Shah et al. 2015). Different bacterial strains utilized for synthesizing AgNPs are listed in the Table 19.1. The biosynthesis of AgNPs using a bacterial strain, *Pseudomonas stutzeri* AG259 isolated from a silver mine was achieved (Klaus et al. 1999). These AgNPs were synthesized in the periplasmic region of the bacterial cell. The particles had a pyramidal and hexagonal shapes and their size ranged up to 200 nm. The occurrence of the Ag-binding proteins act as a source of amino acid moieties for initiating the nucleation reaction during the biosynthesis of AgNPs. It is reported that small silver-binding proteins are found in the periplasmic layer of the bacterial cell bind to silver ions and through ion efflux, prevents the further entry of metals and thus, protect the cell from metal toxicity (Li et al. 1997; Gupta and Silver 1998). The silver ions in the aqueous solution of silver nitrate were shown to get precipitated by the specific silver precipitating peptides namely, AG3 and AG4 to produce silver crystals with a face centered cubic structure (Naik et al. 2002). According to them, these peptides contains specific amino acids mainly, methionine, arginine, lysine, and cysteine which recognize and reduce the silver ions. The correct mechanism of AgNPs biosynthesis from bacteria is still not clear. However, a study by Parikh et al. (2008) has highlighted the possible

Table 19.1 Silver nanoparticles (AgNPs) biosynthesized from bacteria

Microorganisms	Size (nm)	Shape	References
<i>Aeromonas</i> sp. SH10	–	–	Mouxing et al. (2006)
<i>Arthrobacter kerguelensis</i>	4.2–26.1	Spherical	Shivaji et al. (2011)
<i>Arthrobacter gangotriensis</i>	3.6–22.8	Spherical	Shivaji et al. (2011)
<i>Bacillus amyloliquefaciens</i>	15.9–80	Spherical	Fouad et al. (2016)
<i>Bacillus indicus</i>	2.5–13.3	Spherical	Shivaji et al. (2011)
<i>Bacillus cecembensis</i>	2.8–18.2	Spherical	Shivaji et al. (2011)
<i>Bacillus cereus</i> PGN1	4–5	Spherical	Babu and Gunasekaran (2009)
<i>Bacillus flexus</i>	12–61	Spherical/triangular	Priyadarshini et al. (2013)
<i>Bacillus licheniformis</i>	3–170	Spherical	Sarangadharan and Nallusamy (2015)
<i>Bacillus licheniformis</i>	~50	–	Kalimuthu et al. (2008)
<i>Bacillus licheniformis</i>	~40	Spherical	Kalishwaralal et al. (2008)
<i>Bacillus megaterium</i>	80–98.56	Spherical, truncated irregular	Saravanan et al. (2011)
<i>Bacillus megaterium</i>	46.10–80.62	–	Banu and Balasubramanian (2015)
<i>Bacillus subtilis</i>	20–60	Spherical	Paulkumar et al. (2013)
<i>Bacillus subtilis</i>	5–60	Spherical and triangular	Saifuddin et al. (2009)
<i>Bacillus subtilis</i>	15.9–80	Spherical	Fouad et al. (2016)
<i>Bacillus</i> sp.	42–92	Spherical	Das et al. (2014)
<i>Bacillus</i> sp. AZ1	~7–31	Spherical	Deljou and Goudarzi (2016)
<i>Bacillus stratosphericus</i>	2–20	Spherical/triangular/cubic/hexagonal	Hosseini-Abari et al. (2014)
<i>Bacillus thuringiensis</i>	43.52–142.97	–	Banu et al. (2014)
<i>Corynebacterium</i> sp. SH09	10–15	–	Zhang et al. (2005)
<i>Corynebacterium glutamicum</i>	5–50	Irregular	Sneha et al. (2010)
<i>Escherichia coli</i>	40–60	–	Kannan et al. (2010)
<i>Escherichia coli</i>	5–25	Spherical	Divya et al. (2016)
<i>Escherichia coli</i>	42.2–89.6	Spherical	Gurunathan et al. (2009)
<i>K. pneumonia</i>	28.2–122	–	Shahverdi et al. (2007a)
<i>Lactobacillus</i> sp.	100–300	Hexagonal/triangular/other shapes	Nair and Pradeep (2002)
<i>Morganella</i> sp.	~20	Spherical	Parikh et al. (2008)
<i>Pseudomonas mandelii</i> SR1	1.9–14.1	Spherical	Mageswari et al. (2015)
<i>Pseudomonas stutzeri</i> AG259	3–200	Pyramidal/hexagonal	Klaus et al. (1999)
<i>Pseudomonas antarctica</i>	3.4–33.6	Spherical	Shivaji et al. (2011)
<i>Pseudomonas proteolytica</i>	2.8–23.1	Spherical	Shivaji et al. (2011)
<i>Pseudomonas meridiana</i>	2.2–21.5	Spherical	Shivaji et al. (2011)

(continued)

Table 19.1 (continued)

Microorganisms	Size (nm)	Shape	References
<i>Staphylococcus aureus</i>	160–180	–	Nanda and Saravan (2009)
<i>Streptomyces</i> sp.	20–40	Spherical	El-Naggar et al. (2016)
<i>Streptomyces</i> sp. VITSTK7	20–60	Spherical	Thenmozhi et al. (2013)
<i>Streptomyces</i> sp. VITPK1	20–45	Spherical	Sanjenbam et al. (2014)
<i>Streptomyces ghanaensis</i> VITHM1	30–50	Spherical	Abirami and Kannabiran (2016)
<i>Ureibacillus thermosphaericus</i>	10–100	Spherical	Juibari et al. (2011)

molecular mechanism involved in the extracellular biosynthesis of AgNPs by *Morganella* sp. RP-42, isolated from the insect midgut. They observed that *Morganella* sp. produced crystals of spherical AgNPs with an approximate size of 20 nm. The molecular identification revealed the existence of three silver resistant genes namely, silE, silP and silS in *Morganella* sp. The nucleotide sequence of the gene silE obtained from *Morganella* sp. Showed 99% similarity match with known gene, silE known to express periplasmic silver-binding proteins. The study clearly indicated that *Morganella* sp. secretes silver-binding proteins to their extracellular environment during their growth and these proteins probably involve in the reduction of silver metal ions into AgNPs formation and provides stability to the formed nanocrystals (Parikh et al. 2008). Using *Corynebacterium* sp. SH09 cells isolated from a silver mine, Zhang et al. (2005) showed the biosorption and bioreduction of diamine silver complex. The *Corynebacterium* sp. SH09 showed a stronger biosorption capability for $[\text{Ag}(\text{NH}_3)_2]^+$. According to them, ionized carboxyl of amino acid moieties involves in trapping $[\text{Ag}(\text{NH}_3)_2]^+$ onto the cell walls. The presence of certain reducing agents for example, aldehydes and ketones involve in bioreduction of $[\text{Ag}(\text{NH}_3)_2]^+$ to elemental Ag(0). The biosynthesized AgNPs on the cell walls of this bacterium were having the size ranged between 10 and 15 nm. Likewise, Sneha et al. (2010) synthesized irregular shaped AgNPs from *Corynebacterium glutamicum*. The bioreduction of Ag^+ to Ag^0 was achieved through an airborne *Bacillus* sp. and importantly, the synthesized AgNPs were localized in the periplasmic region of the cells. Further characterization using Transmission Electron Microscopy (TEM) and Energy Dispersive X-ray (EDX) analysis established the synthesized AgNPs with a size of 5–15 nm. A monodispersed uniform sized AgNPs were synthesized from the dried cells of *Aeromonas* sp. SH10. The bioreduction of $[\text{Ag}(\text{NH}_3)_2]^+$ to elemental Ag^0 took place rapidly in the solution and on the cells (Mouxing et al. 2006). A new isolate, *Bacillus cereus* PGN1 resistant to metal was used to form intracellular AgNPs (Babu and Gunasekaran 2009). The characterization of these particles revealed that AgNPs had a spherical shape with 4–5 nm of size. Likewise, a spherical shaped AgNPs with a size range of 3–170 nm were produced from *B. licheniformis* (an isolate from Al Thwara hot spring, Oman) (Sarangadharan and Nallusamy 2015). Similarly, *B. licheniformis* culture supernatant was used to synthesize AgNPs with an

approximate size of 40–50 nm (Kalishwaralal et al. 2008; Kalimuthu et al. 2008). The biosynthesis of silver chloride NPs having the size range of 20–60 nm and spherical shape was prepared from *Bacillus subtilis* (Paulkumar et al. 2013). In another study, a rapid synthesis of AgNPs using *B. subtilis* culture supernatant with microwave irradiation was achieved (Saifuddin et al. 2009). The NPs were having spherical and occasionally triangular shapes. Using *B. stratosphericus*, Hosseini-Abari et al. (2014) synthesized AgNPs having various shapes (spherical, triangular, cubic, and hexagonal) and a size of 2–20 nm. Likewise, Das et al. (2014) synthesized BACILLUS sp. mediated AgNPs with size ranging 42–92 nm and the particles were having spherical shape. Likewise, a thermophile, *Bacillus* sp. AZ1, *Bacillus megaterium* and *Bacillus flexus* were also capable of synthesizing AgNPs extracellularly (Saravanan et al. 2011; Priyadarshini et al. 2013; Deljou and Goudarzi 2016). *Bacillus thuringiensis* and *Bacillus megaterium* mediated AgNPs were also synthesized (Banu and Balasubramanian 2015; Banu et al. 2014). More recently, used *Bacillus amyloliquefaciens* and *Bacillus subtilis* to produce spherical shaped AgNPs (Fouad et al. 2016). A rapid biosynthesis of AgNPs from the culture supernatant of *Klebsiella pneumonia* was achieved. AgNPs sizes ranged between 28.2 and 122 nm. When piperitone was added, reduction process was inhibited and thus, suggesting the role of an enzyme, nitroreductase involvement in the process (Shahverdi et al. 2007a, b). *Escherichia coli* was used to biosynthesize well dispersed AgNPs with a size ranging between 40 and 90 nm (Gurunathan et al. 2009; Kannan et al. 2010). Likewise, green synthesis of AgNPs using *E. coli* has been achieved by Divya et al. (2016). A thermophilic bacteria, *Ureibacillus thermosphaericus* was capable to biosynthesize polydispersed spherical 10–100 nm sized AgNPs through extracellular mechanism (Juibari et al. 2011). Extracellular synthesis of AgNPs was reported by Shivaji et al. (2011) by using culture supernatants of *Arthrobacter kerguelensis*, *Bacillus cecembensis*, *Bacillus indicus*, *Pseudomonas meridiana*, *Pseudomonas antarctica*, *Pseudomonas proteolytica*, *Arthrobacter gangotriensis*. Bioreduction of silver ions to AgNPs using *Staphylococcus aureus* was shown by Nanda and Saravanan (2009). *Pseudomonas mandelii* SR1 assisted in synthesizing AgNPs having an average diameter of 1.9–10 nm. These AgNPs were highly stable even after 19 months of storage period (Mageswari et al. 2015). Several *Streptomyces* sp. isolates were used to biofabricate spherical shaped AgNPs with the size in the range of 20–60 nm (Thenmozhi et al. 2013; Sanjenbam et al. 2014; El-Naggar et al. 2016). Likewise, *Streptomyces ghanaensis* VITHM1 strain was used to produce highly stable spherical shaped AgNPs with an average size between 30 and 50 nm range (Abirami and Kannabiran 2016).

19.2.2 Gold Nanoparticles (AuNPs)

A variety of AuNPs have been successfully synthesized by using various bacterial strains (Table 19.2). These AuNPs with different shapes have a unique properties to be considered for biomedical applications. The application of AuNPs for curing

Table 19.2 Gold nanoparticles (AuNPs) biosynthesized from bacteria

Bacterial strain	Size (nm)	Shape	References
<i>Bacillus clausii</i>	20–30	Spherical	Zhang et al. (2016)
<i>Bacillus licheniformis</i>	38	Spherical	Singh et al. (2014)
<i>Bacillus licheniformis</i>	10–100	–	Kalishwaralal et al. (2009)
<i>Bacillus marisflavi</i>	~14	Spherical	Nadaf and Kanase (2016)
<i>Bacillus niabensis</i> 45	10–20	Spherical	Li et al. (2016a, b)
<i>Deinococcus radiodurans</i>	43.75	Spherical/triangular/irregular	Li et al. (2016a, b)
<i>Escherichia coli</i> DH5 α	25 \pm 8	Spherical	Du et al. (2007)
<i>Klebsiella pneumoniae</i>	4–10	Spherical	Srinath and Rai (2015)
<i>Klebsiella pneumoniae</i>	35–65	Spherical	(Malarkodi et al. 2013)
<i>Lactobacillus</i> sp.	100–300	Hexagonal/triangular/other	Nair and Pradeep 2002
<i>Marinobacter pelagius</i>	2–10	Spherical/triangular	Sharma et al. (2012)
<i>Pseudomonas aeruginosa</i>	15–30	–	Husseiny et al. (2007)
<i>Pseudomonas aeruginosa</i>	10–20	Spherical	Singh and Kundu (2014)
<i>Shewanella oneidensis</i>	12 \pm 5	Spherical	Suresh et al. (2011)
<i>Rhodopseudomonas capsulata</i>	10–12	Spherical	He et al. (2007)
<i>Rhodopseudomonas capsulata</i>	50–400	Spherical	Singh and Kundu (2014)
<i>Shewanella algae</i>	10–20	–	Konishi et al. (2004)
<i>Stenotrophomonas maltophilia</i>	~40	Oval	Nangia et al. (2009)

numerous diseases has been practiced ever since from 2500 BC to till date. The importance of AuNPs was recognized over 150 year back when Michael Faraday observed different properties of colloidal gold solution differing from their bulk material, gold (Li et al. 2011). In recent times, biosynthesis and applications of AuNPs has been highly acknowledged. Microbe assisted synthesis of AuNPs is an eco-friendly approach thus, gained more attention compared to other methods as synthesis occurs immediately in the surrounding temperature and pressure (Das et al. 2014; Srinath and Rai 2015). *Lactobacillus* strains, commonly occurring in buttermilk were used to synthesize AuNPs crystalline structures with submicron dimensions (Nair and Pradeep 2002). *Shewanella algae* and *Shewanella oneidensis* were also successfully employed to biosynthesize monodispersal AuNPs in nano regime (Konishi et al. 2004; Suresh et al. 2011). AuNPs formed extra-cellularly from *Pseudomonas aeruginosa* possessed size in the range of 15–30 nm (Husseiny et al. 2007). The bacteria, *Rhodopseudomonas capsulata* was successfully used to produce AuNPs of varied size and shape (He et al. 2007). An average size of AuNPs formed on the bacterial cells (*E. coli* DH5 α) surface was found to be 25 \pm 8 nm (Du et al. 2007). For the first time, Sharma et al. (2012) employed the marine bacteria,

Marinobacter pelagius to biosynthesize AuNPs Du et al. (2007). They obtained spherical AuNPs in the range of 10–20 nm. Likewise, AuNPs from *Stenotrophomonas maltophilia* were having an approximate size of ~40 with oval shape (Nangia et al. 2009). A successful biosynthesis of AuNPs from *Rhodospseudomonas capsulata* and *Pseudomonas aeruginosa* was achieved by Singh and Kundu (2014). *Rhodobacter capsulatus*, one of the photosynthetic bacteria was shown to have a strong biosorption capability for the AuCl_4^- . The presence of carotenoids and certain enzymes on the cell membrane and/or found in their surroundings are believed to involve in the bioreduction of Au^{3+} to Au^0 . Further, they speculated that due to this phenomenon the bacterium can exhibit metal tolerance capability (Feng et al. 2007). Likewise, *B. licheniformis*, *B. niabensis* 45 and *B. clausii* were also used for extracellular biosynthesis of AuNPs (Kalishwaralal et al. 2009; Singh et al. 2014; Zhang et al. 2016; Li et al. 2016a). Further, Li et al. (2016a) predicted the role of a cyclic peptide (P2) with a molecular weight of about 1122 Da involvement in the stabilization of nanocrystals. AuNPs had a spherical shape with an average diameter of 38 nm. Similarly, *Klebsiella pneumoniae* was employed to synthesize spherical shaped AuNPs having monodispersal nature with a spherical shape and their size ranged between 4 and 65 nm (Malarkodi et al. 2013; Srinath and Rai 2015). *Deinococcus radiodurans*, known for its extreme radiations and oxidant stress resistance was used to reduce Au (III) and AuNPs synthesis (Li et al. 2016b). The particles showed polydisparsity with spherical, triangular and irregular shapes and had an average size of 43.75 nm. Nadaf and Kanase (2016) used *Bacillus marisflavi* to produce spherical shaped AuNPs with an average size of ~14 nm.

19.2.3 Magnetic Nanoparticles

Bio-mineralization is a naturally occurring process mainly mediated by certain microbes commonly called as magnetotactic bacteria. These bacteria use bio-mineralization proteins to form a well-organized magnetite nanocrystal structures (Bazylinski and Frankel 2004; Arakaki et al. 2008). Most of these magnetotactic bacteria have a diverse morphological features and exist mainly in the sediments of freshwater as well as marine region (Narayanan and Sakthivel 2010). Many kinds of magnetic NPs are currently produced due to their potential nanobiotechnological applications including cancer cure through magnetic hyperthermia. The bacterial nanoparticles are synthesized under stringent biological conditions with bacterial cell membrane lipid layer and definite membrane proteins (Chen et al. 2016). More recently, nanoscience research is focused on magnetic NPs due to the fact that they possess a unique nanoconfiguration with superior properties including high coercive force and super paramagnetic, thus broadly applied in various biomedical fields (Li et al. 2014; Rudramurthy et al. 2016; Chen et al. 2016). The isolated magnetotactic bacteria from marine sulfide-rich water and sediments produced intracellular nanocrystals of ferromagnetic iron sulfide and greigite (Fe_3S_4). They were aligned in chains in association with iron pyrite (FeS_2) and each chain

contained about ten NPs with irregular shape and 75 nm in size. Most of the particles have irregular shape, whereas some exhibit octahedral and cubo-octahedral symmetry with strong diffraction contrast (Mann et al. 1990; Narayanan and Sakthivel 2010). *Magnetospirillum magneticum* has the capability to form 50–100 nm sized ferromagnetic particles (Fe_3O_4 or Fe_3S_4). These NPs were surrounded by magnetosomes, an intracellular phospholipid membrane (Schuler and Frankel 1999). Magnetosomes from *Desulfovibrio magneticus* RS-1 were irregular/bullet shaped with ~ 35 nm sized were produced by (Posfai et al. 2006). Each magnetosome contained with 1–18 NPs per chain. Likewise, *Magnetobacterium bavaricum*, another magnetic bacterium had a more than 100 NPs per chain of one magnetosome measuring 110–150 nm. The magnetosome had a irregular shape (Hanzlik et al. 1996). Magnetite crystals with a uniform size were produced by magnetotactic bacteria. *M. magnetotacticum* produced ~ 50 nm sized Fe_3O_4 NPs (Lang and Schuler 2006). Likewise, bacterial magnetic NPs (Fe_3O_4) with an average diameter of 70 nm were synthesized from *M. gryphiswaldense* MSR-1 cells (Guo et al. 2008). Magnetic iron sulfide (FeS) NPs measuring 2 nm in size were produced on the cell surface of *Desulfovibrio vulgaris*, a sulfate-reducing bacteria (Watson et al. 1999). A study by Bose et al. (2009) reports the biosynthesis of Fe_2O_3 by *Shewanella oneidensis* MR-1 with an average size of 30–43 nm. An iron reducing bacterium, *Shewanella oneidensis* was used by Perez-Gonzalez et al. (2010) to produce Fe_3O_4 NPs with 40–50 nm size. Bharde et al. (2005) synthesized iron oxide NPs by using aqueous iron complexes with *Actinobacter* spp. bacterium. Ferromagnetic particles in the size range of 10–50 nm were produced from *Geobacter metallireducens* GS-15 and *Magnetospirillum* strain AMB-1 and (Vali et al. 2004; Elblbesy et al. (2014). Different bacterial strains utilized for synthesizing magnetic NPs are listed in the Table 19.3.

19.2.4 Sulfide Nanoparticles

Sulfide NPs, being nano-sized possess a unique novel optical and electronic properties and thus, widely applied as used as quantum dots fluorescent biomarker, for cancer diagnosis, radio/chemosensitizing, drug delivery and labeling of cells (Juzenas et al. 2008; Smith et al. 2008; Li et al. 2011). *Clostridium thermoaceticum* precipitated CdS from 1 mM CdCl_2 on its cell surface and to the surrounding medium when cultured in the growth media containing cysteine hydrochloride. It was proclaimed that cysteine acted as the sulfide source (Cunningham and Lundie 1993). *Klebsiella aerogenes* and *Klebsiella pneumoniae* formed CdS on their cell surface measuring 5–200 nm when exposed to cadmium ions in the culture medium (Holmes et al. 1995; Smith et al. 1998). These NPs demonstrated optical as well as photoactive features comparable to inorganically synthesized CdS systems (Smith et al. 1998). Likewise, zinc sulfide (ZnS) NPs synthesis has been reported by a sulfate-reducing bacteria (*Desulfobacteriaceae*). In another study by Gong et al. (2007), PbS NPs of 13 nm were synthesized from *Desulfotomaculum* sp. under

Table 19.3 Magnetic nanoparticles biosynthesized from bacteria

Microorganisms	Metal NPs	Size (nm)	Shape	References
<i>Desulfovibrio vulgaris</i>	FeS	2	–	Watson et al. (1999)
<i>Desulfovibrio magneticus RS – 1</i>	Magnetosome	~35	Irregular/bullet	Posfai et al. (2006)
<i>M. gryphiswaldense</i> MSR-1	Fe ₃ O ₄	60	Irregular	Guo et al. (2008)
<i>Magnetospirillum magneticum</i>	Fe ₃ O ₄ or Fe ₃ S ₄	50–100	–	Schuler and Frankel (1999)
<i>Magnetospirillum gryphiswaldense</i>	Fe ₃ O ₄	~50	Octahedral prism/hexagonal prism	Lang and Schuler (2006)
<i>Magnetospirillum</i> strain AMB-1	Fe ₃ O ₄	48	–	Elblbesy et al. (2014)
<i>Magnetobacterium bavaricum</i>	Magnetosome	110–150	Irregular	Hanzlik et al. (1996)
<i>Geobacter metallireducens</i> GS-15	Fe ₃ O ₄	10–50	–	Vali et al. (2004)
<i>Shewanella oneidensis</i>	Fe ₃ O ₄	40–50	Rectangular/rhombic/hexagonal	Perez-Gonzalez et al. (2010)
<i>Shewanella oneidensis</i> MR-1	Fe ₂ O ₃	30–43	Pseudo-hexagonal/irregular/rhombohedral	Bose et al. (2009)

mild conditions. In this biosynthetic process, *Desulfotomaculum* sp. used sulfate as electron acceptor to form sulfide which acts as sulfur source for forming PbS nanocrystals. The particles were found to have a spherical shape with 2–5 nm diameter (Labrenz et al. 2000). Similarly, Bai et al. (2006) reported a novel synthesis of ZnS NPs of 8 nm by an immobilized *Rhodobacter sphaeroides*. In another study, *E. coli* was shown to synthesize intracellular CdS crystals in nanoregime when cultured along with sodium sulfide and cadmium chloride. These nanocrystals showed the wurtzite crystal structure and their size was about 2–5 nm. Further, biosynthesis of CdS nanocrystals was found to increase up to 20-fold when cells were in the stationary phase as compared to their log phase (Sweeney et al. 2004). *Lactobacillus* sp. mediated biosynthesis of CdS NPs has been reported by Prasad and Jha (2010). According to them *Lactobacilli* sp. with a negative electro-kinetic potential readily attracted cations during the process of biosynthesis. CdS NPs had an average size of 4.93 ± 0.23 nm. Li et al. (2009) reported the CdS nanofibres formation by using the bacterial cellulose obtained from *Gluconoacetobacter xylinus* strains. Similarly, *Rhodopseudomonas palustris* assisted extracellular CdS nanocrystals formation was reported by Bai et al. (2009). According to them, the lyase activity of an enzyme (cysteine desulhydrase) was responsible for the synthesis of these spherical shaped NPs with an average diameter of 8.01 ± 0.25 nm. Similarly, Bai and Zhang (2009) demonstrated a reliable method of biosynthesizing extracellular lead

Table 19.4 Sulphide nanoparticles biosynthesized from bacteria

Microorganisms	Metal NPs	Size (nm)	Shape	References
<i>B. anthracis</i> PS2010	PbS	–	–	El-Shanshoury et al. (2012)
<i>Desulfobacteraceae</i>	ZnS	2–5	Spherical	Labrenz et al. (2000)
<i>Desulfotomaculum</i> sp.	PbS	13	–	Gong et al. (2007)
<i>Escherichia coli</i>	CdS	2–5	Wurtzite crystal	Sweeney et al. (2004)
Recombinant <i>Escherichia coli</i>	CdS	6	–	Kang et al. (2008), Chen et al. (2009) and Mi et al. (2011)
<i>Gluconoacetobacter xylinus</i>	CdS	30	–	Li et al. (2009).
<i>Klebsiella aerogenes</i>	CdS	20–200	Spherical	Holmes et al. (1995)
<i>Klebsiella pneumoniae</i>	CdS	5–200	Spherical/elliptical	Smith et al. (1998)
<i>Lactobacillus</i> sp.	CdS	4.93 ± 0.23	Spherical	Prasad and Jha (2010)
<i>Klebsiella planticola</i>	CdS	–	–	Sharma et al. (2000)
<i>Pseudomonas</i> spp.	CdS	10–40	Spherical	Gallardo et al. (2014)
<i>Rhodopseudomonas palustris</i>	CdS	8.01 ± 0.25	Cubic	Bai et al. (2009)
<i>Rhodobacter sphaeroides</i>	ZnS	8	Hexagonal lattice	Bai et al. (2006)
<i>Rhodobacter sphaeroides</i>	PbS	10.5 ± 0.15	Spherical	Bai and Zhang (2009)

sulfide (PbS) NPs of 10.5 ± 0.15 nm size by using immobilized *R. sphaeroides*. Likewise, *B. anthracis* PS2010 was demonstrated to biosynthesize PbS NPs (El-Shanshoury et al. 2012). Interestingly, CdS quantum dots in genetically engineered *E. coli* by overexpressing CdS binding peptide (Kang et al. 2008; Chen et al. 2009; Mi et al. 2011). Using Antarctic psychrotolerant bacteria (*Pseudomonas* spp.) quantum dots were biosynthesized at low temperature (Gallardo et al. 2014). The hypothesized mechanism of PbS nanocrystals biosynthesis could be because of Pb precipitation. Lately, Plaza et al. (2016) explored the biosynthesis of CdS and CdTe quantum dots by using Antarctic bacteria (*Pseudomonas* strains) resistant to cadmium and tellurite. Different bacterial strains utilized for synthesizing sulphide NPs are listed in the Table 19.4.

19.2.5 Selenium Nanoparticles

Selenium NPs possess optical, photochemical, and semiconducting properties. Thus, they are widely used in electronic circuit devices and photocopiers (Narayanan and Sakthivel 2010). Different bacterial strains utilized for synthesizing selenium NPs are listed in the Table 19.5. A rhizobacterial strain (*Stenotrophomonas maltophilia* SELTE02) from the soil of selenium successfully transformed selenite to

Table 19.5 Selenium nanoparticles biosynthesized from bacteria

Bacterial strain	Size (nm)	Shape	References
<i>Agrobacterium</i> sp.	185–190	Spherical	Bajaj et al. (2012)
<i>Azoarcus</i> sp. CIB	123 ± 35	Spherical	Fernández-Llamosas et al. (2016)
<i>Bacillus cereus</i>	150–200	Spherical	Dhanjal and Cameotra (2010)
<i>P. aeruginosa</i> SNT1	–	–	Yadav et al. (2008)
<i>Stenotrophomonas maltophilia</i> SELTE02	–	–	Gregorio et al. (2005)
<i>Halococcus salifodinae</i> BK18.	–	–	Srivastava et al. (2014)
<i>Pseudomonas putida</i> KT2440	100–500	Spherical	Avendaño et al. (2016)
<i>Duganella</i> sp.	140–200	Spherical	Bajaj et al. (2012)
<i>Thauera selenatis</i>	20–300	–	Debieux et al. (2011)
<i>Enterobacter cloacae</i> SLD1a–1	200	Spherical	Yee et al. (2007)
<i>Bacillus mycoides</i> SeITE01	50–400	Spherical	Lampis et al. (2014)
<i>Pantoea agglomerans</i>	30–300	Spherical	Torres et al. (2012)
<i>Pseudomonas aeruginosa</i>	47–165	Spherical	Kora and Rastogi (2016)

elemental selenium (Se^0). They found that selenium granules accumulated in the cell cytoplasm and extracellular space (Gregorio et al. 2005). In a study by Bajaj et al. (2012) produced spherical shaped selenium NPs from *Duganella* sp. and *Agrobacterium* sp. with an approximate diameter of 140–200 and 185–190 nm respectively. Also, *P. aeruginosa* SNT1 from seleniferous soil was found to biosynthesize spherical amorphous selenium nanostructure both intracellularly and extracellularly (Yadav et al. 2008). Selenium NPs were also synthesized from *Enterobacter cloacae* SLD1a-1 (Yee et al. 2007), *Bacillus cereus* (Dhanjal and Cameotra 2010), *Thauera selenatis* (Debieux et al. 2011), *Pantoea agglomerans* (Torres et al. 2012) and *Bacillus mycoides* SeITE01 (Lampis et al. 2014). The size of these NPs ranged from 20 to 400 nm. Srivastava et al. (2014) synthesized selenium NPs from *Halococcus salifodinae* BK18. More recently, *Pseudomonas putida* KT2440 was employed to biosynthesize selenium NPs. Measurements by the transmission electron microscope showed that selenium NPs had a size between 100 and 500 nm. These particles were found either attached to the cell membrane or in the surrounding medium (Avendaño et al. 2016). Similarly, Kora and Rastogi (2016) reported the biosynthesis of selenium NPs with a size range of 47–165 nm from a Gram-negative bacterial strain, *Pseudomonas aeruginosa*. Lately, *Azoarcus* sp. CIB, a facultative anaerobic β -Proteobacterium mediated synthesis of selenium NPs was reported by Fernández-Llamosas et al. (2016). The NPs had a spherical shape and possessed an average size of 123 ± 35 nm.

Table 19.6 Other nanoparticles biosynthesized from bacteria

Microorganisms	NPs type	Size (nm)	Shape	References
<i>Aeromonas hydrophila</i>	TiO ₂	40.5	Spherical	Jayaseelan et al. (2013)
<i>Actinobacter</i> sp.	Si	10	Quasi-spherical	Singh et al. (2008)
<i>Brevibacterium casei</i>	Co ₃ O ₄	5–7	Cubic	Kumar et al. (2008)
<i>Enterobacter</i> sp.	PbO	–	–	El-Shanshoury et al. (2012)
<i>Escherichia coli</i>	CuO	10–40	Quasi-spherical	Singh et al. (2010)
<i>Lactobacillus</i> sp.	BaTiO ₃	20–80	Tetragonal	Jha and Prasad (2010)
<i>Lactobacillus</i> sp.	TiO ₂	50–60	Spherical	Prasad et al. (2007)
<i>Lactobacillus</i> sp.	TiO ₂	8–35	Spherical	Jha et al. (2009a)
<i>Lactobacillus</i> sp.	Sb ₂ O ₃	3–12	Cubic	Jha et al. (2009b)
<i>Lactobacillus sporoge</i>	ZnO	5–15	Hexagonal	Prasad and Jha (2009)
<i>Propionibacterium jensenii</i>	TiO ₂	<80	Dumb-bell	Babitha and Korrapati (2013)

19.2.6 Other Nanoparticles (Palladium, Uranium, Lead, Cobalt etc.)

Various other types of NPs including Pd, Ti, Ba, Co, Pb, Zn etc. NPs synthesized from different bacteria are shown in Table 19.6. Soluble palladium (Pd) salts like Na₂PdCl₄ was reduced to produce palladium Pd (0) metallic NPs on the cell walls and within the periplasmic space of the bacterium, *Shewanella oneidensis* MR-1 cells (Windt et al. 2005). Pd NPs were also synthesized from *Citrobacter braakii* (Hennebel et al. 2011). The presence of H₂, lactate, formate, ethanol and pyruvate were reported to function in the process of biosorption and succeeding bioreduction of Pd (II). Likewise, bioreduction of uranium (VI) by *S. oneidensis* MR-1 and *Desulfovibrio desulfuricans* was also reported (Burgos et al. 2008; Bargar et al. 2008). The average size of uranite NPs was 3 nm as determined by high-resolution transmission electron microscopy and X-ray absorption spectroscopy. Also, scanning electron microscopy revealed that uraninite (UO₂) NPs were observed to be formed and accumulated on exopolymeric substances of the cell surface (Marshall et al. 2006; Wall and Krumholz 2006; Bargar et al. 2008; Burgos et al. 2008). Likewise, the bioreduced UO₂ NPs from *S. putrefaciens* were found deposited extracellularly or in the periplasmic space (Baranska and Sadowski 2013). Similarly, *S. oneidensis* MR-1 synthesized a long, unique uranium (VI) nanowires that differed from other biogenic uraninite NPs (Jiang et al. 2011). Kumar et al. (2008) synthesized cubic shaped Co₃O₄ NPs attached with proteins by using *Brevibacterium casei*, a metal-tolerant bacterium and aqueous cobalt acetate. These extracellularly synthesized particles had a size in the range of 5–7 nm. Both *Enterobacter* sp. and *Bacillus anthracis* when treated with dried Pb(NO₃)₂ produced lead oxide (PbO) NPs (El-Shanshoury et al. 2012). *Enterobacter* sp. showed intracellular synthesis

within the periplasmic space and later exported exterior to the cell wall. While, *B. anthracis* showed extracellular route of biosynthesis. *Lactobacillus* sp. assisted titanium dioxide (TiO_2) NPs were produced at ambient room temperature by Prasad et al. (2007). The NPs were in spherical form and their size ranged from 40 to 60 nm. Similarly, the biogenic synthesis of TiO_2 NPs from *Aeromonas hydrophila* and *Propionibacterium jensenii* was described by Jayaseelan et al. (2013) and Babitha and Korrapati (2013), respectively. Likewise, a cost-effective and reproducible green synthesis of BaTiO_3 NPs was reported by using *Lactobacillus* sp. (Jha and Prasad 2010). NPs were having crystalline structure of tetragonal shape with the size of 20–80 nm. According to them, reactive oxygen species and hydrogen (rH_2) gas of the culture solution possibly play a role in the process of biosynthesizing nano- BaTiO_3 . Similar mechanistic view was proposed by Jha et al. (2009a) for the biosynthesis of TiO_2 NPs by using *Lactobacillus* sp. TiO_2 NPs had a spherical shape and the size ranged from 8 to 35 nm. Further, cubic shaped antimony trioxide (Sb_2O_3) NPs of 3–12 nm size were also synthesized from *Lactobacillus* sp. (Jha et al. 2009b). Zinc oxide (ZnO) NPs of 5–15 nm size were biosynthesized from *Lactobacillus sporoge* (Prasad and Jha 2009). Biosynthesis of silicon/silica nanocomposites by *Actinobacter* sp. was demonstrated by Singh et al. (2008). These extracellularly produced quasi-spherical particles were having a size of about 10 nm. Using *E. coli*, extracellular biosynthesis of copper oxide (CuO) NPs was reported by Singh et al. (2010). The spectral characterization revealed the occurrence of a quasi-spherical shaped and 10–40 nm sized CuO NPs.

19.3 Different Nanoparticles from Cyanobacteria

A filamentous cyanobacteria (*Plectonema boryanum* UTEX 485) when interacted with $\text{Au}(\text{S}_2\text{O}_3)_2^{3-}$ solution promoted the biosynthesis of cubic AuNPs of size <10–25 nm (Lengke et al. 2006a). A research work on the mechanistic approach revealed that *P. boryanum* UTEX 485 interacts with aqueous AuCl_3 and initially promote gold(I)–sulfide precipitation on the cell walls, followed by depositing octahedral metallic gold of nanosize range between ~10 nm and 6 μm near the cell surface and in the solution (Lengke et al. 2006b). Further, the same strain was used for the extracellular biosynthesis of platinum (Pt) NPs of size ranging between 30 and 300 nm (Lengke et al. 2006c). Using some cyanobacterial strains (*Limnothrix* sp. 37-2-1, *Anabaena* sp. 66-2 and *Synechocystis* sp. 48-3), irregular and elongated shaped AgNPs measuring between 14 and 31 nm were synthesized by Patel et al. (2015). Likewise, the extracts of 30 Cyanobacterial strains were used to synthesize AgNPs (Husain et al. 2015). Among them, *Cylindrospermum stagnale* NCCU-104 was observed to produce smallest sized (38–40 nm) extracellular AgNPs with different shapes (Table 19.7). More recently, *Nostoc* sp. strain HKAR-2 mediated AgNPs synthesis has been reported with particle size of 51–100 nm (Sonker et al. 2017). Various NPs synthesized from cyanobacteria are shown in Table 19.7.

Table 19.7 Nanoparticles biosynthesized from cyanobacteria

Microorganisms	Metal NPs type	Size (nm)	Shape	References
<i>Arthrospira indica</i> PCC7940	Ag	48	Spherical	Husain et al. (2015)
<i>Arthrospira indica</i> SAE-85	Ag	67	Spherical	Husain et al. (2015)
<i>Arthrospira indica</i> SOSA-4	Ag	48	Spherical	Husain et al. (2015)
<i>Arthrospira maxima</i> SAE-49-88	Ag	61	Triangular	Husain et al. (2015)
<i>Arthrospira platensis</i> NEERI	Ag	46	Triangular	Husain et al. (2015)
<i>Chroococcus</i> NCCU-207	Ag	48	Spherical	Husain et al. (2015)
<i>Gloeocapsa gelatinosa</i> NCCU-430	Ag	88	Spherical	Husain et al. (2015)
<i>Lyngbya</i> NCCU-102	Ag	54	Spherical	Husain et al. (2015)
<i>Oscillatoria</i> sp. NCCU-369	Ag	80	Spherical	Husain et al. (2015)
<i>Phormidium</i> sp. NCCU-104	Ag	48	Cubic	Husain et al. (2015)
<i>Plectonema</i> sp. NCCU-204	Ag	61	Spherical	Husain et al. (2015)
<i>Spirulina</i> CFTRI	Ag	47	Hexagonal	Husain et al. (2015)
<i>Spirulina</i> NCCU-477	Ag	49	Cubic	Husain et al. (2015)
<i>Spirulina</i> NCCU-479	Ag	52	Spherical	Husain et al. (2015)
<i>Spirulina</i> -481	Ag	64	Spherical	Husain et al. (2015)
<i>Spirulina</i> NCCU-482	Ag	42	Spherical	Husain et al. (2015)
<i>Spirulina</i> NCCU-483	Ag	51	Pentagonal	Husain et al. (2015)
<i>Spirulina platensis</i> NCCU-S5	Ag	46	Spherical	Husain et al. (2015)
<i>Synechocystis</i> NCCU-370	Ag	80	Spherical	Husain et al. (2015)
<i>Anabaena ambigua</i> NCCU-1	Ag	48	Spherical	Husain et al. (2015)
<i>Anabaena variabilis</i> NCCU-441	Ag	50	Spherical	Husain et al. (2015)
<i>Aulosira fertilissima</i> NCCU-443	Ag	58	Spherical	Husain et al. (2015)
<i>Calothrix brevissema</i> NCCU-65	Ag	42	Cubic	Husain et al. (2015)
<i>Cylindrospermum stagnale</i> NCCU	Ag	38	Pentagonal	Husain et al. (2015)
<i>Hapalosiphon fontinalis</i> NCCU-339	Ag	50	Triangular	Husain et al. (2015)
<i>Microchaete</i> sp. NCCU-342	Ag	40	Spherical	Husain et al. (2015)
<i>Nostoc muscorum</i> NCCU-442	Ag	42	Spherical	Husain et al. (2015)
<i>Scytonema</i> sp. NCCU-126	Ag	70	Spherical	Husain et al. (2015)
<i>Tolypothrix tenuis</i> NCCU-122	Ag	44	Spherical	Husain et al. (2015)
<i>Westiellopsis prolifica</i> NCCU-331	Ag	52	Spherical	Husain et al. (2015)
<i>Anabaena</i> sp. 66-2	Ag	24.13 ± 2	Irregular	Patel et al. (2015)
<i>Synechocystis</i> sp. 48-3	Ag	14.64 ± 2	Irregular	Patel et al. (2015)
<i>Limnothrix</i> sp. 37-2-1	Ag	31.86 ± 1	Elongated	Patel et al. (2015)
<i>Plectonema boryanum</i> UTEX 485	Au	<10–25	Cubic	Lengke et al. (2006a)
<i>Plectonema boryanum</i> UTEX 485	Au	10–6000	Octahedral	Lengke et al. (2006b)
<i>Plectonema boryanum</i> UTEX 485	Pt	30–300	Spherical	Lengke et al. (2006c)
<i>Nostoc</i> sp. strain HKAR-2	Ag	51–100	Spherical	Sonker et al. (2017)

19.4 Different Nanoparticles from Actinomycetes

The secondary metabolites produced from Actinomycetes serve as a source of medicaments including antibiotics. Besides, easy genetic manipulation of actinomycetes allow to better control over size (Bhosale et al. 2015; Abd-Elnaby et al. 2016). Exploration of Actinomycetes have proved to be suitable for potential application of NPs synthesis. Actinomycetes assisted NPs exhibit relatively good stability and polydispersity (Bhosale et al. 2015; Abd-Elnaby et al. 2016). Using a *Rhodococcus* sp. (alkalotolerant actinomycete), AuNPs were synthesized intracellularly with the dimension of 5–15 nm (Ahmad et al. 2003a). Electron microscopic data revealed that AuNPs had a monodispersity and were produced on both cell walls and cytoplasmic membranes. They also, predicted the possible role of the cell wall and cytoplasmic membrane specific enzymes in carrying out reduction of metal ions. Likewise, by using an extremophile, *Thermomonospora* sp. Ahmad et al. (2003b) have proved the biosynthesis of monodispersed, and spherical AuNPs with an average size of 8 nm. Further, characterization data of Fourier transform infrared spectroscopy confirmed the possible role of amide (I) and (II) bands of protein acting as capping and stabilizing agents on NPs surface. Likewise, *Actinomycetes* spp. mediated synthesis of AgNPs was reported by many researchers (Chauhan et al. 2013; Abdeen et al. 2014; Bhosale et al. 2015; Mohamedin et al. 2015; Składanowski et al. 2016). Most of these particles were in the nanoregime (<100 nm) and possessed spherical or oval shapes. The presence of reductase enzymes are believed to possibly involve in reducing metal ions. An industrially reliable green approach of synthesizing extracellular AgNPs using *Streptomyces hygroscopicus* has been proposed by Sadhasivam et al. (2010). AgNPs (20–30 nm) were observed to possess a spherical shape. Lately, AgNPs and AuNPs biosynthesized from *Streptomyces* sp. possessed spherical and oval shapes. The size of AgNPs remained in the nanoregime of about 8–44 nm while, AuNPs had 10 nm size (Składanowski et al. 2016). Using *Streptomyces hygroscopicus* (Waghmare et al. 2014), synthesized spherical AuNPs spherical in the range of 10–20 nm. Lately, Abd-Elnaby et al. (2016) biosynthesized AgNPs of 22–85 nm from *S. rochei* MHM13. Extracellular synthesis of CuO NPs with 100–150 nm size was recorded using *Streptomyces* sp., an isolate of Pichavaram mangrove, India (Usha et al. 2010). Various NPs synthesized from cyanobacteria are shown in Table 19.8.

19.5 Different Nanoparticles from Yeast

AgNPs with a size range of 2–5 nm were biosynthesized extracellularly by Kowshik et al. (2002a) using a silver tolerant yeast strain, MKY3. Likewise, Korbekandi et al. (2016) biologically synthesized spherical AgNPs with 2–20 nm in diameter by using dried yeast cells. Lately, Abdehgah et al. (2017) used *Candida albicans* to biologically synthesize crystalline AgNPs ranging 20–80 nm in size with spherical

Table 19.8 Nanoparticles synthesized from cyanobacteria and yeast

Microorganism	Metal NPs	Size (nm)	Shape	References
Actinomycetes				
<i>Rhodococcus</i> sp.	Au	5–15	Spherical	Ahmad et al. (2003a)
<i>Streptomyces</i> sp.	CuO	100–150	–	Usha et al. (2010)
<i>Streptomyces hygroscopicus</i>	Ag	20–30	Spherical	Sadhasivam et al. (2010)
<i>Actinomycetes</i> sp.	Ag	10–20	Spherical	Abdeen et al. (2014)
<i>Actinomycetes</i> sp.	Ag	68.13	–	Chauhan et al. (2013)
<i>Actinomycetes</i> sp.	Ag	8–44	Spherical/oval	Składanowski et al. (2016)
<i>Actinomycetes</i> sp.	Au	10	Spherical/rod	Składanowski et al. (2016)
<i>Streptomyces hygroscopicus</i>	Au	10–20	Spherical	Waghmare et al. (2014)
<i>Streptomyces rochei</i> MHM13	Ag	22–85	Spherical	Abd-Elnaby et al. (2016)
<i>Streptomyces viridodiataticus</i> SSHH-1	Ag	15–45	Spherical	Mohamedin et al. (2015)
Yeast				
<i>Candida glabrata</i>	CdS	2	Hexagonal	Dameron et al. (1989)
<i>Candida albicans</i>	Ag	20–80	Spherical/oval	Abdehghah et al. (2017)
<i>Yarrowia lipolytica</i>	Au	15	Hexagonal/triangular	Agnihotri et al. (2009)
<i>Sachharomyces cerevisiae</i>	Au	13.0 ± 0.9	Spherical	Attia et al. (2016)
<i>Sachharomyces cerevisiae</i>	CdS	3.57 ± 0.21	Spherical	Prasad and Jha (2010)
<i>Schizosaccharomyces pombe</i>	CdS	1–1.5	Hexagonal	Kowshik et al. (2002b)
<i>S. cerevisiae</i>	Sb ₂ O ₃	2–10	Spherical	Jha et al. (2009b)
<i>S. cerevisiae</i>	CdTe	2–3.6	Cubic	Bao et al. (2010)
<i>Sachharomyces cerevisiae</i>	TiO ₂	8–35	Spherical	Jha et al. (2009a)
<i>Sachharomyces cerevisiae</i>	Ag	2–5	Spherical	Kowshik et al. (2002a)
<i>Sachharomyces cerevisiae</i>	Ag	2–20	Spherical	Korbekandi et al. (2016)
<i>Sachharomyces cerevisiae</i>	Fe ₃ O ₄	80–130	Spherical	Fakhrullin et al. (2010)
<i>Rhodotorula mucilaginosa</i>	Cu ₂ O	10.5	Spherical	Salvadori et al. (2014)

and oval morphologies. Agnihotri et al. (2009) reported the biosynthesis of hexagonal and triangular shaped AuNPs with a mean size of 15 nm from the non-conventional yeast *Yarrowia lipolytica*. Dameron et al. (1989) reported the biosynthesis of quantum crystallites from *C. glabrata* and *Schizosaccharomyces pombe* when grown in the presence of cadmium salts. CdS NPs synthesis from *Sachharomyces cerevisiae* has been reported by Prasad and Jha (2010). These CdS NPs had an average size of 3.57 ± 0.21 nm. Likewise, intracellular precipitation of CdS NPs was observed when a strain, *S. pombe* was challenged with cadmium (1 mM) solution (Kowshik et al. 2002b). Jha et al. (2009b) biosynthesized TiO₂ NPs using *Lactobacillus* sp. and the nanocrystals were having a spherical shape with 8–35 nm diameter. Sb₂O₃ NPs were synthesized from *S. cerevisiae*. These nanostructures were spherical in shape with 2–10 nm size and possessed a face centered cubic unit cell structure (Jha et al. 2009b). Intracellular biosynthesis of copper NPs using *Rhodotorula mucilaginosa* showed the occurrence of spherically shaped particles with an average size of 10.5 nm (Salvadori et al. 2014). An efficient biosynthesis and easy harvesting method was proposed by Bao et al. (2010) to obtain biocompatible cadmium telluride (CdTe) quantum dots by using yeast cells. Fakhruddin et al. (2010) reported the possible preparation of viable yeast cells deposited with Fe₃O₄ NPs on the exterior of the cell's wall. Similarly, yeast cells modified with magnetic NPs have been achieved lately (Gorobets et al. 2011, 2013; Safarik et al. 2015). AuNPs of size 13.0 ± 0.9 nm were biologically synthesized using an *S. cerevisiae* cells extract. The presence of yeast cell metabolites including glucose, trimethylsilyl derivatives of butan-2,3-diol, undecanoic acid and indole-3-acetic acid acted as a capping/reducing agents during AuNPs formation (Attia et al. 2016). Various NPs synthesized from cyanobacteria are shown in Table 19.8.

19.6 Fungal Based Nanoparticles

Fungi commonly called as decomposing organisms are considered as eukaryotic organisms which reside in almost every corner of the earth. Fungi are capable of performing several tasks which include digestion of extracellular food, conversion of complicated molecules into simpler one by enzymatic hydrolysis, and utilize the energy (Blackwell 2011). Fungi are also causative agents of many medical complications in humans as well as animals. However, apart from being pathogenic, fungi play significant role in medicine field for instance, production of antibiotics, and their role in the synthesis of NPs which are playing a key role in biomedical field and many more. NPs have been synthesized through many different techniques; one among these techniques is the biological synthesis, which includes plants, yeast, bacteria and fungi. The application of fungi in biosynthesis NPs was first reported in the production of CdSe NPs by *Candida albicans* (Dameron et al. 1989; Xue et al. 2016). Fungi are regarded as more advantageous compared to any other microorganisms in the biosynthesis of NPs due to several characteristic features, which include, fast growth and easy to handle (many species), fungal mycelia can better

withstand bioreactor conditions such as, high pressure and agitation, secretion of more extracellular enzymes, large biomass capacity, economic livability, high metal accumulation capacity, and many more (Castro-Longoria et al. 2011; Musarrat et al. 2011a; Moghaddam et al. 2015). The tolerance and metal bioaccumulation capability of fungi has also attracted and put them to research in the biological production of metallic NPs (Sastry et al. 2003). Moreover, the scale-up of fungi is easy and is an additional advantage in utilizing them in biosynthesis of NPs, the effective secretion of enzymes (extracellular enzymes), also helps in achieving the vast production of enzymes a feasibility (Castro-Longoria et al. 2012). Most of the fungi have intracellular metal uptake and high wall-binding capacities (Volesky and Holan 1995; Moghaddam et al. 2015), which are significant in the nanoparticle synthesis. The metabolic diversity of fungi attracted them as potential candidates in biosynthesis of NPs. Fungi synthesize NPs either by intracellular or extracellular process and reduction is the key process involved in the synthesis of metallic NPs (Sadowski et al. 2008). Intracellular process involves attachment of metal ions on to the fungal cell surface, through electrostatic interaction. The opposite charges on the surface of metal ion and fungal cell surface generate electrostatic force of attraction. After the absorption of metal ions, enzymes of fungal cell wall which contain positively charged groups reduce metal ions leading to aggregation of nano structures and finally metal NPs. However, In case of extracellular synthesis the enzymes secreted by fungi (Eg. nitrate reductase) reduce metal ions, which finally leads to the formation of stable NPs (Khandel and Shahi 2016). Several different NPs such as gold, silver, zinc oxide and many more have been synthesized using different species of fungi including *Fusarium oxysporum*, *Aspergillus niger*, *Aspergillus fumigatus* etc. Various fungi employed in the synthesis of different NPs is shown in Table 19.9.

19.6.1 Silver Nanoparticles (AgNPs)

Silver and its compounds are known to have potential applications in biomedicine field. Several different techniques are available for the synthesis and characterization of AgNPs. Fungi play significant role in synthesis of AgNPs; several different species of fungi have been explored in the biosynthesis. *Fusarium oxysporum* has been widely employed in NP synthesis and the secretion of proteins in to the aqueous solution helps in the development of sulfate diminishing enzyme-based protocol for NPs production. AgNPs with varying morphology with a size ranging from 5 to 50 nm (Ahmad et al. 2003c) and spherical structures with size range 20–50 nm were synthesized from *F. oxysporum* (Durán et al. 2005). The variation in morphology and size could be due to variations in temperature, and different structures can be obtained based on the metallic ion solution and incubation parameters (Riddin et al. 2006; Moghaddam et al. 2015). Earlier studies have reported that *F. oxysporum* synthesizes various sizes and forms of NPs by extracellular synthesis mechanism (Moghaddam et al. 2015). Mukherjee et al. (2001) reported that *F. oxysporum*

Table 19.9 Different nanoparticles biosynthesized from fungi

Microorganisms	NPs Type	Size (nm)	Shape	References
<i>Fusarium oxysporum</i>	Ag	5–50	Varying	Ahmad et al. (2003)
<i>Fusarium oxysporum</i>	Ag	20–50	Spherical	Durán et al. (2005)
<i>Rhizopus stolonifer</i>	Ag	10–25	Quasi-spherical	Binupriya et al. (2010)
<i>Arthroderma fulvum</i>	Ag	15.5 ± 2.5	Spherical	Xue et al. (2016)
<i>Fusarium acuminatum</i>	Ag	5–40	Spherical	Ingle et al. (2008)
<i>Aspergillus fumigatus</i>	Ag	13.88 ± 4.1	Spherical	Magdi et al. (2014)
<i>Aspergillus ochraceus</i>	Ag	13.88 ± 4.1	Spherical	Magdi et al. (2014)
<i>Fusarium oxysporum</i>	Ag	13.88 ± 4.1	Spherical	Magdi et al. (2014)
<i>Penicillium italicum</i>	Ag	13.88 ± 4.1	Spherical	Magdi et al. (2014)
<i>Syncephalastrum racemosum</i>	Ag	13.88 ± 4.1	Spherical	Magdi et al. (2014)
<i>Aspergillus fumigatus</i>	Ag	15–45	Spherical	Alani et al. (2012)
<i>Trichoderma viride</i>	Ag	2–4	Spherical	Fayaz et al. (2010)
<i>Aspergillus fumigatus</i>	Au	22 ± 2	Variable	Gupta and Bector (2013)
<i>Aspergillus flavus</i>	Au	22 ± 2	Variable	Gupta and Bector (2013)
<i>Aspergillus niger</i>	Au	12.79 ± 5.61	Spherical	Sawle et al. (2008)
<i>Aureobasidium pullulans</i>	Au	29 ± 6	Spherical	Bhambure et al. (2009)
<i>Fusarium semitectum</i>	Au	25	Spherical	Philip (2009)
<i>Neurospora crassa</i>	Au	32	Spherical	Zhang et al. (2011)
<i>Volvariella volvacea</i>	Au	20–150	Spherical	Castro-Longoria et al. (2011)
<i>Colletotrichum</i> sp.	Au	20–40	Decahedral/icosahedral	Shankar et al. (2003)
<i>Rhizopus stolonifer</i>	Au	1–5	Irregular	Sarkar et al. (2012)
<i>Nigrospora oryzae</i>	Au	6–18	Spherical	Kar et al. (2014)
<i>Aspergillus terreus</i>	Au	10–20	Spherical	Balakumarana et al. (2016)
<i>Aspergillus terreus</i>	Au	10–50	Anisotropic	Balakumarana et al. (2016)
<i>Fusarium oxyporum</i>	Fe ₃ O ₄	20–50	Irregular	Bharde et al. (2006)
<i>Verticillium</i> sp.	Fe ₃ O ₄	20–50	Cubo-octahedral and quasi-spherical	Bharde et al. (2006)
<i>Aspergillus japonicus</i>	Iron oxide	60–70	Cubical	Bhargava et al. (2013)
<i>Aspergillus oryzae</i>	FeCl ₃	10–24.6	Spherical	Tarafdar and Raliya (2013)
<i>Coriolus versicolor</i>	CdS	100–200	Spherical	Sanghi and Verma (2009)

(continued)

Table 19.9 (continued)

Microorganisms	NPs Type	Size (nm)	Shape	References
<i>Phanerochaete chrysosporium</i>	CdS	2.56	Face-centered cubic	Chen et al. (2014)
<i>Fusarium</i> sp.	ZnS	100–2000	Irregular	Velmurugan et al. (2010)
<i>Fusarium oxysporum</i>	CdS	9–15	Spherical	Kumar et al. (2007)
<i>Fusarium oxysporum</i>	CdS	5–20	Hexagonal	Ahmad et al. (2002)
<i>Aspergillus terreus</i>	Se	–	–	Sarkar et al. (2011)
<i>Aspergillus terreus</i>	Se	–	–	Vetchinkina et al. (2013)
<i>Lentinula edodes</i>	Se	–	–	Zare et al. (2012)
<i>Fusarium</i> sp.	Se	–	–	Gharieb et al. (1995)
<i>Trichoderma reesei</i>	Se	–	–	Gharieb et al. (1995)
<i>Neurospora crassa</i>	PtNPs	4–35	Spherical	Castro-Longoria et al. (2012)
<i>Aspergillus flavus</i>	TiO ₂	62–74	Spherical	Rajakumar et al. (2012)
<i>Aspergillus versicolor</i>	Hg NPs	20.5 ± 1.82	–	Das et al. (2008)

decreases the metal ions through NADH-based reductases and also by shuttle Quinone extracellular procedure (Mukherjee et al. 2001).

Several groups have synthesized and characterized AgNPs from different species of fungi. AgNPs with size range of 10–25 nm and Quasi-spherical were successfully produced using *Rhizopus stolonifer* by extracellular process exploring purified α -NADPH-dependent nitrate reductase which acts as an electron carrier (Binupriya et al. 2010). Furthermore, AgNPs synthesized using *Arthroderma fulvum* range in size from 15.5 ± 2.5 nm, and are spherical in shape (Xue et al. 2016). Earlier study by Gade et al. reported that AgNPs with a definite size range of 5–25 nm were synthesized within 72 h by *Aspergillus niger* when incubated with silver nitrate solution. The synthesized NPs were observed as aggregates on the surface of cell wall, which were then reduced to stabilize using reducing enzymes and proteins produced by the fungus *A. niger* (Khandel and Shahi 2016). The NPs synthesized by exposing aqueous silver nitrate solution to *Fusarium acuminatum* cell extract were found to be spherical in shape with a size range of 5–40 nm with an average diameter of 13 nm. The nitrate-dependent reductase could be responsible for reduction of silver ions which is found in the extra-cellular medium (Ingle et al. 2008). Further, a study by Magdi et al. (2014), reports the reduction of silver salt into AgNPs by *Aspergillus fumigatus*, *Candida albicans*, *Penicillium italicum*, *Syncephalastrum racemosum*, *Fusarium oxysporum* and *Aspergillus ochraceus*. These AgNPs were spherical in shape, with a mean size of 13.88 ± 4.11 nm (Magdi et al. 2014). Furthermore, AgNPs synthesized using *Aspergillus fumigatus* by extracellular process were mostly spherical with a size range of 15–45 nm (Alani et al. 2012). However, AgNPs obtained from *Trichoderma viride* were intracellular and mostly spherical with size range of 2–4 nm (Fayaz et al. 2010).

19.6.2 Gold Nanoparticles (AuNPs)

The characteristic features of AuNPs such as biocompatibility, stability and resistant to oxidation, bio-available surface, allowed them gain significant importance in medicine and biology. The chemical methods of AuNPs synthesis which raise the environmental concerns due to release of toxic residues may be replaced by low-cost and environment friendly process such as, biological synthesis. Several viable microorganisms and their cell-free extracts have been employed by different groups in the synthesis of AuNPs. The biosynthetic process of AuNPs involves two main precursors such as, gold chloride (HAuCl_4) and AuCl . HAuCl_4 dissociates to Au^{3+} ions (Khan et al. 2013) and AuCl dissociates to Au^+ (Zeng et al. 2010). Like AgNPs, AuNPs can also be synthesized by either intracellular or extracellular process. In extracellular process Au^{3+} ions are reduced through proteins by trapping them in the cell wall. However, in the case of intracellular process, cytosolic redox mediators reduces Au^{3+} ions upon diffusion through the cell membrane (Das et al. 2012; Kitching et al. 2015). Nicotinamide adenine dinucleotide (NADH)/nicotinamide adenine dinucleotide phosphate (NADPH) oxidoreductases reduce Au ions either in the cytoplasm or in the cell surface. However, the mechanism of enzymatic reduction of Au^{3+} remains the same in both intra and extracellular process (Gupta and Bector 2013).

AuNPs synthesized by fungi vary in their shape and size, a study by Gupta and Bector (2013) reports the intracellular production of AuNPs by *Aspergillus fumigatus* and *Aspergillus flavus*, with an average diameter of 22 ± 2 nm. Spherical shaped AuNPs with varying size were synthesized using different fungi including *Aspergillus niger* (12.79 ± 5.61 nm), *Aureobasidium pullulans* (29 ± 6 nm), *Fusarium semitectum* (25 nm), *Neurospora crassa* (32 nm) and *Volvariella volvacea* (20–150 nm) (Sawle et al. 2008; Bhambure et al. 2009; Philip 2009; Zhang et al. 2011; Castro-Longoria et al. 2011). Furthermore, AuNPs produced from *Colletotrichum* sp. were decahedral and icosahedral in shape with a size range of 20–40 nm, while AuNPs from *Rhizopus stolonifer* were reported as irregular (uniform) with size ranging from 1 to 5 nm (Shankar et al. 2003; Sarkar et al. 2012). Gold NPs with a diameter range of 6–18 nm and spherical shape were synthesized by treating gold chloride solution with culture filtrate of the *Nigrospora oryzae* (Kar et al. 2014). On the other hand, Balakumarana et al. (2016) reported the synthesis of AuNPs from mycelial free filtrate of *Aspergillus terreus* which were spherical shape and 10–20 nm in size with; however some particles were observed in anisotropic morphology with a size of 10–50 nm. Several other fungi species have been explored in the successful synthesis of AuNPs which include *Volvariella volvacea*, *Phanerochaete chrysosporium*, *Fusarium oxysporum*, *Rhizopus stolonifer*, *Cylindrocladium floridanu* and many more through extracellular process. However, the species including *Fusarium oxysporum*, *Verticillium luteoalbum*, produces AuNPs through intracellular process. Some species are capable producing AuNPs

by both extracellular and intracellular processes which include *Coriolis versicolor*, *Rhizopus oryzae*, *Aspergillus niger*, *Candida albicans*. Organisms such as *Verticillium* sp. and *Rhizopus oryzae* produce NPs on cell wall and cell surface respectively (Moghaddam et al. 2015).

19.6.3 Magnetic Nanoparticles

Magnetic NPs have broad and potential applications in biological and biomedicine fields due to their super-paramagnetic, high coercive force and unique micro-configuration properties. Magnetic NPs exhibit remarkable characteristic features such as super-paramagnetism, high saturation field, high field irreversibility, extra anisotropy contributions/shifted loops after field cooling. For biomedical applications, iron oxide NPs such as magnetite (Fe_3O_4) or its oxidized form maghemite ($\gamma\text{-Fe}_2\text{O}_3$) are most commonly employed. Even though, cobalt and nickel exhibit higher magnetic property, they are of less importance in biomedical science, due to their toxicity and susceptibility to oxidation (Akbarzadeh et al. 2012). The well-known biocompatible magnetic NPs such as Fe_3O_4 (magnetite) and Fe_2O_3 (maghemite) have been employed various biological and medicine field. Magnetite (Fe_3O_4) NPs have been synthesized extracellularly with the aqueous mixture of ferricyanide/ferrocyanide using fungi *F. oxysporum* and *Verticillium* sp. The proteins secreted by these fungi hydrolyze iron precursors to form magnetite (Fe_3O_4) at room temperature. The particles obtained from *Fusarium oxysporum* were found to be irregular in shape with an overall quasi-spherical morphology and size range from 20 to 50 nm; however, particles from *Verticillium* sp. were cubo-octahedral and quasi-spherical in shape (Bharde et al. 2006). However, iron oxide NPs synthesized by extracellular process using *Aspergillus japonicus* varied in size from 60 to 70 nm having cubical shape with crystal structure which corresponds to magnetite (Bhargava et al. 2013). Further, FeCl_3 NPs synthesized extracellularly from *Aspergillus oryzae* were 10–24.6 nm in size with spherical shape (Tarafdar and Raliya 2013).

19.6.4 Fluorescent/Luminescent NPs

The unique size-dependent properties of fluorescent/luminescent colloidal NPs or quantum dots (QDs) which are in the size range of 1–20 nm and composed group II–IV, III–V or IV–VI elements such as, Cd, Te, Se, Zn, In, As), have attracted the researchers in both basic and applied field (Kovalenko et al. 2015; Plaza et al. 2016). Several different groups have synthesized these fluorescent/luminescent NPs and characterized for their applications in biology and medicine. Cadmium sulfide (CdS) QDs were synthesized extracellularly from the white rot fungus *Phanerochaete chrysosporium* by incubating in cadmium nitrate tetrahydrate solution. X-ray analysis of the CdS NPs showed face-centered cubic crystal structure with an average

size of approximately 2.56 nm. Furthermore, the formation and stabilization of CdS QDs may be attributed to the secretion of cysteine and proteins from *Phanerochaete chrysosporium* (Chen et al. 2014). Zinc sulphide (ZnS) and CdS NPs have also been synthesized using *Fusarium sp.* by exposing CdSO₄ and ZnSO₄ solutions having sizes from 20 to 150 nm. Cadmium NPs *Fusarium oxysporum* produced extracellular process were found to be spherical with the size range of 9–15 nm (Kumar et al. 2007). Moreover, ZnNPs produced by an intracellular process using *Fusarium spp.* were irregular in shape and 100–200 nm in size range (Velmurugan et al. 2010). In another study CdS NPs have been produced extracellularly from CdSO₄ solution using *Fusarium oxysporum* and it has been reported that CdS particles were in the size range 5–20 nm with hexagonal shape. The possibility of synthesizing PbS, ZnS, and MoS₂ NPs by enzymatic reduction of sulfate ions by *Fusarium oxysporum* was also tested and preliminary investigations indicated the possible realization of such chemical biotransformations using fungal extracts (Ahmad et al. 2002). Several reports have described synthesis of selenium NPs (SeNPs) using fungi (Gharieb et al. 1995; Sarkar et al. 2011; Vetchinkina et al. 2013; Zare et al. 2012). Mono-dispersed spherical SeNPs have been extracellularly produced using *Aspergillus terreus* and *Alternaria alternate* and intracellularly by *Lentinula edodes* (Sarkar et al. 2011; Vetchinkina et al. 2013; Zare et al. 2012). *Fusarium sp.* and *Trichoderma reesei* have also been reported in the production of SeNPs (Gharieb et al. 1995).

19.6.5 Other Nanoparticles

Apart from the above discussed NPs several other NPs having potential biomedical applications have been mycosynthesized and characterized by several groups. Platinum NPs (PtNPs), unlike the widely researched AgNPs and AuNPs, have been synthesized from the fungus *Neurospora crassa*. It has been reported that intracellular single PtNPs are in the size range of 4–35 nm in diameter, while nano-agglomerates which are spherical in shape are of 20–110 nm in diameter (Castro-Longoria et al. 2012). A study by Riddin et al. (2006) also reports the production of PtNPs by another fungus *F. oxysporum*, which were formed both intracellularly and extracellularly (Riddin et al. 2006). A novel eco-friendly approach of producing CdS NPs was achieved under ambient conditions by immobilizing the fungus, *Coriolus versicolor* in a continuous column (Sanghi and Verma 2009). The CdS nanocrystals had a spherical shape with size ranging 100–200 nm. *Aspergillus flavus* has been employed in the synthesis of TiO₂NPs which range in size from 62 to 74 nm having spherical shape (Rajakumar et al. 2012). Furthermore, Hg NPs have been synthesized using *Aspergillus versicolor* mycelia, the synthesized NPs accumulated on the surface of mycelia which are 20.5 ± 1.82 nm in size (Das et al. 2008).

19.7 Applications of Microbial Nanoparticles

Different types of NPs synthesized using fungi have found potential applications in various fields of medicine and biology including cancer treatment, treatment of bacterial infections (antibacterial activity), acts as biosensors and bioimaging agents. Antibiotics such as amoxicillin, erythromycin, clindamycin, penicillin G, and vancomycin when used along with AgNPs enhanced their antimicrobial effect against *Staphylococcus aureus* and *Escherichia coli* (Shahverdi et al. 2007b). The AgNPs synthesized from bacterial strains have shown superior antimicrobial activity against several pathogens including methicillin-resistant *S. aureus*, vancomycin-resistant *Staphylococcus aureus*, methicillin-resistant *Staphylococcus epidermidis* and *Streptococcus pyogenes*, *E. coli*, *B. subtilis*, *B. cereus*, *S. pyogenes* and *P. aeruginosa*, *Salmonella typhi*, *S. typhimurium*, *Haemophilus influenzae* and *Klebsiella pneumonia* (Nanda and Saravan 2009; Priyadarshini et al. 2013; Abirami and Kannabiran 2016). BioNPs synthesized from *B. megaterium* were effective against multi-drug resistant pathogens *Streptococcus pneumoniae* and *Salmonella typhi* (Saravanan et al. 2011). The biosynthesized AgNPs from *Streptomyces* sp. exhibited antifungal activity against *Aspergillus niger*, *A. flavus* and *A. fumigatus* (Thenmozhi et al. 2013). Likewise, anticandidal properties of AgNPs from *Streptomyces* sp. VITPK1 was shown against *Candida albicans*, *C. tropicalis* and *C. krusei* (Sanjenbam et al. 2014). Biosynthesized AgNPs from *S. hygroscopicus* significantly inhibited several microbial pathogens such as *B. subtilis*, *E. faecalis*, *E. coli*, *S. typhimurium* and *C. albicans* (Sadhasivam et al. 2010; Chauhan et al. 2013; Abdeen et al. 2014; Mohamedin et al. 2015; Skladanowski et al. 2016). CuO NPs from an actinomycete showed greater activity against *E. coli*, *S. aureus*, and *A. niger* (Usha et al. 2010). Likewise, the microbes, *E. coli*, and *S. typhi* were greatly inhibited by AgNPs synthesized from *Bacillus* sp. AZ1 (Deljou and Goudarzi 2016). The AgNPs fabricated to cotton cloth significantly showed antimicrobial activity against *E. coli*, *S. aureus*, and *C. albicans* (El-Naggar et al. 2016). ***E. coli* assisted AgNPs exhibited inhibitory activity against pathogens namely, Salmonella typhi, Bacillus subtilis, Vibrio cholerae, and Klebsiella pneumoniae** (Divya et al. 2016). AgNPs synthesized from yeast cells effectively inhibited a haploid pathogenic yeast, *Candida glabrata* (Abdehgah et al. 2017). Further, microbially synthesized AgNPs function as an anti-biofouling agents (Abd-Elnaby et al. 2016). Likewise, cyanobacterial assisted AgNPs against *B. megaterium*, *E. coli*, *B. subtilis*, *M. luteus* and *S. aureus* have shown a significant antibacterial effect (Patel et al. 2015). Likewise, *Aspergillus niger*, *Trichoderma harzianum*, *Ralstonia solanacearum* and *Xanthomonas campestris* were inhibited by *Nostoc* sp. strain HKAR-2 mediated AgNPs (Sonker et al. 2017). Several groups have reported the potential applications of mycosynthesized NPs. Silver NPs produced from *Arthroderma fulvum* had shown considerable antifungal activity against *Candida* spp., *Aspergillus* spp., and *Fusarium* spp. (Xue et al. 2016). The effective antibacterial activity of AgNPs synthesized from *F. acuminatum* was observed against several pathogenic bacteria, including multidrug resistant *Staphylococcus aureus*, *Staphylococcus epidermidis*,

Salmonella typhi, and *Escherichia coli* (Ingle et al. 2008). Gold NPs derived from *Trichoderma viride* exhibited potential antimicrobial activity (Mishra et al. (2014). Mycosynthesized AuNPs have potential applications in various fields such as in agriculture (pesticidal agents), in optro-electronics, in cancer treatment, and as anti-bacterial agents (Das et al. 2009; Sawle et al. 2008; Mishra et al. 2011; Moghaddam et al. 2015). *B. megaterium* mediated biosynthesized AgNPs exhibited a potent larvicidal activity against *Culex quinquefasciatus* and *Aedes aegypti* (Banu and Balasubramanian 2015; Banu et al. 2014). *Anopheles subpictus* and *Culex tritaeniorhynchus* larvae were inhibited by AgNPs synthesized from psychrotolerant *Pseudomonas mandelii* (Mageswari et al. 2015). Likewise, AgNPs synthesized using *B. amyloliquefaciens* and *B. subtilis* were effective in controlling the growth of mosquito colonies of *Culex pipiens pallens* (Fouad et al. 2016). The biosynthesized AuNPs from *E. coli* DH5a are demonstrated to be beneficial for understand the electrochemistry of hemoglobin (Du et al. 2007). The immobilized doxorubicin on bacterial magnetic NPs easily dissolved in an aqueous solution and possessed very high magnetic and ferromagnetic properties. Also, these particles exhibited strong cytotoxicity against cancer cells namely, HePG2 and MCF-7 (Guo et al. 2008). Selenium NPs by *Halococcus salifodinae* BK18 exhibited potent anti-proliferative activity against HeLa cell lines (Srivastava et al. 2014). AuNPs from yeast cells shows potent anticancer activity against Ehrlich ascites carcinoma cells. The cell toxicity is mainly due to the photothermal properties of AuNPs (Attia et al. 2016). More recently, *Nostoc* sp. strain HKAR-2 mediated AgNPs showed potent anticancerous activities against MCF-7 cells (Sonker et al. 2017). The AgNPs synthesized using fungi had shown anticancer activity against several human cancers such as, colon carcinoma, breast cancer, and hepato-cellular carcinoma cells (Magdi et al. 2014). The AgNPs synthesized from *Aspergillus fumigatus* exhibited antiviral against HIV-1 (Alani et al. 2012); while AgNPs obtained from *Trichoderma viride* finds potential applications in biosensor and bio-imaging (Fayaz et al. 2010). Further, AuNPs obtained from *Penicillium brevicompactum* showed in vitro cytotoxic activity against mouse mayo blast cancer cells (C2C12) (Mishra et al. 2011). AuNPs produced using mycelia-free culture filtrate of *Nigrospora oryzae* exhibited detrimental effect on the ultra-structure of parasite belonging to *Raillietina* sp.; (Kar et al. 2014). Antibody-conjugated AuNPs/gold nanoparticle-based probe can serve as a simple diagnostic tool in the diagnosis of cancer that is they can differentiate between cancer and normal cells (Chuhan et al. 2011). Yeast cells with magnetic NPs can be used for biotechnological applications such as bioreactors, biosensors, and bioseparations (Fakhrullin et al. 2009). NPs that possess super paramagnetic behavior at room temperature and magnetic particles which are stable in water at pH 7 have significant and potential biomedical applications such as in therapy, biology and medical diagnosis (Cabuil 2004; Morcos 2007; Ersoy and Rybicki 2007; Akbarzadeh et al. 2012). Magnetic NPs such as Fe_3O_4 (magnetite) and Fe_2O_3 (maghemite) have been employed in magnetic resonance imaging (MRI), categorization and manipulation of stem cell, magnetic hyperthermia (cancer therapy), gene therapy, examination of DNA and trained drug delivery (Xiang et al. 2007). Magnetic iron oxide NPs coated on viral nanofibers can be explored as biomarkers in the

detection of human serum antibody (Wang et al. 2015). QDs are more photostable, brighter, and display narrower fluorescence emission spectra which upon excitation by a single wavelength allow multiplexing applications (Liu et al. 2005). SeNPs have exhibit several activities including anticancer activity against breast, lung, kidney, and osteosarcoma, antibacterial, and antioxidant activity. Moreover, they have potential environmental applications also (Sweety et al. 2016).

19.8 Conclusion and Future Directions

Overall, there is an increased awareness towards the better utilization of cost-effective, economically feasible, biological approaches for biosynthesizing eco-friendly biosynthesis of toxic-free NPs. Over the past few decades, various metal based functional nanomaterials from microorganisms including bacteria, fungi, yeast and cyanobacteria have been successfully synthesized. These nanostructures have been shown to have monodispersity and occur in different sizes, shapes and morphology. Importantly, the microbe assisted nanoparticle biosynthesis do not involves any toxic chemicals or cumbersome processes. Further, NPs from microbe origin have shown to exhibit an excellent physic-chemical or material characteristics with an improved biological properties. Therefore, microbes have been widely used as a new source for synthesizing several metallic NPs with different crystalline structures and properties in the current era of nanobiotechnology. Microbes have high diversity and adopt metal tolerance capabilities and thus, can innately bioreduce metal ions to form metallic NPs which is also sometimes due to a detoxification process in the harsh environment. However, there may occurs many more possible mechanisms during the biological process of nanoparticle biosynthesis which yet to be completely elucidated in detail. Some of the studies have highlighted that metal ions are trapped on the cell surface due to ionic interaction between hydroxyl, carboxyl and other chemical groups occurring on the cells. In some studies, it is reported that metal ions are bioreduced due to enzymatic reactions involving NADPH as a reducing agents. However, Further, high diversity, easy growth, maintenance and genetic manipulation of microbial cells are quite easier, they could be considered as probable biofactories to synthesize NPs in large scale. However, controlled synthesis of a nanostructures with a definite shape, size depends on various factors including the concentration of metal ions, reaction time, temperature, pH and the type of organism used in the bioreduction process. In specific, the microbially produced NPs should possess high stability which is proposed to occur due to proteins expressed by the microbes. Hence, future research should focus on developing a simple, reliable microbe based biological protocol for synthesizing different metallic NPs with uniform shape, size, monodispersity and high stability. In addition, manipulation of genes at the genetic level to overexpress specific enzymes or proteins that involve in reduction reaction or acts as capping agents during the NPs synthesis is another trust area of future discovery. Likewise, the understanding of NPs synthesis by microbes will certainly benefit in mediating the controlled

synthesis of functional nanostructures. Thus, microbes based biosynthesis of NPs can be more advantageous for various biomedical applications due to their incredible physic-chemical, optoelectrical, electronic and biological properties.

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