Chapter 19
Synthesis of Metallic Nanoparticles by Halotolerant Fungi

Sonia M. Tiquia-Arashiro

19.1 Introduction

Halotolerance is the adaptation of living organisms to conditions of high salinity. Halotolerant organisms tend to live in hypersaline environments, along with halophilic organisms. However, they are different from halophilic organisms in that they do not require elevated concentrations of salt to grow. Microbial diversity studies of hypersaline environments including saltern ponds worldwide (Gunde-Cimerman et al. 2000; Butinar et al. 2005; Diaz-Munoz and Montalvo-Rodriguez 2005; Cantrell et al. 2006; Nayak et al. 2012), the Great Salt Lake (Baxter et al. 2005), the Dead Sea (Buchalo et al. 1998; Kis-Papo et al. 2003a, b; Wasser et al. 2003; Bodaker et al. 2010; Nazareth et al. 2012), saline lakes in Inner Mongolia (Pagaling et al. 2009), African soda lakes (Jones and Grant 1999), deep-sea brines (van der Wielen et al. 2005), salt pans or salt marshes (Setati 2010), Mono Lake in California (Steiman et al. 2004), coastal environments of Arctics (Gunde-Cimerman et al. 2005), saline soils of Soos in the Czech Republic (Hujslova et al. 2010), and many others have led to the isolation of halophiles and halotolerant microorganisms.

Fungi hypersaline environments are mostly halotolerant (Gunde-Cimerman et al. 2009; Zajc et al. 2012) rather than halophilic. Thus, they constitute a relatively large and constant part of hypersaline environment communities. Well-studied examples include the yeast *Debaryomyces hansenii* and black yeasts *Aureobasidium pullulans* (Gunde-Cimerman et al. 2009). Surprisingly, more and more cases are being reported of the isolation of halophilic and halotolerant microorganisms from low-salinity environments (Abdel-Hafez et al. 1978; Tiquia et al. 2007; Gunde-Cimerman et al. 2009; Tiquia 2010; Gonsalves et al. 2012). Halophilic and halotolerant fungi

S. M. Tiquia-Arashiro (✉)
Department of Natural Sciences, University of Michigan-Dearborn, Dearborn, MI, USA
e-mail: smtiquia@umich.edu

S. M. Tiquia-Arashiro, M. Grube (eds.), *Fungi in Extreme Environments: Ecological Role and Biotechnological Significance*,
https://doi.org/10.1007/978-3-030-19030-9_19

are often found in unexpected environments such as domestic dishwashers and polar ice, and even on spider webs in desert caves (Gunde-Cimerman et al. 2009).

Halotolerant fungi represent a versatile reservoir of bioactive metabolites and potential source of halotolerant genes that could be used in biotechnology (Tiquia 2010; Tiquia and Mormile 2010). They are a valuable resource of enzymes and other metabolites with stability in harsh conditions of pH, temperature, and/or ionic strength (Margesin and Schinner 2001; Oren 2010). Hence, their use as biocatalysts in the presence of novel nanomaterials is attractive. Combining these bioactive molecules with various nanomaterials like thin layers, nanotubes, and nanospheres results in novel compounds harboring both biological properties of biomolecules and physicochemical characteristics of nanomaterials. While the biosynthesis of nanoparticles in bacteria is well understood (Rai et al. 2012), very few fungal (halotolerant) species have been investigated so far for nanoparticle biosynthesis. In general, the microbiology of fungi is much less investigated, mainly because fungi are difficult to characterize, as their structure complicates the microscopic and mechanistic studies that are required for nanoparticle characterization in it. However, fungi may have some advantages over bacteria for bioprocess, including nanoparticle biosynthesis. Fungi also harbor untapped biological diversity and may provide novel metal reductases for metal detoxification and bioreduction. This review focuses on halotolerant fungi that have been exploited for nanomaterial synthesis; the mechanisms in the nanomaterial fabrication; and possible applications.

19.2 Synthesis of Nanoparticles by Halotolerant Fungi

Reports on nanoparticle synthesis by halotolerant fungi are mostly confined to metallic nanoparticles. These halotolerant fungi capable of synthesizing metallic nanoparticles include *Penicillium fellutatum* (Kathiresan et al. 2009); *Aspergillus niger* (Kathiresan et al. 2009); *Pichia capsulata* (Manivannan et al. 2010); *Yarrowia lipolytica* (Bankar et al. 2009; Pawar et al. 2012); *Rhodosporidium diobovatum* (Seshadri et al. 2011); *Schizosaccharomyces pombe* (Kowshik et al. 2002a, b); *Thraustochytrium* sp. (Asmathunisha and Kathiresan 2013); *Schwanniomyces occidentalis* (Mohite et al. 2016); and *Williopsis saturnus* (Mohite et al. 2017).

Metallic nanoparticles have fascinated scientists for over a century and are now heavily utilized in biomedical sciences and engineering. They are a focus of interest because of their huge potential in nanotechnology (Tiquia-Arashiro and Rodrigues 2016a). Metallic nanoparticles have possible applications in diverse areas such as electronics, cosmetics, coatings, packaging, and biotechnology (Tiquia-Arashiro and Rodrigues 2016b, c). For example, nanoparticles can be induced to merge into a solid at relatively lower temperatures, often without melting, leading to improved and easy-to-create coatings for electronics applications. Typically, nanoparticles possess a wavelength below the critical wavelength of light. This renders them transparent, a property that makes them very useful for applications in cosmetics, coatings, and packaging. Metallic nanoparticles can also be attached to single

strands of DNA nondestructively, which opens avenues for medical diagnostic applications (Tiquia-Arashiro and Rodrigues 2016c).

19.2.1 Synthesis of Gold (Au) Nanoparticles

Gold nanoparticles (AuNPs) have attracted attention in biotechnology due to their unique optical and electrical properties, high chemical and thermal ability, and good biocompatibility and potential applications in various life sciences-related applications including biosensing, bioimaging, and drug delivery for cancer diagnosis and therapy (Jiang et al. 2013). Covalently modified gold nanoparticles have attracted a great deal of interest as a drug delivery vehicle. Their predictable and reliable surface modification chemistry, usually through gold-thiol binding, makes the desired functionalization of nanoparticles quite possible and accurate. Recently, many advancements have been made in biomedical applications of AuNPs with better biocompatibility in disease diagnosis and therapeutics (Tiquia-Arashiro and Rodrigues 2016b). AuNPs can be prepared and conjugated with many functionalizing agents, such as polymers, surfactants, ligands, dendrimers, drugs, DNA, RNA, proteins, peptides, or oligonucleotides. Overall, AuNPs is a promising vehicle for drug delivery and therapies.

Yarrowia lipolytica, a halotolerant yeast (Gunde-Cimerman and Zalar 2014), is known to synthesize AuNPs (Apte et al. 2013a; Nair et al. 2013; Tiquia-Arashiro and Rodrigues 2016d). Melanin (a dark-colored pigment from this yeast) plays an important role in its ability to synthesize nanoparticles. Since the inherent content of melanin in *Y. lipolytica* is low, the yeast is induced to overproduce melanin by incubation with a precursor, L-3,4-dihydroxyphenylalanine (L-DOPA). This process mediates the rapid formation of AuNPs. The AuNPs display antibiofilm activity against pathogenic bacteria (Apte et al. 2013a). They also display effective antifungal properties (Apte et al. 2013b). In addition to AuNPs, some strains of *Y. lipolytica* (e.g., *Y. lipolytica* NCIM 3589) can also synthesize CdO and CdS nanostructures in a cell-associated and extracellular manner (Pawar et al. 2012).

19.2.2 Synthesis of Silver (Ag) Nanoparticles

Silver nanoparticles (AgNPs) are already being commercially used as antimicrobial agents. For example, silver NPs are currently found in surgically implanted catheters to reduce the infections caused during surgery, in toys, personal care products, and silverware. The reason for using silver for antimicrobial applications is because silver possesses antifungal, antibacterial, anti-inflammatory, and anticancer effects (Li et al. 2010, 2014; Chernousova and Epple 2013; Tiquia-Arashiro and Rodrigues 2016c; Zhang et al. 2016).

The halotolerant fungus *Penicillium fellutanum* (De Hoog et al. 2005) can produce AgNPs at a faster rate by extracellular means (Kathiresan et al. 2009). Silver nanoparticles are synthesized within 10 min of silver ions being exposed to the *P. fellutanum* culture filtrate. The increase in color intensity of culture filtrate corresponds to the increase in number of nanoparticles formed by reduction of silver ions (Wang et al. 2009). The AgNPs obtained from this assay has a good monodispersity, with maximum synthesis occurring at pH 6.0, temperature of 5 °C, 24 h of incubation time, and silver nitrate concentration of 1 mM and 0.3% NaCl. Most of the AgNPs generated by *P. fellutanum* are spherical in shape with size ranging from 5 to 25 nm. In this study, the enzyme nitrate reductase is secreted by the *P. fellutanum* biomass and is involved in the reduction of the silver ions (Wang et al. 2009).

Other halotolerant fungi capable of synthesizing AgNPs include *Pichia capsulata* (Manivannan et al. 2010), *Aspergillus niger* (Zomorodian et al. 2016), *Yarowinia lipotyca* (Bankar et al. 2009), *Thraustochytrium* sp. (Asmathunisha and Kathiresan 2013), and *Schwanniomyces occidentalis* (Mohite et al. 2016).

19.2.3 Synthesis of Cadmium Sulfide (CdS) Nanoparticles

Cadmium sulfide (CdS) is a II–VI semiconductor which has been synthesized by microorganisms (Prasad and Jha 2010; Kowshik et al. 2002a). It is insoluble in water but soluble in dilute mineral acids. CdS has a bandgap energy of 2.42 eV (Zhang et al. 2007), at room temperature, and it shows great potential for uses in photochemical catalysis, solar cells, nonlinear optical materials, and various luminescence devices (Ma et al. 2007; Tiquia-Arashiro and Rodrigues 2016c). CdS nanocrystals have generated great interest due to their unique size-dependent chemical and physical properties (Zhao et al. 2006). Thus, extensive research has focused on the synthesis of various CdS nanostructures. In the classical studies by Dameron et al. (1989), it was shown that the halotolerant yeasts *Schizosaccharomyces pombe* can produce of CdS nanocrystallites when challenged with cadmium in solution. Short chelating peptides of general structure (γ-Glu-Cys)*n*-Gly control the nucleation and growth of CdS crystallites to peptide-capped intracellular particles of diameter 20 Å. These quantum CdS crystallites are more monodisperse than CdS particles synthesized chemically. X-ray data indicate that, at this small size, the CdS structure differs from that of bulk CdS and tends towards a six-coordinate rock-salt structure (Dameron et al. 1989).

19.2.4 Synthesis of Lead Sulfide (PbS) Nanoparticles

Semiconductor PbS nanoparticles have attracted great attention in recent decades because of their interesting optical and electronic properties (Bai and Zhang 2009). *Rhodospiridium diobovatum* synthesizes PbS nanoparticles intracellularly with the help of nonprotein thiols (Seshadri et al. 2011). The nanoparticles are in the range

of 2–5 nm. Elemental analysis by energy dispersive X-ray (EDAX) reveals that the particles are composed of lead and sulfur in a 1:2 ratio, and that they are capped by a sulfur-rich peptide. Quantitative study of lead uptake through atomic absorption spectrometry reveals that 55% of lead in the medium accumulated in the exponential phase, whereas a further 35% accumulated in the stationary phase; thus, the overall recovery of PbS nanoparticles is 90%. The lead-exposed *R. diobovatum* displayed a marked increase (280% over the control) in nonprotein thiols in the stationary phase. A sulfur-rich peptide is suggested to be the capping agent. In the presence of lead, *R. diobovatum* produces increasing amount of nonprotein thiols during the stationary phase, which are possibly involved in forming the nanoparticles (Seshadri et al. 2011). *Schizosaccharomyces pombe* is another halotolerant fungus capable of synthesizing PbS nanoparticles (Kowshik et al. 2002b).

19.2.5 Synthesis of Zinc Oxide (ZnO) Nanoparticles

Zinc oxide (ZnO) NPs have unique optical and electrical properties. As a wide bandgap semiconductor, they have found more uses in biosensors, nanoelectronics, and solar cells. These NPs are being used in the cosmetic and sunscreen industry due to their transparency and ability to reflect, scatter, and absorb UV radiation and as food additives. Furthermore, zinc oxide NPs are also being considered for use in next-generation biological applications including antimicrobial agents, drug delivery, and bioimaging probes (Jayaseelan et al. 2012). The potential ability of the halotolerant fungi *Pichia kudriavzevii* (Cai et al. 2014) in the synthesis of zinc oxide nanoparticles (ZnO-NPs) was explored recently (Boroumand Moghaddam et al. 2017). The ZnO nanoparticles synthesized by *P. kudriavzevii* possess hexagonal wurtzite structure with an average crystallite size of ~10–61 nm. They are less toxic and displayed antioxidant and antibacterial activities and show strong 1,1-diphenyl-2-picrylhydrazyl (DPPH) radical effect with a dose-dependent activity. The synthesized ZnO nanoparticles also displayed antibacterial activity against both Gram-positive (*Staphylococcus aureus*, *Bacillus subtilis*, and *Staphylococcus epidermidis*) and Gram-negative (*Escherichia coli* and *Serratia marcescens*) bacteria.

19.3 Nanoparticle Formation Mechanisms in Fungi

The nanoparticles are produced either intracellularly or extracellularly. In case of intracellular synthesis, the nanoparticles are produced inside the cells by the reductive pathways. The synthesis occurs when the metal (e.g., Au^{3+}) concentration available is high and when the membrane integrity is compromised to allow for metal ion diffusion within the cell. In extracellular synthesis, the nanoparticles are produced extracellularly when the cell wall reductive enzymes or soluble secreted

enzymes are extracted outside the cell and are involved in the reductive process of metal ions. The extracellular biosynthesis of metallic nanoparticles is similar to the enzymatic machinery required for metal detoxification. Overall, nanoparticle biosynthesis is essentially a reduction process followed by a stabilization step (capping). There is no evidence available yet showing that fungi use biosynthetic nanoparticles for their metabolism. The biosynthesis of metal NPs by fungi is a function of heavy metal toxicity resistance mechanisms, whereby toxic metals are converted to nontoxic species and precipitated as metal clusters of nanoscale dimension and defined shape (Narayanan and Sakthivel 2010). Resistance mechanisms include redox enzymes that convert toxic metal ions to inert forms, structural proteins that bind protein. It is proposed that such mechanism works to coordinate synthesis.

One of the enzymes involved in the biosynthesis of metal nanoparticles is the nitrate reductase which reduces the metal ions (Me^{1+}) to the metallic form (Me^{0}). This enzyme is a NADH- and NADPH-dependent enzyme. Some fungi are known to secrete cofactor NADH- and NADH-dependent enzymes that can be responsible for the biological reduction of Me^{1+} to Me^{0} and the subsequent formation of nanoparticles. This reduction is initiated by electron transfer from the NADH by NADH-dependent reductase as electron carrier during which the metal ions gain electrons and are therefore reduced to Me^{0}. Synthesis of silver nanoparticles using α-NADPH-dependent nitrate reductase and phytochelatin in vitro has been demonstrated by Anil Kumar et al. (2007). The silver ions are reduced in the presence of nitrate reductase, leading to the formation of a stable silver hydrosol 10–25 nm in diameter and stabilized by the capping peptide. Nitrate reductase is suggested to initiate nanoparticle formation by many fungi including *Penicillium* species, while several enzymes, α-NADPH-dependent reductases, nitrate-dependent reductases, and an extracellular shuttle quinone, are implicated in silver NP synthesis for *Fusarium oxysporum*. Jain et al. (2011) indicated that silver NP synthesis for *Aspergillus flavus* occurs initially by a 33 kDa protein followed by a protein (cystein and free amine groups) electrostatic attraction which stabilizes the nanoparticle by forming a capping agent (Soni and Prakash 2011). Several researchers supported nitrate reductase for extracellular synthesis of metallic NPs (Vigneshwaran et al. 2006; Wang et al. 2009; Deepa and Panda 2014; Siddiqi and Husen 2016; Boroumand Moghaddam et al. 2017).

Cadmium sulfide nanoparticle synthesis by yeast involves sequestration of Cd^{2+} by glutathione-related peptides followed by reduction within the cell. Ahmad et al. (2002) reported that cadmium sulfide nanoparticle synthesis by *Fusarium oxysporum* was based on a sulfate reductase (enzyme) process. The nanoparticle formation proceeds by release of sulfate reductase enzymes by *F. oxysporum*, conversion of sulfate ions to sulfide ions that subsequently react with aqueous Cd^{2+} ions to yield highly stable CdS nanoparticles. While the reduction of sulfate to sulfite is known in sulfate-reducing bacteria (which are strictly anaerobic), this is the first report on the secretion of sulfate-reducing enzymes by a fungus. The extracellular synthesis of AgNP by *P. chrysosporium* is attributed to laccase, while intracellular gold nanoparticle synthesis was attributed to ligninase (Sanghi et al. 2011).

Fungi have several advantages over bacteria for NP biosynthesis. They secrete larger amounts of extracellular proteins with diverse functions. The so-called secretome in fungi include all the secreted proteins into the extracellular space (Girard et al. 2013). The high concentration of the fungal secretome has been used for industrial production of homologous and heterologous proteins. For instance, the expression of a functionally active class I fungal hydrophobin from the entomopathogenic fungus *Beauveria bassiana* has been reported (Kirkland and Keyhani 2011). The tripeptide glutathione is a well-known reducing agent involved in metal reduction and is known to participate in cadmium sulfide (CdS) biosynthesis in yeasts and fungi (Chen et al. 2009). However, the knowledge of the fungal secretome is still largely underexplored especially for halophilic and halotolerant fungi. The large and relatively unexplored fungal secretome is an advantage because of the role of extracellular proteins and enzymes it generates have in metal reduction and nanoparticle synthesis.

19.4 Potential Applications

Bionanoparticles have found uses in biomedical and environmental fields. In the biomedical field, these nanoparticles have been investigated for antimicrobial applications (Sondi and Salopek-Sondi 2004), biosensing (Yu et al. 2003; Mckindles and Tiquia-Arashiro 2012; Tiquia-Arashiro 2012), imaging (Boisselier and Astruc 2009), and drug delivery (Muller et al. 2013). In the environmental field, nanoparticles have been investigated for applications in bioremediation of diverse contaminants (Srivastava et al. 2012; Tiquia-Arashiro and Rodrigues 2016c), water treatment (Ma et al. 2012; Yu et al. 2013), improving plant resistance (McKnight et al. 2003; Rai et al. 2012), and production of clean energy (Wan et al. 2015; Tiquia-Arashiro and Rodrigues 2016c). Overall, bionanoparticles have attracted the attention of diverse researchers because their synthesis is more environmentally friendly and produces more homogeneously distributed nanoparticles, and some of them can be easily biodegradable. Although there are several studies investigating the application of fungal-based nanoparticles, they are still way less studied than bacterial-based nanoparticles. Researchers are still identifying the microbiological synthetic pathways of these bionanoparticles. It is expected that with the advancement of the understanding of bionanoparticle synthesis pathways, the application of bionanoparticles will expand to many more fields than biomedical and environmental and they will be potentially applied in diverse nanotechnological industries.

19.5 Conclusions and Future Perspectives

The interest for bionanoparticles has increased in the past years because they present very different properties and functions than synthetic nanoparticles and they tend to be more biocompatible than their inorganic nonbiological counterparts. The

"green" method for nanoparticle synthesis, which is rapidly replacing traditional chemical syntheses, is of great interest because of eco-friendliness, economic views, feasibility, and wide range of applications in several areas such as nanomedicine and catalysis medicine. The most obvious disadvantages of biological nanoparticles (BNP) are that they frequently do not withstand high or low temperatures, extreme pH values, high salt concentrations, presence of harsh chemicals and potential environmental conditions that could lead to their hydrolysis (Tiquia-Arashiro and Rodrigues 2016e, f). It is possible, however, that BNPs from extremophiles or extremotolerant microorganisms might overcome these issues. While a variety of prokaryotic and eukaryotic microorganisms have been investigated with respect to their nanoparticle synthetic abilities, the vast biodiversity encountered in the fungal halophilic/halotolerant world has been relatively less explored. Furthermore, most of the studies are related to the synthesis of silver nanoparticles, followed by those of gold and less on cadmium, lead, and zinc. One reason for this could be the relative ease with which the noble metal ions of gold and silver are reduced. Currently, there are no reports on synthesis of nanoparticles of platinum, bismuth, antimony sulfide, and titanium oxide by halotolerant fungi. As summarized in this review, biologically active products from halotolerant fungi represent excellent scaffolds for this purpose. However, there is a need to understand the mechanisms involved in the synthetic process. Another limitation of the studies is that the experiments have been conducted at laboratory scale and there are hardly any efforts for the scale-up of these processes. In the future, these shortcomings need to be addressed in an effective manner to harness the actual nanoparticle synthetic potential of the halotolerant to their full extent.

References

Abdel-Hafez SII, Maubasher AH, Abdel-Fattah HM (1978) Cellulose decomposing fungi of salt marshes in Egypt. Folia Microbiol 23:3744

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 124:12108–12109

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

Apte M, Girme G, Nair R, Bankar A, Kumar AR, Zinjarde S (2013a) Melanin mediated synthesis of gold nanoparticles by *Yarrowia lipolytica*. Mater Lett 95:149–152

Apte M, Sambre D, Gaikawad S, Joshi S, Bankar A, Kumar AR, Zinjarde S (2013b) Psychrotrophic yeast *Yarrowia lipolytica* NCYC 789 mediates the synthesis of antimicrobial silver nanoparticles via cell-associated melanin. AMB Express 3:32. https://doi.org/10.1186/2191-0855-3-32

Asmathunisha N, Kathiresan K (2013) A review on biosynthesis of nanoparticles by marine organisms. Colloids Surf B Biointerfaces 103:283–287

Bai HJ, Zhang ZM (2009) Microbial synthesis of semiconductor lead sulfide nanoparticles usingimmobilized Rhodobacter sphaeroides. Mater Lett 63:764–766

Bankar AV, Kumar AR, Zinjarde SS (2009) Environmental and industrial applications of *Yarrowia lipolytica*. Appl Microbiol Biotechnol 84:847–865

Baxter BK, Litchfield CD, Sowers K, Griffith JD, Dassarma PA, Dassarma S (2005) Microbial diversity of Great Salt Lake. In: Gunde-Cimerman N, Oren A, Plemenitaš A (eds) Adaptation to life at high salt concentrations in Archaea, Bacteria, and Eukarya, Cellular origin, life in extreme habitats and astrobiology, vol 9. Springer, Dordrecht, pp 9–25

Bodaker I, Sharon I, Suzuki MT, Reingersch R, Shmoish M, Andreishcheva E, Sogin ML, Rosenberg M, Belkin S, Oren A, Béjà O (2010) The dying Dead Sea: comparative community genomics in an increasingly extreme environment. ISME J 4:399–407

Boisselier E, Astruc D (2009) Gold nanoparticles in nanomedicine: preparations, imaging, diagnostics, therapies and toxicity. Chem Soc Rev 38:1759–1782

Boroumand Moghaddam AB, Moniri M, Azizi S, Rahim RA, Ariff AB, Saad WZ, Namvar F, Navaderi M, Mohamad R (2017) Biosynthesis of ZnO nanoparticles by a new *Pichia kudriavzevii* yeast strain and evaluation of their antimicrobial and antioxidant activities. Molecules 22(6):872. https://doi.org/10.3390/molecules22060872

Buchalo AS, Nevo E, Wasser SP, Oren A, Molitoris HP (1998) Fungal life in the extremely hypersaline water of the Dead Sea: first records. Proc R Soc Lond 265:1461–1465

Butinar L, Sonjak S, Zalar P, Plemenitas A, Gunde-Cimerman N (2005) Melanized halophilic fungi are eukaryotic members of microbial communities in hypersaline waters of solar salterns. Bot Mar 48:73–79

Cai F, Chen FY, Tang YB (2014) Isolation, identification of a halotolerant acid red B degrading strain and its decolorization performance. APCBEE Proc 9:131–139

Cantrell SA, Casillas-Martinez L, Molina M (2006) Characterization of fungi from hypersaline environments of solar salterns using morphological and molecular techniques. Mycol Res 110:962–970

Chen YL, Tuan HY, Tien CW, Lo WH, Liang HC, Hu YC (2009) Augmented biosynthesis of cadmium sulfide nanoparticles by genetically engineered *Escherichia coli*. Biotechnol Prog 25:1260–1266

Chernousova S, Epple M (2013) Silver as antibacterial agent: ion, nanoparticle, and metal. Angew Chem Int Ed 52:1636–1653

Dameron CT, Reese RN, Mehra RK, Kortan AR, Carroll PJ, Steigerwald ML, Brus LE, Wingeet DR (1989) Biosynthesis of cadmium-sulfide quantum semiconductor crystallites. Nature 338:596–597

De Hoog GS, Zalar P, van den Ende BG, Gunde-Cimerman N (2005) Relation of human pathogenicity in the fungal tree of life: an overview of ecology and evolution under stress. In: Gunde-Cimerman N, Oren A, Plemenitaš A (eds) Adaptation to life at high salt concentrations in *Archaea*, *Bacteria* and *Eukarya*. Springer, Dordrecht, pp 397–423

Deepa K, Panda T (2014) Synthesis of gold nanoparticles from different cellular fractions of *Fusarium oxysporum*. J Nanosci Nanotechnol 14:3455–3463

Diaz-Munoz G, Montalvo-Rodriguez R (2005) Halophilic black yeasts *Hortaea wernekii* in the Cabo Rojo Solar Salterns: its first record for this extreme environment in Puerto Rico. Caribb J Sci 41:360–365

Girard V, Dieryckx C, Job C, Job D (2013) Secretomes: the fungal strike force. Proteomics 13:597–608

Gonsalves V, Nayak S, Nazareth S (2012) Halophilic fungi in a polyhaline estuarine habitat. J Yeast Fungal Res 3:30–36

Gunde-Cimerman N, Zalar P, de Hoog GS, Plemenitasˇ A (2000) Hypersaline waters in salterns: natural ecological niches for halophilic black yeasts. FEMS Microbiol Ecol 32:235–240

Gunde-Cimerman N, Butinar L, Sonjak S, Turk M, Uršic V, Zalar P, Plemenitaš A (2005) Halotolerant and halophilic fungi from coastal environments in the Arctics. In: Gunde-Cimerman N, Oren A, Plemenitaš A (eds) Adaptation to life at high salt concentrations in *Archaea*, *Bacteria* and *Eukarya*. Springer, Dordrecht, pp 397–423

Gunde-Cimerman N, Ramos J, Plemenitas A (2009) Halotolerant and halophilic fungi. Mycol Res 113:1231–1241

Hujslova M, Kubatova A, Chudickova M, Kolarik M (2010) Diversity of fungal communities in saline and acidic soils in the Soos National Natural Reserve, Czech Republic. Mycol Prog 9:1–15

Jain N, Bhargava A, Majumdar S, Tarafdar JC, Panwar J (2011) Extracellular biosynthesis and characterization of silver nanoparticles using *Aspergillus flavus* NJP08: a mechanism perspective. Nanoscale 3:635–641

Jayaseelan C, Rahuman AA, Kirthi AV, Marimuthu S, Santhoshkumar T, Bagavan A, Gaurav K, Karthik L, Rao KV (2012) Novel microbial route to synthesize ZnO nanoparticles using *Aeromonas hydrophila* and their activity against pathogenic bacteria and fungi. Spectrochim Acta A Mol Biomol Spectrosc 90:78–84

Jiang L, Li X, Liu L, Zhang Q (2013) Thiolated chitosan-modified PLA-PCLTPGS nanoparticles for oral chemotherapy of lung cancer. Nanoscale Res Lett 8:1–11

Jones BE, Grant WD (1999) Microbial diversity and ecology of the Soda Lakes of East Africa. In: Bell CR, Brylinsky M, Johnson-Green P (eds) Proceedings of the 8th international symposium on microbial ecology. Atlantic Canada Society for Microbial Ecology, Halifax, 7 p

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. Colloids Surf B Biointerfaces 71:133–137

Kirkland BH, Keyhani NO (2011) Expression and purification of a functionally active class I fungal hydrophobin from the entomopathogenic fungus *Beauveria bassiana* in *Escherichia coli*. J Ind Microbiol Biotechnol 38:327–335

Kis-Papo T, Grishkan I, Gunde-Cimerman N, Oren A, Wasser SP, Nevo E (2003a) Spatiotemporal patterns of filamentous fungi in the hypersaline Dead Sea. In: Nevo E, Oren A, Wasser SP (eds) Fungal life in the Dead Sea. Gantner Verlag, Ruggel, pp 271–292

Kis-Papo T, Oren A, Wasser SP, Nevo E (2003b) Survival of filamentous fungi in hypersaline Dead Sea water. Microb Ecol 45:183–190

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

Kowshik M, Vogel W, Urban J, Kulkarni SK, Paknikar KM (2002b) Microbial synthesis of semiconductor PbS nanocrystallites. Adv Mater 14:815–818

Li WR, Xie XB, Shi QS, Zeng HY, Ou-Yang YS, Chen YB (2010) Antibacterial activity and mechanism of silver nanoparticles on *Escherichia coli*. Appl Microbiol Biotechnol 8:1115–1122

Li CY, Zhang YJ, Wang M, Zhang Y, Chen G, Li L, Wu D, Wang Q (2014) In vivo real-time visualization of tissue blood flow and angiogenesis using Ag_2S quantum dots in the NIR-II window. Biomaterials 35:393–400

Ma RM, Wei XL, Dai L, Huo HB, Qin GG (2007) Synthesis of CdS nanowire networks and their optical and electrical properties. Nanotechnology 18:1–5

Ma H, Hsiao BS, Chu B (2012) Ultrafine cellulose nanofibers as efficient adsorbents for theremoval of UO_2^{2+} in water. ACS Macro Lett 1:213–316

Manivannan S, Alikunhi NM, Kandasamy K (2010) In vitro synthesis of silver nanoparticles by marine yeasts from coastal mangrove sediment. Adv Sci Lett 3:1–6

Margesin R, Schinner F (2001) Potential of halotolerant and halophilic microorganisms for biotechnology. Extremophiles 5:73–83

McKindles K, Tiquia-Arashiro SM (2012) Functional gene arrays for analysis of microbial communities on ocean platform. In: Tiquia-Arahiro SM (ed) Molecular biological technologies for ocean sensing. Humana Press, Totowa, NJ, Chap. 9, 169–701 p

McKnight TE, Melechko AV, Griffin GD, Guillorn MA, Merkulov VI, Serna F, Hensley DK, Doktycz MJ, Lowndes DH, Simpson ML (2003) Intracellular integration of synthetic nanostructures with viable cells for controlled biochemical manipulation. Nanotechnology 14:551–556

Mohite P, Apte M, Kumar AR, Zinjarde S (2016) Biogenic nanoparticles from *Schwanniomyces occidentalis* NCIM 3459: mechanistic aspects and catalytic applications. App Biochem Biotechnol 179:583–596

Mohite P, Kumar AR, Zinjarde S (2017) Relationship between salt tolerance and nanoparticle synthesis by Williopsis saturnus NCIM 3298. World J Microbiol Biotechnol 33:163
Muller A, Ni Z, Hessler N, Wesarg F, Muller FA, Kralisch D, Fischer D (2013) The biopolymer bacterial nanocellulose as drug delivery system: investigation of drug loading and release using the model protein albumin. J Pharm Sci 102:579–592
Nair V, Sambre D, Joshi S, Bankar A, Kumar AR, Zinjarde S (2013) Yeast-derived melanin mediated synthesis of gold nanoparticles. J Bionanosci 7:159–168
Narayanan KB, Sakthivel N (2010) Biological synthesis of metal nanoparticles by microbes. Adv Colloid Interface Sci 156:1–13
Nayak S, Gonsalves V, Nazareth S (2012) Isolation and salt tolerance of halophilic fungi from mangroves and solar salterns in Goa–India. Indian J Mar Sci 41:164–172
Nazareth S, Gonsalves V, Nayak S (2012) A first record of obligate halophilic aspergilli from the Dead Sea. Indian J Microbiol 52:22–27
Nina Gunde-Cimerman N, Zalar P (2014) Extremely halotolerant and halophilic fungi inhabit brine in solar salterns around the globe. Food Technol Biotechnol 52(2):170–179
Oren A (2010) Industrial and environmental applications of halophilic microorganisms. Environ Technol 31:825–834
Pagaling E, Wang HZ, Venables M, Wallace A, Grant WD, Cowan DA, Jones BE, Ma Y, Ventosa A, Heaphy S (2009) Microbial biogeography of six salt lakes in Inner Mongolia, China, and a salt lake in Argentina. Appl Environ Microbiol 75:5750–5760
Pawar V, Shinde A, Kumar AR, Zinjarde S, Gosavi S (2012) Tropical marine microbe mediated synthesis of cadmium nanostructures. Sci Adv Mater 4:135–142
Prasad K, Jha AK (2010) Biosynthesis of CdS nanoparticles: an improved green and rapid procedure. J Colloid Interface Sci 342(1):68–72
Rai M, Deshmukh S, Gade A, Elsalam KA (2012) Strategic nanoparticles-mediated gene transfer in plants and animals—a novel approach. Curr Nanosci 8:170–179
Sanghi R, Verma P, Puri S (2011) Enzymatic formation of gold nanoparticles using *Phanerochaete chrysosporium*. Adv Chem Eng Sci 1:154–162
Seshadri S, Saranya K, Kowshik M (2011) Green synthesis of lead sulfide nanoparticles by the lead resistant marine yeast, *Rhodosporidium diobovatum*. Biotechnol Prog 7:1464–1469
Setati ME (2010) Diversity and industrial potential of hydrolase-producing halophilic/halotolerant eubacteria. Afr J Biotechnol 9:1555–1560
Siddiqi KS, Husen A (2016) Fabrication of metal nanoparticles from fungi and metal salts: scope and application. Nanoscale Res Lett 11:98
Sondi I, Salopek-Sondi B (2004) Silver nanoparticles as antimicrobial agent: a case study on *E. coli* as a model for Gram-negative bacteria. J Colloid Interface Sci 275:177–182
Soni N, Prakash S (2011) Factors affecting the geometry of silver nanoparticles synthesis in *Chrysosporium tropicum* and *Fusarium oxysporum*. Am J Nanotechnol 2:112–121
Srivastava S, Kardam A, Raj KR (2012) Nanotech reinforcement onto cellulose fibers: green remediation of toxic metals. Int J Green Nanotechnol 4:46–53
Steiman R, Ford L, Ducros V, Lafond JL, Guiraud P (2004) First survey of fungi in hypersaline soil and water of Mono Lake area (California). Antonie Van Leeuwenhoek 85:69–83
Tiquia SM (2010) Salt-adapted bacteria isolated from the Rouge River and potential for degradation of contaminants and biotechnological applications. Environ Technol 31:967–978
Tiquia SM, Mormile M (2010) Extremophiles—a source of innovation for industrial and environmental applications. Environ Technol 31(8–9):823
Tiquia SM, Davis D, Hadid H, Kasparian S, Ismail M, Sahly R, Shim J, Singh S, Murray KS (2007) Halophilic and halotolerant bacteria from river waters and shallow groundwater along the Rouge River of southeastern Michigan. Environ Technol 28:297–307
Tiquia-Arashiro SM (2012) Molecular biological technologies for ocean sensing. Humana Press, Totowa, NJ, 295 p
Tiquia-Arashiro SM, Rodrigues D (2016a) Extremophiles: applications in nanotechnology. Springer International Publishing, New York, 193 p

Tiquia-Arashiro SM, Rodrigues D (2016b) Nanoparticles synthesized by microorganisms. In: Extremophiles: applications in nanotechnology. Springer International Publishing, New York, pp 1–51

Tiquia-Arashiro SM, Rodrigues D (2016c) Applications of nanoparticles. In: Extremophiles: applications in nanotechnology. Springer International Publishing, New York, pp 163–193

Tiquia-Arashiro SM, Rodrigues D (2016d) Halophiles in nanotechnology. In: Extremophiles: applications in nanotechnology. Springer International Publishing, New York, pp 53–58

Tiquia-Arashiro SM, Rodrigues D (2016e) Thermophiles and psychrophiles in nanotechnology. In: Extremophiles: applications in nanotechnology. Springer International Publishing, New York, pp 89–127

Tiquia-Arashiro SM, Rodrigues D (2016f) Alkaliphiles and acidophiles in nanotechnology. In: Extremophiles: applications in nanotechnology. Springer International Publishing, New York, pp 129–162

van der Wielen PW, Bolhuis H, Borin S, Daffonchio D, Corselli C, Giuliano L, D'Auria G, de Lange GJ, Huebner A, Varnavas SP, Thomson J, Tamburini C, Marty D, McGenity TJ, Timmis KN (2005) The enigma of prokaryotic life in deep hypersaline anoxic basins. Nature 307:121–123

Vigneshwaran N, Ashtaputre NM, Varadarajan PV, Nachane RP, Paralikar KM, Balasubramanya RH (2006) Biological synthesis of silver nanoparticles using the fungus *Aspergillus flavus*. Mater Lett 61:1413–1418

Wan Y, Yang Z, Xiong G, Ruisong G, Liu Z, Luo H (2015) Anchoring Fe_3O_4 nanoparticles on three-dimensional carbon nanofibers toward flexible high-performance anodes for lithium-ion batteries. J Power Sources 294:414–419

Wang CC, Luconi MO, Masi AN, Fernández LP (2009) Derivatized silver nanoparticles as sensor for ultra-trace nitrate determination based on light scattering phenomenon. Talanta 77:1238–1243

Wasser SP, Grishkan I, Kis-Papo T, Buchalo AS, Paul AV, Gunde-Cimerman N, Zalar P, Nevo E (2003) Species diversity of the Dead Sea fungi. In: Nevo E, Oren A, Wasser SP (eds) Fungal life in the Dead Sea. Gantner Verlag, Ruggel, pp 203–270

Yu A, Liang Z, Cho J, Caruso F (2003) Nanostructured electrochemical sensor based on dense gold nanoparticle films. Nano Lett 3:1203–1207

Yu X, Tong S, Ge M, Wu L, Zuo J, Cao C, Song W (2013) Adsorption of heavy metal ions from aqueous solution by carboxylated cellulose nanocrystals. J Environ Sci (China) 25:933–943

Zajc J, Zalar P, Plemenitaš A, Gunde-Cimerman N (2012) The mycobiota of the salterns. In: Raghukumar C (ed) Biology of marine fungi. Progress in molecular and subcellular biology, vol 53. Springer, Berlin, pp 133–158

Zhang YC, Wang GY, Hu XY (2007) Solvothermal synthesis of hexagonal CdS nanostructures from a single-source molecular precursor. J Alloys Compd 437:47–52

Zhang XF, Liu ZG, Shen W, Gurunathan S (2016) Silver nanoparticles: Synthesis, characterization, properties, applications, and therapeutic approaches. Int J Mol Sci 17(9):pii: E1534. https://doi.org/10.3390/ijms17091534

Zhao PQ, Wu XL, Fan JY, Chu PK, Siu GG (2006) Enhanced and tunable blue luminescence from CdS nanocrystal–polymer composites. Scr Mater 55:1123–1126

Zomorodian K, Pourshahid P, Sadatsharifi A, Mehryar P, Pakshir K, Rahimi MJ, Monfared AA (2016) Biosynthesis and characterization of silver nanoparticles by *Aspergillus Species*. Biomed Res Int 2016:5435397, 6 p. https://doi.org/10.1155/2016/5435397