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Metal-Fungus interaction: Review on cellular processes underlying heavy metal detoxification and synthesis of metal nanoparticles

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1 **Metal-Fungus Interaction: Review on cellular processes underlying heavy metal**
2 **detoxification and synthesis of metal nanoparticles**

3
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14 **Abstract**

15 The most adverse outcome of increasing industrialization is contamination of the ecosystem with
16 heavy metals. Toxic heavy metals possess a deleterious effect on all forms of biota; however,
17 they affect the microbial system directly. These heavy metals form complexes with the microbial
18 system by forming covalent and ionic bonds and affecting them at the cellular level and
19 biochemical and molecular levels, ultimately leading to mutation affecting the microbial
20 population. Microbes, in turn, have developed efficient resistance mechanisms to cope with
21 metal toxicity. This review focuses on the vital tolerance mechanisms employed by the fungus to
22 resist the toxicity caused by heavy metals. The tolerance mechanisms have been basically
23 categorized into biosorption, bioaccumulation, biotransformation, and efflux of metal ions. The
24 mechanisms of tolerance to some toxic metals as copper, arsenic, zinc, cadmium, and nickel have
25 been discussed. The article summarizes and provides a detailed illustration of the tolerance
26 means with specific examples in each case. Exposure of metals to fungal cells leads to a response

27 that may lead to the formation of metal nanoparticles to overcome the toxicity by immobilization
28 in less toxic forms. Therefore, fungal-mediated green synthesis of metal nanoparticles, their
29 mechanism of synthesis, and applications have also been discussed. An understanding of how
30 fungus resists metal toxicity can provide insights into the development of adaption techniques
31 and methodologies for detoxification and removal of metals from the environment.

32 **Keywords:** Fungus, Metal resistance, Heavy metals, Metal adsorption, Bioaccumulation, Metal
33 nanoparticles

34

35 **1. Introduction**

36 Heavy metal pollution is a significant concern in many countries where many industrial effluents
37 comprise toxic metal ions. The extent of absorption and distribution, species of origin,
38 bioavailability, ubiquity, and degree of use determines the toxicity of a metal (Zaidi and Pal,
39 2017). The highly persistent nature of these pollutants results in increased accumulation in soil
40 and water bodies (Zafar et al., 2006), making bioremediation difficult. As per the World Health
41 Organization (WHO), metals such as cadmium (Cd), lead (Pb), nickel (Ni), cobalt (Co), and
42 copper (Cu) exhibit severe toxicological effects on aquatic animals and microorganisms.
43 Therefore, the WHO has stipulated tolerable limits of these heavy metals in drinking water. Such
44 maximum permissible limit for specific heavy metals are as follows, Cu 2.0 mg/l; Mercury (Hg)
45 0.006 mg/l; Cd 0.003 mg/l; Arsenic (As) 0.01 mg/l; Pb 0.01mg/l; Chromium (Cr) 0.05 mg/l and
46 Nickel (Ni) 0.07 mg/l (WHO, 2011). However, innate defense strategies of prokaryotes allow the
47 uptake of heavy metal ions and their utilization as nutrients by absorptive and accumulative
48 capacity. Likewise, a eukaryotic microbial system such as fungus has been reported to have
49 enough strategies to survive with metal stress. The different mechanism utilized by the fungus to

50 survive in the presence of metals includes binding of metal ions to high-affinity functional
51 groups, metal accumulation, complexation with different microbial biomolecules and active
52 efflux or exclusion of metals. This review focuses on the detailed investigation and comparative
53 analysis of the different mechanisms employed by the fungus to survive in a hostile metal-
54 contaminated ecosystem. The toxicological impact of heavy metals and the subsequent strategies
55 used by fungal species to limit their effects are described in the subsequent sections with
56 examples of fungal species exhibiting resistant strategies.

57 **2. Toxic effect of heavy metals on fungus**

58 Both natural and anthropogenic activities can be articulated for the occurrence and accumulation
59 of metals in the environment. Effluents from mineral, tanning, automobile, fossil fuels,
60 fertilizers, agricultural, and petroleum industries are few anthropogenic means that significantly
61 contribute towards the release of metals in the atmosphere (Basta et al. 2004; Alloway et al.
62 1995). These effluents constituted of Cu, manganese (Mn), Hg, Pb, and zinc (Zn), along with
63 other inorganic components, which are not degradable and, hence, retained by the soil
64 (Kirpichikova et al. 2006). Because of the high persistence of these metal ions, they accumulate
65 over time with soil acting as a reservoir or metal sink (Adriano, 2003). Industrial and
66 anthropogenic activities are major contributors of heavy metal accumulation in environment,
67 whose excessive presence in soil have adverse effect on fungal growth, and microbial-plant
68 symbiotic association thereby affecting soil fertility, uptake of minerals and nutrient availability
69 to plants (Miransari 2016).

70 Variation in soil physicochemical parameters such as pH and redox potential leads to
71 immobilization of metal ions that exert toxic effect on soil microbes (Gupta 1992). The

72 interaction of fungus with toxic heavy metals induces stress conditions leading to a significant
73 reduction in microbial growth, thereby exerting selective pressure on the microbiota (Nwuche
74 and Ugoji, 2008). Excessive concentration of accumulated metals causes microbial membrane
75 damage, organelle damage, lipid peroxidation and cell apoptosis contributed by generation of
76 reactive oxygen species (Igiri et al. 2018). Literature also signifies that excessive concentration
77 heavy metal can inhibit mycorrhizal fungus functioning (Del et al, 1999). Additionally, pH also
78 affects availability of metals and microbial population in soil. Alkaline pH is known to restrict
79 microbial growth and subsequently decreases the amount of metals (Cd and Zn) available to
80 plants by action of symbiotic fungus (Wang et al, 2006), due to immobilization of metal ions due
81 to precipitation. Soil pH is also known to affect the availability of certain heavy metals ions. A
82 positive correlation between alkaline pH and metal concentration above allowable limit has been
83 suggested (Lenart and Wolny-Koladka, 2012).

84 The fungus is known to utilize both metabolism dependent and independent means to survive
85 under high metal stress conditions (Akar et al., 2005). Table 1 summarizes the various metal-
86 binding sites in fungal cells.

87 As evident the accumulated metal ions introduce several physiological and morphological
88 changes in the microbes. Similarly, toxicity of metal ions is observed at both cellular and
89 molecular levels. Broadly, the cellular defense mechanisms exhibited by fungus can be
90 categorized into extracellular and intracellular means. While the former inhibits the uptake and
91 internalization of metal ions, the later reduces the toxic effect of entrapped metals by binding
92 with biomolecules or efflux channels.

93

94 **2.1. Effect on fungal cell growth**

95 Studies have reported that heavy metal ions adversely affect the fungal cellular life process,
96 ultimately leading to growth inhibition and death. The growth of various species of *Aspergillus*
97 fungus and *Sterigmatomyces halophilus* were observed to be inhibited by heavy metals like Cu,
98 Cd, Mn, Pb, and Zn (Bano et al. 2018). Pb inhibits the growth of *Aspergillus biennis* at a
99 concentration of 10 to 30 mM range (Graz et al. 2011), while Cd inhibits the growth of
100 *Schizophyllum commune* at a concentration of 0.1–0.2 mM (Lilly et al. 1992). Ni induces
101 pyruvate release by altering carbohydrate metabolism, thereby disintegrating the membrane
102 structure in *Neurospora crassa* (Mohan and Sastry 1984). Excessive accumulation of Cd in
103 microbes induces protein and nucleic acid damage resulting in inhibition of cell division, as well
104 as, transcription. At the same time, Hg ions are known to disrupt the microbial cell membrane,
105 impair enzyme function, and denature proteins (Ayangbenro and Babalola, 2017).

106 **2.2. The effect at the biochemical and molecular level**

107 Studies report that a high concentration of toxic metals inhibit enzyme activity, alters enzyme specificity,
108 and leads to conformational changes in nucleic acid and proteins affecting transcriptional and
109 translational steps (Bong et al. 2010). Furthermore, metal ions form precipitates or complexes with
110 microbial metabolites leading to disruption of cellular organelles and whole-cell membranes
111 (Sobolev and Begonia 2008). Ni is reported to induce the deregulation of iron and organic acid
112 metabolism in *A. niger* (Yang et al. 2016; Adiga et al. 1961). Elevated concentration of Cu
113 disintegrates membrane integrity causing the release of solute molecules from cells, ultimately
114 inducing cell death. Cu is also known to cross-link between the DNA strands distorting the
115 helical structure of DNA (Rifkind et al. 2001). Griffiths et al. (1997) assayed the % (G+C)
116 profiling and community hybridization by extracting DNA from a contaminated abatable soil

117 sample and suggested that Cd contamination brings about a decrease in carbon biomass. Cd at a
118 concentration of 50 mg/kg diminishes enzyme activity, precisely that of dehydrogenase, alkaline,
119 and acid phosphatase in sludge (Dar 1996; Landi et al., 2000). A schematic representation of the
120 mode of action of heavy metals on fungus has been illustrated in Figure 1. Exposure of fungal
121 species to heavy metal ions thus induces stress conditions resulting in drastic increase in
122 production of reaction oxygen species as superoxide, peroxides and hydroxyl radicals, that
123 damage fungus cell, organelle structure and alter metabolism (Luna et al 2015, Zang et al 2015,
124 Lin et al 2020). Thus, oxidative stress can be considered as prime reason behind heavy metal
125 induced cell death in microbes.

126

127 **3. Fungal tolerance to heavy metals**

128 As heavy metals are potentially toxic to fungus leading to cell lysis and death, numerous studies
129 focused on deducing the extent of tolerance of various fungi. It was inferred that the specificity
130 and maximum tolerance limit for metals greatly vary at the genus and species levels. Fungus
131 belonging to the species *Aspergillus* sp. and *Penicillium* sp. are among the most resistant strains
132 (Ezzouhri et al. 2009). The difference in the tolerance level of fungal strains (*Aspergillus* sp,
133 *Penicillium* sp, and *Fusarium* sp) isolated from the same location was due to the different
134 resistance strategies employed to tolerate metals (Jacob et al., 2013). *Aspergillus flavus* (ASC1)
135 and *A. niger* (ASB3) were capable of growing in As supplemented media up to a concentration
136 of 2000 ppm and 1200 ppm, respectively (Mukherjee et al. 2013). While *Aspergillus* sp. was
137 resistant to Pb, Cr, Cu, and Zn, In another similar study, *A. niger*, *A. flavus*, and *Fusarium* sp.
138 were reported to be most tolerant to Cr and Pb (Iram et al. 2013).

139 *Penicillium chrysogenum* and *Trichoderma viride* were reported to tolerate Cr up to a
140 concentration of 600 mg/l (Levinskaite, 2002). Few other strains of *Fusarium* sp. and *Penicillium*
141 sp. can tolerate up to 100mg/l Cr while *A. flavus* tolerated up to 400 mg/l Cr (Iram et al. 2012).
142 Similarly, a study comprising 36 strains of *Anthrodia vaillantii* showed that some were able to
143 tolerate up to 40 mM Cu. In contrast, the growth of other strains was inhibited at a mere 3 mM
144 concentration indicating variance in metal tolerance capacity (Collet, 1992).

145 Further, there have been disparities in the tolerance limit of fungal strains isolated from metal
146 contaminated and non-contaminated sites (Howe et al. 1997). *Suillus luteus* fungi, isolated from
147 metal contaminated sites, were observed to be more tolerant than those isolated from non-
148 contaminated sites (Colpaert et al. 2000). However, no relation was observed in a Cd resistant
149 fungus *P. betulinus* isolated from the contaminated and non-contaminated site (Baldrian and
150 Gabriel 2002). The above reports suggest that the striking difference in metal tolerance capacity
151 and specificity. This is probably due to the use of different strategies to resist the toxic effect of
152 metals. Additionally, physiochemical properties of soil and carbon content also affect the
153 capacity of metal tolerance in fungus. A high content of carbon and acidified soil favors fungal
154 growth and so fungal community growing under such conditions have increased metal tolerance.
155 Table 2 clearly shows the variance in the type of metal tolerated by different fungal strains and
156 also gives information on how well they tolerate a particular metal ion or range of metal ions.

157 **4. Mechanism of heavy metal resistance in fungus**

158 The development of metal resistance in microorganisms has evolved due to their continual
159 exposure to toxic metals since life started at least 3.5 billion years ago. Interaction between
160 metals and fungus depends on several factors such as type and concentration of metal, organism
161 and the nature of the contaminated environment. In response to the presence of undesirable

162 metal, fungi have developed both intracellular and extracellular strategies to resist its toxic
163 effect. A detailed investigation of the heavy metal tolerance in fungi suggested the involvement
164 of extracellular system as metal chelation and cellular binding, wherein the entry of the metal ion
165 to the cell interior is prevented. Intracellular strategies involved the conjugation of the metal ion
166 with fungal biomolecules like proteins and organic ligands. On the basis of this, we have broadly
167 categorized the defense mechanism used by fungus under four subheadings (1) biosorption (2)
168 bioaccumulation and compartmentalization (3) metal chelation, and (4) efflux transport for metal
169 exclusion. Figure 2 depicts the different strategies employed by fungus for resistance to toxic
170 heavy metals.

171

172 **4.1. Biosorption**

173 Biosorption describes the adsorption of metal ions via physicochemical interaction with fungal
174 cellular compounds (Kapoor and Viraraghavan, 1998). Biosorption prevents the uptake of metal
175 ions into cell interior aided by the interaction of metals with the microbial surface through
176 electrostatic interactions, Van der Waals forces, covalent bonding, or a combination of these.
177 The microbial cell surface has a net negative charge due to the presence of biomolecules
178 polysaccharides, proteins, and phenolic acids, which have functional groups like hydroxyl,
179 carbonyl, amine and phosphoryl groups, thereby favoring interactions with the cationic heavy
180 metal ions (Blanco A, 2000; Choi and Yun 2006, Remacle 1990). The fungus is considered to be
181 the most efficient biosorbent organism, as its cell wall is composed of around 90% of
182 polysaccharide. *Aspergillus* sp. and *Penicillium* sp. have been reported to be most efficient in
183 biosorption of different metals and have been utilized in numerous sorption studies. A
184 comparative study of Cr adsorption in bacteria, yeast, and fungi, revealed that the fungal species

185 under study (*A. niger*) was most efficient compared to *Streptococcus equisimilis* and
186 *Saccharomyces cerevisiae* in adsorbing Cr (Goyal et al., 2003). Studies suggest that microbial
187 species may be specific towards metal ions because of the variation in cellular compositions of
188 microbial systems and the functional sites responsible for metal binding (Das et al. 2008).

189 Adsorption of Cd by the fungus *Penicillium chrysogenum* XJ-1 requires the involvement of –
190 C=O and –OH groups (Xu et al. 2012). However, the amino groups of chitosan are the primary
191 sites responsible for heavy metal adsorption in the fungus *Penicillium chrysogenum*; and pre-
192 treatment with alkaline solution enhances adsorption efficiency (Tan and Chen 2003). In
193 subsequent studies, they subjected the fungal mycelium to amine modification by treating with
194 epichlorohydrin, a by-product of penicillin fermentation, and found that Ni adsorption got
195 enhanced from 60 mg/g to 260 mg/g. Further, the modified biomass could retain the adsorption
196 efficiency to 10 cycles after treatment with dilute HCl (Tan et al. 2004). While treatment with
197 NaOH markedly improves binding efficiency, as alkaline treatment leads to the removal of
198 proteins, thereby providing more functional sites for metal binding (Baik et al. 2002).

199 Physicochemical parameters as ionic potential, ionic radius, ionic stability of metal ion play
200 significant role in metal adsorption (Tsekova and Ilieva 2001). The fungus, *A. niger* 405 was
201 reported to efficiently adsorb Cr, Cu, Ni and Zn in the pH range of 4 to 6 and stated that at pH
202 value above 6, chemical precipitation inhibited the uptake of metal ions, while at pH below 3,
203 competitive effects between metal cations and hydronium ions hinder metal uptake (Filipovic-
204 Kovacevic et al. 2000). Generally, a decrease in biosorption capacity is observed with increasing
205 metal concentration due to the saturation of metal-binding sites (Rao and Bhargavi 2013).
206 Studies also suggest two-fold removal of Cu in trained/adapted *Talaromyces helices* fungal cells
207 compared to their untrained counterparts, which were because the efficiency of Cu adsorption of

208 mycelium was transferred to the spores (Romero et al. 2006). The whole mycelia of the fungus
209 *A. niger*, *Rhizopus oryzae*, and *Mucor rouxii* were more efficient in adsorbing metals compared
210 to the cell materials (chitosan, glucan, and mannan) extracted from their cell walls. Of the
211 extracted cell materials, chitosan showed the highest metal uptake capacity in comparison to
212 mannan and glucan. Chitosan from *A. niger*, *Rhizopus oryzae*, and *Mucor rouxii* showed Cu
213 binding efficiency of 0.72, 0.85, and 1.13 mmol/g, respectively (Baik et al. 2002).

214 Similarly, live, and heat-inactivated biomass of fungus, *Trametes versicolor* immobilized in
215 carboxymethyl cellulose was observed to adsorb Cu, Pd, and Zn efficiently. Higher metal
216 adsorption efficiency was observed in inactivated forms compared to corresponding live strains.
217 It was inferred that an increase in surface area due to the rupturing of a cell during cell death
218 caused higher metal adsorption by dead biomass than live forms (Bayramoglu et al. 2003). The
219 studies that focused on deducing the mechanism behind biosorption revealed involvement of ion
220 exchange reaction between the negatively charged functional groups of the fungal cell wall and
221 metal ions (Sintuprapa et al. 2000, Fan et al. 2008). Sintuprapa et al. (2000) reported the
222 involvement of a biphasic mode of Zn biosorption in the fungus *Penicillium*, involving the
223 binding of Zn ions in an energy-dependent step followed by slow intracellular accumulation.
224 Ramasamy et al. (2011) speculated the involvement of a protein molecule (66 kDa) in
225 biosorption of Pb by the fungus *Aspergillus fumigates*. They utilized this sorption capacity in the
226 mycoremediation of Pb from electronic-wastes and observed a maximum Pb removal of 85.25
227 %. The process was temperature-dependent as well as energy-dependent. A similar study aimed
228 at removing metals from municipal sewage samples showed that *Sarcinella* sp. had the most
229 potential in Pb absorption (0.32mg/l). In contrast, *Aspergillus flavus*, *Fusarium* sp., and
230 *Cladosporium* sp. showed efficient Cr adsorption (Chandrakar et al. 2014). Similarly, *M. rouxii*

231 IM-80 isolated from mine wastes were found to be the most promising strains for biosorption of
232 Hg (Martinez-Juarez, 2012). Table 3 summarizes the different fungal species capable of
233 biosorption and their biosorption capacity. Fungal functional group make-up has an integral role
234 in metal biosorption and so their appropriate modification, induction of charge alteration can
235 considerably enhance metal tolerance and be used for effective environment remediation
236 application.

237 **4.2. Bioaccumulation and compartmentalization**

238 Though biosorption is the basic strategy employed to resist metal stress, yet microbes employ
239 additional strategy to fight metal toxicity, lest metal ions are transported across the extracellular
240 membrane. In bioaccumulation, the metal ions are precipitated in different cellular organelles
241 (compartmentalization), thereby generating the non-toxic form of metal ions. Compared to
242 biosorption, bioaccumulation is feasible only in live cells and is thus a metabolism dependent
243 process (Ahalya et al. 2003). Some studies suggest that biosorption is followed by
244 bioaccumulation, where its accumulation follows the non-metabolic uptake of metal ions in
245 different cellular organelles. For instance, Ezzouhri et al. (2010) reported that *Penicillium* sp.
246 makes use of both biosorption and bioaccumulation to resist Pb toxicity, where biosorption is
247 followed by both active and passive uptake of Pb. Transmission electron micrographs (TEM)
248 showed the presence of electron-dense bodies formed by Pb's precipitation indicating its
249 diffusion into the cell. Similarly, the Cd-tolerant fungus *Paxillus involutus* relies on a two-step
250 detoxification mechanism involving the uptake and accumulation of Cd in the vacuolar
251 compartment. Cd uptake is assisted by a Ca²⁺ionophore A23187, a metabolically mediated
252 process dependent on potential gradient (Blaudez and Gabriel 2000). In a similar study, Cd
253 uptake in *Paxillus involutus* was reported to occur in a sulfur dependent mode, where Cd

254 accumulation occurs in the form of electron-dense bodies in the vacuoles by binding to the sulfur
255 components. Radiotracer flux analyses suggested the accumulation of 50%, 30%, and 20% of Cd
256 in the cell wall, cytoplasm, and vacuole of the fungus, respectively (Otto et al. 2002). Sintuprapa
257 et al. 2000 suggested that bioaccumulation of Zn by *Penicillium* sp PT1 occurs in the form of
258 phosphate precipitates/ complexes.

259 Bioaccumulation of metals in fungal cells depends on several factors like metal concentration,
260 temperature, pH, other elements/ compounds. However, the significant variation is species-
261 dependent, where the metabolic machinery plays the leading role. Metal uptake in *Calvatia*
262 *excipuliformis*, *Hygrophorus virgineus*, and *Hypholoma capnoides* significantly depend on
263 temperature. Variation in temperature alters the stability and configuration of the cell wall and
264 even ionizes the chemical moieties, affecting metal uptake. A positive correlation was observed
265 between the metal content in the soil and the metal accumulated by the fungus, as the metal
266 accumulation capacity is greatly affected by the available metal concentration, soil pH, and
267 micronutrients (Elekes and Busuioc, 2011). Likewise, bioaccumulation of metal ions (Pb, Cu,
268 Zn, Ni, Cr and Cd) in *A. niger* and *Aspergillus flavus* showed a decrease in accumulation
269 percentage with an increase in metal concentration which is because of the unavailability of
270 binding sites and competition among the metal ions for binding (Thippeswamy et al. 2012).
271 Bioaccumulation of Cr and Ni in *Aspergillus* sp. and *Micrococcus* sp. was reported to
272 significantly depend on temperature (Congeevaram et al. 2007). Accumulation of Cu in
273 *Acremonium pinkertoniae* resulted in the observation of bluish-green colored mycelium when the
274 fungus was cultured in the presence of CuSO₄. Elemental content analysis showed the
275 accumulation of 70-280 mg/g of Cu. Formation of coordinate bonds between the Cu ions,
276 nitrogen and oxygen atoms of amide and hydroxyl groups of the polysaccharides resulted in the

277 incorporation of Cu ions into the glucan-chitin complex leading to the formation of crystalloids
278 (Zapotoczny et al. 2007). Storage and mobilization of Zn in the vacuoles were recognized as the
279 possible mechanism involved in resisting Zn stress in the fungus *Saccharomyces cerevisiae*
280 (Wilson et al., 2012). The transport of Zn to the vacuoles as assisted by cobalt uptake
281 protein/zinc ion trans-membrane transporter (Cot1/Zrc1), belonging to ZnT type transporters is
282 also reported (Devirgilis et al. (2004). The Cot1/Zrc1 transporters originate from *Saccharomyces*
283 *cerevisiae* ATCC 204508 / S288c strain and function in the uptake of Zn and Co ions (Devirgilis
284 et al. 2004). The resistance is thus assisted by Zincosomes, which are vesicles containing Zn.
285 Certain filamentous fungi as *A. niger*, *Serpula himantioides*, and *Trametes versicolor* also
286 showed the remarkable potential to accumulate As when grown on a solid medium supplemented
287 with arsenopyrite (FeAsS). Accumulation of As was observed to be in the order *T. versicolor* > *S.*
288 *himantioides* > *A. niger* (Adeyemi, 2009). In another study, accumulation of Pb by the fungus
289 *Aureobasidium pullulans* was directly correlated to the amount of extracellular polymeric
290 substance (EPS) secreted by the fungus. TEM micrographs suggested that accumulated Pb could
291 not penetrate cell interior due to the presence of EPS, while when EPS was extracted, Pb
292 efficiently penetrated the cell interior (Suh et al. 1999). Table 4 shows the variation in the metal
293 bioaccumulation capacity of different fungal species.

294 Arbuscular mycorrhizal fungi are reported to help the associated plants to overcome in the metal
295 toxicity in moderately polluted soils. These fungi maintain a mutualistic/symbiotic relationship,
296 with plants and increase the hosts' tolerance to heavy metals (Aly et al., 2011). There limited
297 studies on *in-situ* bioaccumulation efficiency of mycorrhiza species. It has been reported that Zn
298 bioaccumulation properties of bacteria *Brevibacillus* and mycorrhiza species favoured plant
299 growth in Zn contaminated soil (Vivas et al, 2006). Endophyte *Trichoderma atroviride* F6,

300 which is reportedly resistant to Cd²⁺ and Ni²⁺ ions, significantly reduces Cd²⁺ and Ni²⁺ soil
301 toxicity to mustard (Cao et al, 2008). The tree *Clethra barbinervis* could tolerate and grow under
302 high heavy-metal concentrations because the root fungal endophytes like *Phialocephala fortinii*,
303 *Rhizodermea veluwensis*, and *Rhizoscyphus* sp. interacted to help in growth enhancement, and
304 decrease of heavy metal uptake by the plant (Yamaji et al 2016). Arbuscular mycorrhizal fungi
305 belonging to phylum The fungal hyphae immobilize and accumulate toxic heavy metals, thereby
306 preventing their translocation to plant parts and prevent damage (Verma et al, 2019, Sánchez-
307 Castro et al 2017, Zang et al 2019). Glomeromycota survive in symbiotic association with many
308 terrestrial plants. This fungus is widely used in heavy metal detoxification because of its property
309 to adsorb, accumulate and chelate metal ions, as well as, sequestration in vacuoles (Mishra et al,
310 2019). It is also known to promote the growth of *Aster tripolium* roots by accumulating high
311 concentration of Cd in the vesicles. A positive association between fungal growth, mycelia
312 biomass and metal tolerance is observed due to their accumulation property (Carvalho et al,
313 2006). Most heavy metal tolerant plants harbor metal resistant fungi in their roots. In plants
314 growing around mining wastes, the most species associated with their roots include *Glomus*,
315 *Acaulospora*, *Fusarium*, *Phoma*, *Cladosporium*, *Microdiplodia*, *Pisolithu*, *Alternaria* and
316 *Peyronellaea* and *Sporobolomyces* (Ortega-Larrocea et al, 2010, Li et al, 2012). Further, metal
317 tolerant fungal species as *Aspergillus*, *Penicillium* and *Fusarium* were observed to accumulate
318 and chelate heavy metals in polluted soil, thereby decreasing heavy metal toxicity and favoring
319 plant growth. These fungal communities were observed in moderately polluted soil and were
320 effective towards heavy metals as Ni, Cd, Cu, Pb and Cr (Lin et al, 2010). The fungal endophytes
321 possess suitable metal chelation or sequestration systems and can remediate metal toxicity
322 through extracellular metal sequestration and precipitation, metal binding to the fungal cell walls,

323 intracellular sequestration and complexation, compartmentation, and volatilization (Fomina et al,
324 2005b).

325

326 **4.3. Metal Chelation**

327 Detoxification of metal ions or metal chelation is another strategy of heavy metal resistance. In
328 response to heavy metal stress, fungi secrete chelating molecules that bind to metal ions,
329 resulting in alleviation of toxic effects. Thiol (-SH) containing molecules, metallothioneins,
330 homogeneous and heterogeneous proteins, peroxidases, and organic acids (citric acid, oxalic
331 acid) serve as efficient metal detoxifying agents (Tripathi et al. 2007). These chelating molecules
332 combine with toxic metal ions leading to the formation of complex non-toxic forms of metals
333 that get sequestered in different cellular organelles. Studies suggest an increase in microbial
334 metabolism in heavily contaminated soil. This is due to rise in energy demand of microbial
335 functional groups associated with metal ion uptake and chelation (Markowicz et al, 2016; Giller
336 et al, 2009). The functional role of some metal chelating agents has been described in detail in
337 the following sections of this review.

338 **4.3.1. Organic acids**

339 Certain fungi secrete organic acids in response to metal stress, which helps in solubilizing the
340 metal ions and form respective metal oxalates. The process of metal detoxification using acids
341 occurs both in an extracellular and intracellular manner. Oxalic and citric acids secreted by *A.*
342 *niger*, *Penicillium* sp, and *Rhizopus* sp. have been reported to detoxify the effect of Cu and Pb.
343 Oxalic acid is also reported to be produced in a significantly high concentration in response to
344 heavy metals by a mycorrhizal fungal species *Rhizopogonroseolus* (Ulla et al. 2000). The role of

345 oxalic acids as chelators to reduce the toxic effect of heavy metals Cd, Cu, Pb, and Zn in
346 *Beauveriacaledonica* was reported by Fomina et al. 2005. In a similar study, the role of organic
347 acids (acetic, oxalic, and citric acid) as strong metal chelating agents was also reported. X-ray
348 absorption spectroscopic analysis revealed that Cu ions coordinated with the carboxyl (-COO⁻)
349 groups present in oxalic acid and Pb coordinated with phosphate (-PO₄³⁻) groups. It was thus
350 suggested that metal chelation by oxalic acids, ligand formation, and oxalate crystals production
351 served as means of metal resistance by the fungus, *B. caledonica*. An increase in organic acid
352 production was observed in fungus *Aspergillus foetidus* adapted to metal ions compared to the
353 control set (Ge et al. 2011). Nickel oxalate dihydrate crystals are formed in response to Ni
354 toxicity by a multi-tolerant strain of *A.niger*. However, oxalate crystals were not formed in the
355 presence of Cd, Co, Cu, and Cr, indicating a specific defense towards Ni (Magyarosy et al.
356 2002). Utilization of oxalic acid as a means to survive metal stress in certain species of wood
357 rooting fungus, including *Bjerkandera fumosa*, *Fomitopsis pinicola*, *Phlebia radiata*, and
358 *Trametes versicolor* have also been reported (Wilkolazka and Gadd 2003).

359 **4.3.2. Metal chelating compounds**

360 Proteins, peptides, enzymes, and some thiol-containing molecules also assist in detoxification of
361 metal ions. Proline, malondialdehyde, and catalase enzymes are reported to be synthesized in
362 response to Pb (Thippeswamy et al. 2014). Resistance to Zn in the fungus *Russulaatropurpurea*
363 PRM 858109 is reported to be assisted by cysteine-containing peptides RaZBP1 and RaZBP2,
364 wherein Zn coordinates with the cysteine (Cys) and histidine (His) residues of RaZBP, helping in
365 the sequestration of excessive Zn in cellular organelles (Leonhardt et al. 2014). Similarly,
366 *Aspergillus* sp.P37 strain uses reduced glutathione (thiol group compounds) like compounds to
367 resist arsenate toxicity. The molecule complexes with reduced arsenate, thereby forming

368 As(GS)₃, which accumulates in the vacuoles. The acidic pH in the vacuole helps to stabilize the
369 entrapped As(GS)₃ (Canovas et al. 2004). Thiol containing GSH is also known to involve the
370 non-enzymatic detoxification of H₂O₂ and scavenges O₂⁻ radicals formed in response to Cd stress
371 in the fungus *Paxillus involutus* (Otto et al. 2002). However, it was also reported that at a high
372 Cd concentration, GSH was found to be ineffective because Cd binds to glutathione or causes its
373 diminution (Jacob et al. 2001). Cu resistance in wood-rotting fungus *Phanerochaete*
374 *chrysosporium*, *Schizophyllum commune*, *Daedalea quercina*, and *Pleurotus ostreatus* was
375 deduced to be due to the synthesis of Cu bio-ligands. The Cu-binding ligands were of 20–60 kDa
376 size in the case of *P. chrysosporium*, *P. ostreatus*, and *S. commune*, while in the case of *D.*
377 *quercina* was of a small molecular weight. *Phanerochaete chrysosporium* cells grown in the
378 presence of Cu showed variation in the sequence of Cu binding ligand compared to control cells
379 (Vacchina et al. 2002).

380 Melanin is another group of fungal chelators produced in response to heavy metals. They are
381 composed of phenolic units, peptides, carbohydrates, fatty acids, aliphatic hydrocarbons and
382 hence efficiently bind to metal ions and the metal complex accumulate in the form of electron-
383 dense granules (Forgarty and Tobin, 1996). In a study conducted by Gadd and Rome (1988),
384 melanin obtained from the fungus *Aureobasidium pullulans* and *Cladosporium resinae* showed
385 higher sorption for Cu ions compared to whole biomass. Pigmented biomass showed greater
386 biosorption in comparison to albino biomass. Even the addition of melanin to the culture of
387 albino *Aureobasidium pullulans* in the presence of Cu showed a decrease in toxicity level.

388 Metallothiones represent the class of metal chelators composed of thiol groups and are produced
389 in fungi, algae, and plants in response to metal stress. The involvement of metallothionein in
390 resisting Cu and Zn in the fungus *Pisolithus tinctorius* was reported for the first time by Morselt

391 et al. (1986). Later, the involvement of thiol compounds (glutathione, phytochelatins, or
392 metallothioneins) in Cd detoxification was reported in the ecto-mycorrhizal fungi, *Paxillus*
393 *involutus*. An increase in glutathione and γ -glutamylcysteine content was observed on Cd
394 treatment (Courbot et al. 2004). Recently, the possible involvement of metallothionein related
395 compounds in detoxification of Cu and Zn was reported. They suggested an increase in protein-
396 bound disulfide and metal-thiolate clusters with increasing metal concentration. They also
397 speculated the involvement of a cysteine-containing peptide RaZBP, sharing 77% similarity to
398 metallothionein (MT) that helps in bio-accumulating Zn similar to Zn-MT complexes for
399 resisting the toxic effect (Leonhardt et al. 2014).

400 **4.4. Efflux transport for metal exclusion**

401 The efflux system is quite necessary to regulate the concentration of metals in the cell interior.
402 Different non-specific transport systems are present in microorganisms that take up both
403 essential and non-essential metals. However, when metal ions are in a concentration that proves
404 to be potentially toxic to microorganisms, specific active efflux systems assist in the exclusion of
405 the metals. Active transport or efflux mechanism is known to be significantly involved in
406 conferring metal resistance to microorganisms. The metal ions accumulated in the cytoplasm are
407 excreted out from the cell interior. Bacteria mostly use this mechanism though some arsenic
408 resistant fungus has been reported to use this as a defense mechanism. *Aspergillus* P37 utilizes
409 the mechanism of extracellular efflux in addition to intracellular accumulation of arsenite to fight
410 arsenate toxicity. The fungus reduces As(V) to As(III), followed by an efflux of reduced arsenate
411 out of the cell(Canovas et al. 2004).

412 A similar mechanism was proposed in a wild type arsenic tolerant fungus *A. niger* (Mukherjee et
413 al. 2010). A comparative analysis between an arsenate-resistant fungus *Hymenoscyphus ericae*

414 (isolated from contaminated mine sites) and non-resistant *H. ericae*, suggested the involvement
415 of a rapid efflux transport system in the resistant strain compared to non-resistant species
416 (Sharples et al. 2000). Arsenic uptake in both the cases occurred by passive diffusion and
417 followed similar uptake kinetics; the arsenate resistant variety lost 90% of the absorbed arsenate.
418 In comparison, non-resistant strain showed only 40% removal. Rapid efflux of H_3AsO_3 ensues
419 after a reduction step wherein $H_2AsO_4^-$ is reduced to H_3AsO_3 after uptake. This mechanism of As
420 tolerance is similar to that used by the bacteria *Staphylococcus aureus*, which reduces $H_2AsO_4^-$
421 to H_3AsO_3 before it is removed by cells (Broer et al. 1993).

422 **5. Fungus mediated metal nanoparticle synthesis**

423 Fungi have the potential to reduce metal into corresponding metal ions when they adhere to or
424 are absorbed into the cell interior. Fungal proteins, enzymes, cofactors, and other metabolites
425 play crucial roles in the organism's survival and reduce metal ions to their nanoparticulate forms
426 (Mehra and Winge 1991). Nanoparticles are typically in the range of 1-100 nm comprising of,
427 but not limited to, metals such as silver (Ag), gold (Au), iron (Fe), zinc (Zn), cadmium (Cd),
428 copper (Cu), barium (Ba), platinum (Pt), palladium (Pd), titanium (Ti), selenium (Sn), zirconium
429 (Zr), and cobalt (Co). Such nanoparticles might be of pure metallic forms or metal compounds
430 such as oxides and sulfides (Sidiqqi et al. 2016). A common approach of synthesizing metal
431 nanoparticles is by reduction of metal ions using a suitable reducing agent. Various organic and
432 inorganic chemical compounds may serve as a reducing agent. Recently the use of biological
433 entities, such as bacteria, virus, fungi, plants, and their cellular component serve as reducing
434 agents, and provide a greener, sustainable, and effective alternative. In this section, the use of
435 various fungi for metal nanoparticle synthesis has been discussed. Fungi being eukaryotic
436 species produce a diverse abundance of bioactive metabolites. The greater the production of such

437 metabolites, the greater the potential for metal reduction. Fungi belonging to different classes,
438 particularly Ascomycota and Basidiomycota, have been reported to be capable of synthesis of
439 various metal and metal compound nanoparticles (Ovais et al. 2018; Dhillon et al. 2011; Gade et
440 al. 2010). Fungi secrete substantial amounts of enzymes and proteins that help obtain a higher
441 nanoparticle yield. It also offers the advantages of secure downstream processing and handling
442 ease suitable for biotechnological processes. A general protocol followed for the fungal synthesis
443 of metal nanoparticles is shown in Figure 3.

444 The studies provide insight to heavy metal tolerance and uptake by fungus which greatly exceeds
445 the accepted permissible limit in contaminated environment. The specific metal tolerance
446 mechanism can be adapted in clean-up of polluted soil, waste management and at mining sites
447 for extraction and removal of metals without need of modification steps.

448

449 **5.1 Mechanism of nanoparticle synthesis**

450 Biosynthesis of metal nanoparticles using fungal cells follows either of the two mechanisms, 1)
451 intracellular or 2) extracellular synthesis routes. In intracellular synthesis, the nanoparticles are
452 formed and localized in the cytoplasm, cell wall, or cell membrane. The nanoparticle precursor
453 (metal ions) first interacts with oppositely charged cell surface moieties where they may be
454 simultaneously reduced to respective nanoparticles and remain bound to the cell surface. Such
455 nanoparticles may diffuse to the cell membrane or cytoplasm. Alternatively, the ions may be
456 internalized by active or passive transport inside the cell and reduced by intracellular reducing
457 agents (Dhillon et al. 2011).

458 One of the earliest studies with an ascomycete, *Verticillium* sp. showed gold nanoparticles of
459 about 20 nm diameter formed and found localized on the walls and mostly on the inner boundary
460 of the cytoplasmic membranes of the cells (Mukherjee et al. 2001a). The intracellular synthesis
461 observed visually by the change in color of the fungal biomass to pink-purple was due to the
462 accumulation of nanoparticles within the cells. Identical synthesis reactions with different
463 genera of fungi ruled out the non-specific mechanism involving cell-wall sugars. The role of
464 electrostatic interaction between the negatively charged tetrachloroaurate (AuCl_4^-) ions and
465 positively charged groups in the cell wall enzymes was speculated to be necessary for the
466 internalization of the ions and subsequent reduction. The nanoparticles could then diffuse inside
467 the cell and localise on the inner surface of the membrane or in the cytoplasm. The similar
468 intracellular synthesis was studied using the same species of fungus to reduce silver nitrate
469 (AgNO_3) to Ag nanoparticles of $25 \pm 12\text{nm}$ in diameter (Mukherjee et al. 2001b).

470 During extracellular synthesis, nanoparticles are formed outside the fungal cells. Ascomycete,
471 *Fusarium oxysporum*, was used for extracellular synthesis of Au nanoparticles from AuCl_4^- ions
472 by Mukherjee et al. (2002). Enzymes released by the cells into the medium were speculated to
473 cause the reduction. The extracellular synthesis was observed by the color change of the medium
474 from colorless to pink-purple and confirmed by TEM analysis of the solution. The study reported
475 a species-specific synthesis of Au nanoparticles where NADH-dependent reductases specific to
476 *F. oxysporum* were believed to be facilitating nanoparticle formation. However, no specific
477 protein was identified in the study. To understand the mechanism of extracellular synthesis,
478 Duran et al. (2005) synthesized Ag nanoparticles with both mycelial biomass, as well as, cell-
479 free extracts of various *Fusarium* strains. The reduction of the metal ions and subsequent
480 synthesis of nanoparticles took place with nitrate-dependent reductases and electron shuttle

481 quinones. The reductases, which were responsible for the reduction of Ag^+ ions to Ag^0
482 nanoparticles, were found to be species-specific. Under similar conditions, different *F.*
483 *oxysporum* strains produced extracellular Ag nanoparticles, whereas *F. moniliforme* did not
484 produce nanoparticles either extracellular or intracellular (Duran et al. 2005). Further, the
485 specific anthraquinones and naphthoquinones which were identified to be the electron shuttles in
486 *F.oxysporium* were not detected in *F. moniliforme*. It is speculated that a conjugation between
487 the quinone electron shuttle with the reductase somehow facilitated the formation of Ag
488 nanoparticles. Hulikere et al. (2019) demonstrated the role of NADPH for the synthesis of Ag
489 nanoparticles through the reduction in the cell-free extract of endophytic fungus *Cladosporium*
490 *cladosporioides*. The extract was dialyzed against distilled water for 48 h. AgNO_3 solution was
491 added to the dialysate in the presence and absence of NADPH. The formation of Ag
492 nanoparticles only in the presence of NADPH was evidential of the role of an NADPH-
493 dependent reductase enzyme in the formation of Ag nanoparticles. In a thermophilic fungus, the
494 size of the reducing agents for Au nanoparticle synthesis was found to be less than 3 kDa
495 (Molnar et al. 2018). This could indicate that smaller molecular species such as amino acid,
496 cofactors, glucose could also serve as reducing agents. Figure 4 shows a schematic
497 representation of the cellular processes involved in the intracellular and extracellular synthesis of
498 metal nanoparticles.

499 **5.1.1. Ligand capping agents**

500 Ligand capping agents, otherwise called stabilizing or functionalizing agents, are molecules that
501 bind to nanoparticle surface to confer stability and prevent nanoparticle aggregation (Sharma et
502 al. 2019). Unlike physicochemical methods of nanoparticle synthesis, which require additional
503 steps for surface functionalization, in biogenic methods synthesis and capping occur

504 simultaneously (Singh et al. 2016). Likewise, in fungi, enzymes, peptides, and proteins play a
505 vital role as reducing and capping agents (Zhao et al. 2018). However, there are few reports on
506 the exact characterization and identification of the capping biomolecules in biogenic
507 nanoparticles. Some studies on the fungal synthesis of nanoparticles suggest electrostatic
508 interaction of free amine groups or cysteine residues with nanoparticle surface (Mukherjee et al.
509 2008, Sanghi et al. 2009). Using elemental spectroscopy imaging Gade et al. (2008) confirmed
510 the presence of sulfur atom around Ag nanoparticles synthesized using *A. niger*. In this case,
511 native protein molecules stabilized the nanoparticle by binding to their surface through sulfur
512 atoms in their constituent amino acids.

513 Studies on fungal mediated Au nanoparticles synthesis suggest protein capping via their
514 respective amide groups (Das et al. 2009, Binupriya et al. 2010), -CH or -OH groups (Mishra et
515 al. 2011), and aromatic and aliphatic -CN groups (Bhambure et al. 2009, Sanghi et al. 2011).
516 Metal oxide nanoparticles by fungi have also been reported to follow nitrate-reductase mediated
517 synthesis followed by protein capping (Vijayanandan et al. 2020, Abdelhakim et al. 2020).
518 Kadam et al. (2019) identified capping proteins of molecular weight 52 kDa and 58 kDa on
519 fungal ZnO nanoparticles. Likewise, Bharde et al. (2006) reported two capping proteins of 55
520 kDa and 13 kDa on fungi synthesized magnetite nanoparticles. It is evident from most of the
521 studies that nitrate-reductases play a central role in fungal mediated nanoparticle synthesis.
522 However, more in-depth investigations are required to identify capping biomolecules. Since their
523 surface functionalization determines most properties of nanoparticles, specific knowledge about
524 capping proteins can help develop the targeted application of fungi-mediated nanoparticles.

525 **5.2. Ag nanoparticles synthesis**

526 Among the various nanoparticles synthesized using fungi, noble metal nanoparticles, especially
527 Ag nanoparticles, dominate the literature. Several species of fungi reported for silver
528 nanoparticles synthesis, along with their applications, have been enlisted in table 5.

529 *Verticillium* mediated synthesis was one of the first reports on the fungal based intracellular
530 synthesis of Ag nanoparticles (Mukherjee et al. 2001b). Mycelial biomass exposed to the AgNO₃
531 solution produced Ag nanoparticles of about 25 nm diameter. Nanoparticles were observed to
532 have localized both on the cell wall and cytoplasmic membrane. Conversely, *Fusarium* based
533 synthesis was reported to undergo an extracellular mechanism of synthesis, forming
534 comparatively smaller silver nanoparticles of 5-15 nm (Ahmad et al. 2003). The reducing agent,
535 an NADH-dependent reductase, was found specific to the species *Fusarium oxysporum*, and no
536 reduction or nanoparticle formation was observed with *F. moniliforme*. Since then, Ag
537 nanoparticles of various sizes and shapes have been reported. Extracellular synthesis of spherical
538 silver nanoparticles of about 16 nm diameter was reported using *Fusarium solani* extract (Ingle et
539 al. 2008). Both fungi *Verticillium* and *Fusarium oxysporum* have been used to synthesize silver
540 nanoparticles, where the particles are entrapped in the biomass in the form of a film (Senapati et
541 al. 2004). Extracts of *A. fumigates* (Bhainsa et al. 2006), and *A. niger* (Gade et al. 2008) have
542 been reported to form Ag nanoparticles of 5-25 nm and 20 nm, respectively. Mycelial biomass
543 of *A. flavus* followed intracellular synthesis forming reasonably monodisperse silver
544 nanoparticles of about 9 nm (Vigneshwaran et al. 2007). In contrast, those of *A. clavatus* formed
545 particles of size ranging 10-60 nm and varied morphological features, including nanohexagons
546 (Verma et al. 2010). Similarly, cell-free filtrates of *Penicillium fellutanum*, *P. brevicompactum*,
547 *P. citrinum*, and *P. polonicum* have been reported for extracellular Ag nanoparticles synthesis

548 ranging in sizes from 5 to 60 nm (Kathiseran et al. 2009; Shaligram et al. 2009; Honary et al.
549 2013; Neethu et al. 2018).

550 Several physicochemical factors affect the synthesis of Ag nanoparticles by fungi. pH and
551 temperature of the synthesis medium, concentration of Ag ion precursors, and composition of
552 culture media. Various species of ascomycete *Trichoderma* have also been shown to
553 biosynthesize Ag nanoparticles under different conditions. The cell-free extracts of three
554 different strains of *Trichoderma viz, T. longibrachiatum, T. viride, and T. harzianum* were
555 capable of synthesizing Ag nanoparticles in a temperature-dependent manner even within the
556 same genus of fungi (Elawami et al. 2018). In *Fusarium oxysporum*, it was demonstrated that
557 higher temperatures led to increased secretion of proteins, thereby enhancing the synthesis of Ag
558 nanoparticles (Birla et al. 2013). The rate of nanoparticle synthesis and the size of particles are
559 also directly affected by temperature. The nanoparticle synthesis rate increased with an increase
560 in temperature, resulting in faster completion of synthesis using *Aspergillus oryzae* (Phanjom
561 and Ahmed, 2017). However, this effect was observed only in a range of temperatures, in this
562 case, between 30 to 90 °C. Abdelrahim et al. (2016), while using *Rhizopus stolonifer* for
563 extracellular synthesis of Ag nanoparticles, showed that no nanoparticles were formed at both
564 extreme ends of their temperature study, i.e., 10 and 80 °C. This was inevitable due to the
565 inactivation and/or denaturation of biomolecules at extreme temperatures.

566 Another important factor considered while the synthesis of nanoparticles is the reaction pH.
567 Using *Epicoccum nigrum*, Qian et al. (2013) established that alkaline pH favored the successful
568 synthesis of Ag nanoparticles. Similar findings were reported by Birla et al. (2013), where
569 nanoparticles synthesis was optimum between pH 9 and 11, which decreased with lowering pH
570 and immediate destabilization of nanoparticles synthesized below pH 5. It is important to recall

571 that Ag nanoparticle synthesis by *Fusariumis* mediated by nitrate reductase enzymes. Hence,
572 nanoparticle synthesis under a given pH ultimately depends upon the activity of these enzymes,
573 proteins, capping agents, and activity of reducing agents under such conditions. These enzymes
574 retain their activity in the pH range of 5 to 9 *in vitro* (with optimum activity around pH 7)
575 (Gholami-Shabani et al. 2014). This might explain the efficient synthesis of nanoparticle in that
576 range. Extracellular synthesis of Ag nanoparticles was reported in the fungus *Penicillium*
577 *purpurogenum* NPMF, which also depends on the pH of extract during nanoparticle synthesis
578 (Nayak et al. 2011; Pradhan et al. 2011).

579 The concentration of Ag ion precursors in the synthesis mixture, together with the synthesis rate,
580 determines the size of nanoparticles. There exists a competitive interaction between Ag ions and
581 fungal reducing agents, which governs the morphology of the nanoparticles. The amount of
582 fungal biomass determines the concentration of reducing agents in the solution. It was shown
583 that the increase in the quantity of biomass also led to increased production of Ag nanoparticles
584 (Birla et al. 2013). They also presented a positive correlation between the size of nanoparticles
585 and increasing concentration of Ag ions up to a certain limit. Furthermore, excessive amounts of
586 Ag ions led to the formation of larger particles and subsequent aggregation (AbdelRahim et al.
587 2016).

588 Different culture media present different growth conditions for fungi, which leads to the
589 production of different metabolites within the cells. Due to this, fungal cells cultured in different
590 culture medium have been reported to produce Ag nanoparticles with different characteristics.
591 Again Birla et al. (2013) demonstrated the effect of ten different culture media on Ag
592 nanoparticle synthesis by *Fusarium oxysporum*. They reported that fungal cells cultured in
593 MGYP medium produced maximum nanoparticles, whereas Czapek and Richard's broth

594 produced the least amount of nanoparticle. Supplementing culture media with specific
595 metabolites has also been reported to enhance nanoparticle production. In one study, Costa Silva
596 et al. (2017) used chitin enriched media in fungal culture to synthesize Ag nanoparticles using
597 nematophagous fungus *Duddingtonia flagrans*. It was observed that fungal biomass growing in
598 chitin supplemented media secreted up to three times more chitinase enzymes. Also, filtrates
599 from chitin-fed biomass showed enhanced production of silver nanoparticles. Further
600 investigation using FTIR and Raman scattering suggested that chitinases might serve as the
601 reducing and capping agent of the nanoparticles. In yet another study, Barbosa et al. (2019)
602 demonstrated that *Duddingtonia flagrans* grown in chitin enriched media produced nematicidal
603 Ag nanoparticles. They attributed this property to chitinase coating of nanoparticles while
604 synthesis.

605 Ag nanoparticles produced using fungi have been reported to have applications in diverse fields.
606 Soil fungus *Macrophomina phaseolina* was used for the synthesis of protein capped Ag
607 nanoparticles possessing antibacterial properties against human and plant pathogenic multidrug-
608 resistant (MDR) strains of *Escherichia coli* and *Agrobacterium tumefaciens*, respectively
609 (Choudhury et al. 2014). *M. phaseolina* exudate was used for biosynthesis of antibacterial
610 Ag/AgCl nanoparticles and demonstrated its applicability as soybean seed protecting agent
611 (Spagnoletti et al. 2019). The Ag nanoparticles fabricated with *Talaromyces purpureogenus* also
612 had a strong anti-proliferation effect against human lung cancer cells A459 (Hu et al. 2019).
613 Akther et al. (2019) demonstrated similar anticancer activity of Ag nanoparticles synthesized
614 with endophytic fungus *Botryosphaeria rhodina*. However, nanoparticles synthesized with
615 extracts of thermophilic fungus *Humicola* sp. were non-toxic to both normal, as well as, cancer
616 cells (Syed et al. 2013). The *Penicillium* sp. isolated from turmeric resulted in nanoparticles (25-

617 30 nm, spherical) with good antimicrobial property against multi-drug resistant strains of
618 bacteria *Escherichia coli* and *Staphylococcus aureus* (Singh et al. 2014).

619 Basidiomycete, *Piriformospora indica* was reported to produce Ag nanoparticles with
620 anticancer properties and antioxidant properties against three cancer cell lines, MCF-7, HeLa,
621 and HepG2 (Aziz et al. 2019). Filamentous fungus, *Amylomyces rouxii*, was reported for
622 extracellular biosynthesis of stable Ag nanoparticles with antimicrobial property (Mussarat et al.
623 2010). Ag nanoparticles have been widely reported for their antimicrobial efficiency and its
624 utilization in surface-enhanced Raman scattering (SERS) signaling (Jena et al. 2009; Kim et al.
625 2007). Various species of entomopathogenic fungi *Metarhizium* have been reported for the
626 synthesis of Ag nanoparticles. Ag nanoparticles produced using *M. robertsii* exhibited antifungal
627 and antibacterial activities (Rozalska et al. 2016). In contrast, those produced by *M. anisopliae*
628 were found to have potent bioinsecticidal effects on malaria vector *Anopheles culicifacies*, *Culex*
629 *quinquefasciatus*, and *Aedes aegyptimosquitos* (Litwin et al. 2020).

630 **5.3. Au nanoparticle synthesis**

631 As mentioned previously, Mukherjee and co-workers pioneered the fungi-mediated synthesis of
632 Au nanoparticles using fungi derived from *Verticillium* sp. (Mukherjee et al. 2001a). Using a
633 similar approach, *Fusarium oxysporum* was employed for extracellular synthesis as well. The
634 particle size ranged between 8-40 nm (Mukherjee et al. 2002). A comparison between the roles
635 of different parts of the fungal system was presented by a rather interesting study by Xie et al.
636 (2007). Au nanoparticles of distinct morphologies were synthesized using fungal biomass,
637 mycelia-free spent media, and fungal extract of *A. niger* in separate reactions. Fungal biomass
638 produced spherical and triangular Au nanoparticles localized on the hyphal surface, whereas the

639 spent medium synthesized triangular, truncated triangular, and hexagonal nanoplates with
640 smooth edges. The fungal extract, on the other hand, produced spirally stacked nanoplates of
641 three or more layers. This finding demonstrated the effects of different fungal metabolic
642 pathways on the overall biosynthesis of nanoparticles. Xie et al. (2007) also demonstrated the
643 temperature and pH dependency of Au nanoparticle synthesis. The reaction rate was found to
644 increase sharply with temperature. They further explained that higher temperatures led to fast
645 reduction, which increased the number of Au seed particles. This further led to the formation of
646 smaller sized nanoparticles compared to the reaction carried out at lower temperatures.
647 Furthermore, temperature also affected the shape of the nanoparticles; higher temperatures
648 decreased the average lateral size of the anisotropic nanoparticles. As mentioned in earlier
649 sections, here too, alkaline pH facilitated faster and better synthesis of Au nanoparticles.

650 Similarly, fungi belonging to *Aspergillus* sp, *Penicillium* sp, *Verticillium* sp, and *Talaromyces*
651 *flavus* have been reported for the synthesis of Au nanoparticles (Soni and Prakash, 2012;
652 Liangweil et al. 2011; Priyadarshini et al. 2014a, Priyadarshini et al. 2013; Mukherjee et al.
653 2001; Priyadarshini et al. 2014b). Previously, we have reported *Talaromyces flavus* based
654 synthesis of Au nanoparticles having floral morphology (Priyadarshini et al. 2013). For the
655 reduction of H₂AuCl₄, we compared the effects of three different reducing solutions prepared
656 from fungi: 1) extracellular filtrate of the fungus, 2) boiled extracellular filtrate, and 3) boiled
657 biomass filtrate. In the first solution, biomolecules were intact, whereas the latter two solutions
658 had denatured biomolecules (presumably proteins). Though undergoing distinct reaction kinetics,
659 all three solutions produced Au nanoparticles. Particles from the extracellular filtrate possessed
660 irregular floral shape, whereas nanoparticles from boiled biomass filtrate were polydispersed
661 with triangular, spherical, and hexagonal morphologies. We also reported *Aspergillus candidus*

662 mediated extracellular synthesis of Au nanoparticles and evaluated its applicability in visual
663 detection of cerium (Priyadarshini et al. 2015). It is speculated that the presence of negatively
664 charged moieties on the Au nanoparticle, rendered by the functionalization while synthesis,
665 provided electrostatic repulsion and stability to the nanoparticles. In the presence of cerium ion,
666 neutralization of the surface charge led to the aggregation of the nanoparticles. Shift in the SPR
667 peak of the nanoparticle solution before and after interaction with cerium is used as basis of
668 selective optical detection of the cerium. In yet another study, we were able to synthesize Au
669 nanoparticles from extracts of *Aspergillus terreus* and reported its antibacterial activity against
670 gram-negative bacteria (Priyadarshini et al. 2014).

671 *Aspergillus sydowii* demonstrated the effect of different concentrations of fungal biomass on Au
672 nanoparticle size (Vala 2015). Experimental setups such as shaking or stationary conditions were
673 shown to affect the morphology and localization of the Au nanoparticles (Ahmad et al. 2005).
674 *Trichothecium* sp. biomass produced spherical, rod-shaped, and triangular Au nanoparticles
675 extracellularly under stationary conditions. In contrast, it produced spherical nanoparticles
676 localized in the plasma membrane and cell wall when the reaction was carried out under shaking
677 conditions. Other prominent ascomycetes used in Au nanoparticle synthesis include
678 *Yarrowialipolytica* (Agnihotri et al. 2009), *Penicillium berricompactum* (Mishra et al. 2011) and
679 *Candida albicans* (Chauhan et al. 2011). Mishra et al. (2011) demonstrated the cytotoxic effects
680 of Au nanoparticles against mouse myoblast cancer cells. Also, Chauhan *et al.* (2011) further
681 conjugated Au nanoparticles with cell-specific antibodies for possible detection in liver cancer.
682 Extracts of a basidiomycete, *Sclerotium rolfsii* was reported to synthesize isotropic and
683 anisotropic Au nanoparticles with an average size of 25 nm (Narayanan and Sakthivel 2011).

684 **5.4. Synthesis of other metal/metal compound nanoparticles**

685 Apart from Ag and Au nanoparticles, fungal mediated nanoparticle synthesis of Cd, Cu, Pt, and
686 Se compounds, including metal oxides, and sulphides have also been reported. *Fusarium* seems
687 to be the most exploited fungus in the synthesis of Ag, Au, Cu, Pt, Se derived nanoparticles.
688 Ahmad et al. (2002) conducted the extracellular synthesis of CdS nanoparticles with sulfate-
689 reducing enzymatic machinery of *Fusarium oxysporium*. The same fungus was used to
690 synthesize ferroelectric BaTiO₃ nanoparticles of 10 nm under ambient conditions (Bansal et al.
691 2006a). In yet another novel study by Bansal et al. (2006b), amorphous silica (-SiO₂) in rice husk
692 was transformed into its nanocrystalline form using *F. oxysporium*. Proteins present in the
693 fungus were reported to have capped and stabilized the SiO₂ nanoparticles, which then leached
694 out into the reaction solution. Other nanoparticles successfully biosynthesized using *Fusarium*
695 include cadmium selenide (CdSe) quantum dots (Kumar et al. 2007), Zn nanoparticles (Bansal et
696 al. 2004) and hematite, Fe₂O₃ (Mahanty et al. 2019, Bharde et al. 2006). Mahanty et al. (2019)
697 showed the variation between Feoxide nanoparticles formed by three different fungal species viz.
698 *Trichoderma asperellum*, *Phialemoniopsis ocularis* and *Fusarium incarnatum*. Similarly, the
699 formation of magnetite (Fe₃O₄) nanoparticles using *F. oxysporium* and *Verticillium* sp. was
700 demonstrated (Bharde et al. 2006). The *Fusarium oxysporum* et again showed the capability of
701 Pt nanoparticle synthesis (Syed and Ahmad 2012). The mycelia biomass, when exposed to
702 precursor ions form spherical Pt nanoparticles of 15-30 nm. Bismuth oxide nanoparticles also
703 were reported to be synthesized using *Fusarium oxysporium* (Uddin et al. 2008).

704 Another fungus frequently reported for other metal and metal oxide nanoparticle synthesis is
705 *Aspergillus*. TiO₂ nanoparticles were synthesized using *Aspergillus flavus* (Rajakumar et al.
706 2012). The nanoparticles were 55-65 nm in size and possessed antibacterial property. The
707 biosynthesis of sulfur-bearing protein-coated spherical Co oxide nanoparticles using *A. nidulans*

708 was possible (Vijayanandan and Balakrishnan 2018). *A. terreus* and *A. oryzae* were shown to
709 biosynthesize Se nanoparticles (Zare et al. 2013 and Mosallam et al 2018). *A. terreus* cell-free
710 filtrate produced polydisperse Se nanoparticles of the size 10-100 nm. Mosallam et al. (2018)
711 employed a different approach of synthesis by exposing the cell-free filtrate to Se ions in the
712 presence of gamma rays to maximize nanoparticle production. The ZnO nanoparticles were
713 synthesized using the cell-free extract of *Cochliobolus geniculatus*, a Zn tolerant endophytic
714 fungus (Kadam et al 2019). Here, two proteins of 52 kDa and 58 kDa were identified to be the
715 capping material on the spherical nanoparticles of 2 to 6 nm. Cu nanoparticles were synthesized
716 using *Colletotrichum gloeosporioides* biomass and then immobilized in graphene oxide-chitosan
717 composite (Mugesh et al. 2019). The resultant nanocomposite had antibacterial and cytotoxic
718 properties against human breast cancer cells. Fungal derived crude xylanases were utilized in
719 synthesizing Ag-Au alloy nanoparticles with antimicrobial, antioxidant, and anticoagulant
720 properties (Elegbede et al. 2019). *Aspergillus sp.* has been reported to produce lead nanoparticles
721 in a size range of 1.77 to 5.8 μm (Pavani et al. 2012). A summary of different fungal strains
722 showing the capability of nanoparticle synthesis is Table 5.

723 There are many reports of metal-based nanoparticles synthesized using a variety of fungal
724 species. However, very few studies give conclusive information on the biomolecules involved in
725 metal reduction leading to nanoparticle formation and the capping agents of fungal origin
726 responsible for the stability of nanoparticles. Further studies are required to shed light on
727 variation and diversity of biomolecules involved in nanoparticle formation from within
728 individual strains and across fungal species. The efficiency of fungal communities to reduce
729 metals into nanoparticle form promises cost-effective and feasible bioremediation and waste

730 management strategies. Green approaches with minimal resource utilization and on-site
731 application are additional advantages compared to conventional remediation methods.

732 **6. Conclusion and Future Prospects**

733 Fungi have evolved active defense mechanisms as biosorption, bioaccumulation, metal chelation,
734 and efflux transport to provide resistance from heavy metal stress in natural environments. The
735 fungal resource has emerged as a unique proposition in bioremediation of contaminated areas,
736 metal nanoparticle synthesis, and metals extracted from ores. Novel strains of fungus are being
737 studied for their metal extraction and nanoparticle synthesis capability. Economically feasible
738 biotechnological strategies for bioremediation of contaminated soil and water, as well as,
739 biomining strategies of metal oxides signify the natural power of microbes. The potential risk
740 associated with live fungus, and the release of toxic compounds can be avoided by using heat-
741 inactivated fungus or isolated cell fractions that show an equal efficiency of nanoparticle
742 production and biosorption capacity. This would eliminate the toxicological risks and jurisdictional
743 constraints associated with the use of live fungus in bioremediation and water purification
744 processes.

745 Furthermore, selection, genetic manipulation of high metal resistant fungal strains, and a mixed
746 consortium of fungal species may enhance tolerance and resistant capacity. This would assist in
747 the concentrated extraction of metals from dilute solutions, improving biosorption, and
748 nanoparticle formation feasibility. The development of technology for simultaneous detection
749 and removal of toxic metals would assist in the bioremediation of toxic metal from contaminated
750 sites, industrial effluents and electronic-wastes. Understanding the mechanism may enable the
751 utilization of green, non-toxic, and efficient means of bioremediation. Further interdisciplinary

752 studies and scaling up strategies would favour the application of these in large scale
753 bioremediation approaches to improve unwanted outcomes in natural environments.

754

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763 **Compliance with ethical standards**

764 This article does not contain any studies with human participants performed by any of the
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766 **Conflict of interest**

767 The authors declare that they have no conflict of interest.

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773 **References**

774 Abdelhakim, HK, El-Sayed, ER, Rashidi, FB (2020) Biosynthesis of zinc oxide nanoparticles
775 with antimicrobial, anticancer, antioxidant and photocatalytic activities by the endophytic
776 *Alternaria tenuissima*. Journal of Applied Microbiology Jan 18. doi: 10.1111/jam.14581

777 AbdelRahim, K, Mahmoud, SY, Ali, AM (2016) Extracellular biosynthesis of silver
778 nanoparticles using *Rhizopus stonilifer*. Saudi Journal of Biological Sciencesdoi:
779 <http://dx.doi.org/10.1016/j.sjbs.2016.02.025>

780 Adiga, PR, Sastry KS, Venkatasubramanyam V & Sarma PS (1961) Interrelationships in Trace-
781 Element Metabolism in *Aspergillus niger*. Biochemical Journal81: 545–550.

782 Adriano, DC Trace Elements in Terrestrial Environments: Biogeochemistry, Bioavailability and
783 Risks of Metals, Springer, New York, NY, USA, 2nd edition, 2003.
784

785 Agnihotri M, Joshi S, Kumar AR, Zinjarde S, Kulkarni S (2009) Biosynthesis of gold
786 nanoparticles by the tropical marine yeast *Yarrowia lipolytica* NCIM 3589. *Materials Letters* 63:
787 1231–1234.

788 Ahalya N, Ramachandra TV, Kanamadi RD (2003) Biosorption of Heavy Metals. Research
789 Journal of Chemistry and Environment7:71–78

790 Ahmad, A, Mukherjee, P, Mandal, D, Senapati, S, Khan, MI, Kumar, R, Sastry, M (2002)
791 Enzyme mediated extracellular synthesis of CdS nanoparticles by the fungus, *Fusarium*
792 *oxysporum*. Journal of American Chemical Society124: 12108–12109.

793 Ahmad, A, Mukherjee, P, Senapati, S, Mandal, D, Khan, MI, Kumar, R, Sastry, M (2003)
794 Extracellular biosynthesis of silver nanoparticles using the fungus *Fusarium oxysporum*.
795 Colloids and Surfaces B: Biointerfaces28 313–318.

796 Ahmad, A, Senapati, S, Khan, MI, Kumar, R, Sastry, M (2005) Extra-/intracellular biosynthesis
797 of gold nanoparticles by an alkalotolerant fungus, *Trichothecium sp*. Journal of Biomedical
798 Nanotechnology1: 47–53.

799 Ahmad, F (2005) Heavy Metal Biosorption potential of *Aspergillus* and *Rhizopus* sp. isolated
800 from wastewater treated soil. Journal of Applied Sciences and Environmental
801 Management9:123–126

802 Akar, T, Tunali, S, Kiran, I (2005) *Botrytis cinerea* as a new fungal biosorbent for removal of
803 Pb(II) from aqueous solutions. Biochemical Engineering Journal25 227–235.

804 Akhtar, S, Mahmood-ul-Hassan, M, Ahmad, R, Suthor, V, Yasin, M (2013) Metal tolerance
805 potential of filamentous fungi isolated from soils irrigated with untreated municipal effluent. Soil
806 Environment 32: 55–62.

807 Alloway, BJ (1995) Soil Processes and the Behavior of Metals In: Alloway, B.J., Ed., Heavy
808 Metals in Soils, Blackie Academic & Professional, London, pp: 38–57.

809 Arica, Y, Bayramoglu, G, Yilmaz, M, Bektas, S, Genc, O (2004) Biosorption of Hg^{2+} , Cd^{2+} , and
810 Zn^{2+} by Ca–Alginate and immobilized wood–rotting fungus *Funalia trogii*. Journal of Hazardous
811 Materials109:191–199.

812 Ayangbenro, AS, Babalola, OO (2017) A New Strategy for Heavy Metal Polluted Environments:
813 A Review of Microbial Biosorbents. International Journal of Environmental Research and Public
814 Health14: 94

815 Aziz, N, Faraz, M, Sherwani, MA, Fatma, T, Prasad, R (2019) Illuminating the anticancerous
816 efficacy of a new fungal chassis for silver nanoparticle synthesis. Frontiers in Chemistry7: 1–11.

817 Baik, WY, Bae, JH, Cho, KM, Hartmeier, W (2002) Biosorption of heavy metals using white
818 mold mycelia and parts thereof. Bioresource Technology81: 167.

819 Bahadir, T, Baka, G, Altas, L, Büyükgüngör, H (2007) The investigation of lead removal by
820 biosorption: An application at storage battery industry wastewaters. Enzyme and Microbial
821 Technology41: 98–102

822 Balaji, DS, Basavaraja, S, Deshpande, R, Mahesh, DB, Prabhakar, BK, Venkataraman, A (2009)
823 Extracellular biosynthesis of functionalized silver nanoparticles by strains of *Cladosporium*
824 *cladosporioides* fungus. Colloids Surfaces B: Biointerfaces68: 88–92.

825 Baldrian, P, Gabriel, J (2002) Intraspecific variability in growth response to cadmium of the
826 wood–rotting fungus *Piptoporus betulinus*. Mycologia94: 428–436.

827 Bano, A, Hussai, J, Akbarm A, mehmood, K, Anwar, M, Hasni, MS, Ullah, S, Sajid, S, Ali, I, (2018)
828 Biosorption of heavy metals by obligate halophilic fungi. Chemosphere 199:218-222.

829 Bansal, V, Rautaray, D, Ahmad, A, Sastry, M (2004) Biosynthesis of zirconia nanoparticles
830 using the fungus *Fusarium oxysporum*. Journal of Materials Chemistry14: 3303–3305.

831 Bansal, V, Poddar, P, Ahmad, A, Sastry, M (2006a) Room–temperature biosynthesis of
832 ferroelectric barium titanate nanoparticles. Journal of American Chemical Society128: 11958–
833 11963.

834 Bansal, V, Ahmad, A, Sastry, M (2006b) Fungus–mediated biotransformation of amorphous
835 silica in rice husk to nanocrystalline silica. Journal of American Chemical Society128: 14059–
836 14066.

837 Barabadi, H, Ovais, M, Shinwari, ZK, Saravanan, M (2017) Anti–cancer green bionanomaterials:
838 Present status and future prospects. Green Chemistry Letters and Reviews10: 285–314.

839 Barbosa, ACMS, Costa Silva, LP, Ferraz, CM, Tobias, FL, De Araújo, JV, Loureiro, B, Braga,
840 GMAM, Veloso, FBR, Soares, FEF, Fronza, M, Braga, FR (2019) Nematicidal activity of silver

841 nanoparticles from the fungus *Duddingtonia flagrans*. International Journal of Nanomedicine14:
842 2341–2348.

843 Basta, NT, Ryan, JA, Chaney, RL (2004) Trace element chemistry in residual–treated soil key
844 concepts and metal bioavailability. Journal of Environmental Quality34:49–63.

845 Bayramoglu, G, Bekta, S, Arica, MY (2003) Biosorption of heavy metal ions on immobilized
846 white–rot fungus *Trametes versicolor*. Journal of Hazardous MaterialsB101: 285–300.

847 Bhainsa, KC, D’souza, SF (2006) Extracellular biosynthesis of silver nanoparticles using the
848 fungus *Aspergillus fumigatus*. *Colloids Surfaces B: Biointerfaces*47: 160–164.

849 Bhambure, R, Bule, M, Shaligram, N, Kamat, M, Singhal, R (2009) Extracellular Biosynthesis of
850 Gold Nanoparticles using *Aspergillus niger* – its Characterization and Stability. Chemical and
851 Engineering Technology 32: 1036–1041

852 Bharde, A, Rautaray, D, Bansal, V, Ahmad, A, Sarkar, I, Yusuf, SM, Sanyal, M, Sastry, M
853 (2006) Extracellular biosynthesis of magnetite using fungi. *Small*2: 135–141.

854 Binupriya, AR, Satishkumar, M Vijayaraghavan, K, Yun, S-I (2010) Bioreduction of trivalent
855 aurum to nano-crystalline gold particles by active and inactive cells and cell-free extract of
856 *Aspergillus oryzae* var. *viridis*. Journal of Hazardous Materials177: 539–545

857 Birla, SS, Gaikwad, SC, Gade, AK, Rai, MK (2013) Rapid Synthesis of Silver Nanoparticles
858 from *Fusarium oxysporum* by Optimizing Physicocultural Conditions. The Scientific World
859 Journal 2013 Article ID 796018, 12 pages. doi:10.1155/2013/796018.

860 Birla, SS, Tiwari, VV, Gade, AK, Ingle, AP, Yadav, AP, Rai, MK (2009) Fabrication of silver
861 nanoparticles by *Phoma glomerata* and its combined effect against *Escherichia coli*,
862 *Pseudomonas aeruginosa* and *Staphylococcus aureus*. Letters in Applied Microbiology 48: 173–
863 179.

864 Blanco, A (2000) Immobilization of nonviable cyanobacteria and their use for heavy metal
865 adsorption from water. In: Olguin EJ, Sanchez G, Hernandez E (Eds) Environmental
866 biotechnology, Philadelphia, pp 135–151.

867 Bong, CW, Malfatti, F, Azam, F, Obayashi, Y, Suzuki, S (2010) The Effect of Zinc Exposure on
868 the Bacteria Abundance and Proteolytic Activity in Seawater In Interdisciplinary Studies on
869 Environmental Chemistry– Biological Responses to Contaminants, Eds., N Hamamura, S
870 Suzuki, S, Mendo, C M Barroso, H Iwata and S Tanabe, pp 57–63.

871 Broer, S, Ji, G, Broer, A, Silver, S (1993) Arsenic efflux governed by the arsenic resistance
872 determinant of *Staphylococcus aureus* plasmid pI258. Journal of Bacteriology175: 3480–3485.

873 Bruins, MR, Kapil, S, Oehme, FW (2000) Microbial resistance to metals in the environment.
874 Ecotoxicology and Environmental Safety45: 198–207.

875 Caesar–Tonthat, TC, Kloeke, FV, Geesey, GG, Henson, JM (1995) Melanin production by a
876 filamentous soil fungus in response to copper and localization of copper sulfide by sulphide
877 silver staining. Applied Environmental Microbiology61: 1968–1975.

878 Canovas, D, Vooijs, R, Schat, H, De Lorenzo, V (2004) Role of thiol species in the
879 hypertolerance of *Aspergillus sp.* P37 to Arsenic. Journal of Biological Chemistry279: 51234–
880 51240.

881 Carvalho, L.M.; Cacador, I.; Martins-Loucao, M.A. Arbuscular mycorrhizal fungi enhance root
882 cadmium and copper accumulation in the roots of the salt marsh plant *Aster tripolium* L. Plant
883 Soil 2006, 285, 161–169.
884

885 Castro–Longoria, E, Vilchis–Nestor, AR, Avalos–Borja, M (2011) Biosynthesis of silver, gold
886 and bimetallic nanoparticles using the filamentous fungus *Neurospora crassa*. Colloids Surfaces
887 B: Biointerfaces83: 42–48.

888 Chandrakar, V, Sahu, S, Khare, J, Sathpathy, S (2014) Removal of Pb and Cr by fungi in
889 municipal sewage water. Indian Journal of Scientific Research4: 214–217.

890 Chauhan, A, Zubair, S, Tufail, S, Sherwani, A, Sajid, M, Raman, SC, Azam, A, Owais, M (2011)
891 Fungus–mediated biological synthesis of gold nanoparticles: potential in detection of liver
892 cancer. International Journal of Nanomedicine6: 2305–2319.

893 Choi, SB, Yun, YS (2006) Biosorption of cadmium by various types of dried sludge: an
894 equilibrium study and investigation of mechanisms. Journal of Hazardous Material138: 378–383

895 Chowdhury, S, Basu, A, Kundu, S (2014) Green synthesis of protein capped silver nanoparticles
896 from phytopathogenic fungus *Macrophomina phaseolina* (Tassi) Goid with antimicrobial
897 properties against multidrug–resistant bacteria. Nanoscale Research Letters9: 365–376.

898 Colpaert, JV, van Den, KP, Adriaensen, K, van Gronsveld, J (2000) Genetic variation and heavy
899 metal tolerance in the ectomycorrhizal basidiomycete *Suillus luteus*. New Phytology147:367–
900 379.

901 Congeevaram, S, Dhanarani, S, Park, J, Dexilin, M, Thamaraiselvi, K (2007) Biosorption of
902 chromium and nickel by heavy metal resistant fungal and bacterial isolates. Journal of Hazardous
903 Materials146: 270–277

904 Costa Silva, LP, Pinto Oliveira, J, Keijok, WJ, et al (2017) Extracellular biosynthesis of silver
905 nanoparticles using the cell-free filtrate of nematophagous fungus *Duddingtonia flagrans*.
906 International Journal of Nanomedicine 12:6373–6381

907 Courbot, M, Diez, L, Ruotolo, R, Chalot, M, Leroy, P (2004) Cadmium–responsive thiols in the
908 ectomycorrhizal fungus *Paxillus involutus*. Applied Environmental Microbiology 70: 7413–7417.

909 Dar, G (1996) Effects of cadmium and sewage sludge on soil microbial biomass and enzyme
910 activities. Bioresources and Technology 56: 141–145.

911 Dar, MA, Ingle, A, Rai, M (2013) Enhanced antimicrobial activity of silver nanoparticles
912 synthesized by *Cryphonectria* sp. evaluated singly and in combination with antibiotics.
913 Nanomedicine Nanotechnology Biology and Medicine 9: 105–110.

914 Das, N, Vimala, R, Karthika, P (2008) Biosorption of heavy metals– an overview. Indian Journal
915 of Biotechnology 7: 159–169.

916 Das, SK, Das, AR, Guha, AK (2009) Gold nanoparticles: microbial synthesis and application in
917 water hygiene management. Langmuir 25: 8192–8199

918 Das, SK, Dickinson, C, Lafir, F Broughman, DF, Marsili, E (2012) Synthesis, characterization
919 and catalytic activity of gold nanoparticles biosynthesized with *Rhizopus oryzae* protein extract.
920 Green Chemistry 14: 1322–1334

921 Del Val C., J. M. Barea, and C. Azcón-Aguilar, “Diversity of arbuscular mycorrhizal fungus
922 populations in heavy-metal- contaminated soils,” Applied and Environmental Microbiology, vol.
923 65, no. 2, pp. 718–723, 1999

924 Devirgilis, C, Murgia, C, Danscher, G, Perozzi, G (2004) Exchangable zinc ions transiently
925 accumulate in a vesicular compartment in the yeast *Saccharomyces cerevisiae*, Biochemical
926 Biophysical Research Communication 323: 58–64.

927 Dhillon, GS, Brar, SK, Kaur, S, Verma, M (2012) Green approach for nanoparticle biosynthesis
928 by fungi: Current trends and applications. Critical Reviews in Biotechnology 32: 49–73.

929 Durán, N, Marcato, PD, Alves, OL, De Souza, GIH, Esposito, E (2005) Mechanistic aspects of
930 biosynthesis of silver nanoparticles by several *Fusarium oxysporum* strains. Journal of
931 Nanobiotechnology 3: 8. doi: 10.1186/1477–3155–3–8

932 Elamawi, RM, Al–Harbi, RE, Hendi, AA (2018) Biosynthesis and characterization of silver
933 nanoparticles using *Trichoderma longibrachiatum* and their effect on phytopathogenic fungi.
934 Egyptian Journal of Biological Pest Control 28: 28. doi:10.1186/s41938–018–0028–1.

935 Elegbede, JA, Lateef, A, Azeez, MA, Asafa, TB, Yekeen, TA, Oladipo, IC, Hakeem, AS,
936 Beukes, LS, Gueguim–Kana EB (2019) Silver–gold alloy nanoparticles biofabricated by fungal

937 xylanases exhibited potent biomedical and catalytic activities. *Biotechnology Progress*2019,
938 e2829. doi:10.1002/btpr.2829.

939 Elekes, CC, Busuioc, G (2011) The Effect of Metallic Content of Soil on the Absorption and
940 Accumulation for Some Species of Fungi used in Soil's bioremediation. *Lucrări științifice – seria*
941 *Agronomie* 54: 127–132.

942 El-Sayed, E-SR , Abdelhakim, HK,Zakaria,Z (2019) Extracellular biosynthesis of cobalt ferrite
943 nanoparticles by *Monascus purpureus* and their antioxidant, anticancer and antimicrobial
944 activities: Yield enhancement by gamma irradiation. *Materials Science & Engineering C*(2019),
945 doi: <https://doi.org/10.1016/j.msec.2019.110318>.

946 Ezzouhri, L, Castro, E, Moya, M, Espinola, F, Lairini, K (2009) Heavy metal tolerance of
947 filamentous fungi isolated from polluted sites in Tangier, Morocco. *African Journal of*
948 *Microbiology Research*3: 035–048.

949 Ezzouhri, L, Ruiz, E, Castro, E, Moya, M, Espínola, F, Cherrat, L, Er–Raioui, H, Lairini K
950 (2010) Biomass of Fungal Species. *International Journal of Chemistry and Chemical*
951 *Engineering* 67: 39–44.

952 Falih, AM (1998) Effect of heavy–metals on amylolytic activity of the soil yeasts *Geotrichum*
953 *capitatum* and *Geotrichum candidum*. *Bioresource Technology*66: 213–217.

954 Fan, T, Liu, Y, Feng, B, Zeng, G, Yang, C, Zhou, M, Zhou, H, Tan, Z, Wang, X (2008)
955 Biosorption of cadmium(II), zinc(II) and lead(II) by *Penicillium simplicissimum*: Isotherms,
956 kinetics and thermodynamics. *Journal of Hazardous Materials*160: 655–661.

957 Falandysz, J, (2016) Mercury bio-extraction by fungus *Coprinus comatus*: a possible
958 bioindicator and mycoremediator of polluted soils? [Environ Sci Pollut Res Int](#). 23: 7444-7451.

959 Filipovic–Kovacevic, Z, Sipos, L, Briski, F, (2000) Biosorption of chromium, copper, nickel and
960 zinc ions onto fungal pellets of *Aspergillus niger* 405 from aqueous solutions. *Food Technology*
961 *and Biotechnology*38: 211–216.

962 Fogarty, RV, Tobin, JM (1996) Fungal melanins and their interaction with metals. *Enzyme and*
963 *Microbial Technology*19:311–317.

964 Fomina, M, Hillier, S, Charnock, JM, Melville, K, Alexander, IJ, Gadd, GM (2005) Role of
965 oxalic acid over excretion in transformations of toxic metal minerals by *Beauveria caledonica*.
966 *Applied Environmental Microbiology* 71: 371–381.

967 Gadd, GM (1993) Interactions of fungi with toxic metals. *New Phytology*124:25–60.

968 Gadd, GM, De Rome, L (1988) Biosorption of copper by fungal melanins. *Applied*
969 *Microbiology Biotechnology*29: 610–617.

- 970 Gade, A, Ingle, A, Whiteley, C, Rai M (2010) Mycogenic metal nanoparticles: Progress and
971 applications. *Biotechnology Letters*32: 593–600.
- 972 Gade, AK, Bonde, P, Ingle, AP, Marcato, PD, Durán, N, Rai, MK (2008) Exploitation of
973 *Aspergillus niger* for synthesis of silver nanoparticles. *Journal of Biobased Materials and*
974 *Bioenergy*2: 243–247.
- 975 Gajbhiye, M, Kesharwani, J, Ingle, A, Gade, A, Rai, M (2009) Fungus-mediated synthesis of
976 silver nanoparticles and their activity against pathogenic fungi in combination with fluconazole.
977 *Nanomedicine: Nanotechnology, Biology and Medicine*5: 382–386.
- 978 Ge, W, Zamri, D, Mineyama, H, Valix, M (2011) Bioaccumulation of heavy metals on adapted
979 *Aspergillus foetidus*. *Adsorption* 17:901–910.
- 980 Gholami-Shabani, M, Akbarzadeh, A, Norouzian, D et al. Antimicrobial Activity and Physical
981 Characterization of Silver Nanoparticles Green Synthesized Using Nitrate Reductase
982 from *Fusarium oxysporum*. *Applied Biochemistry and Biotechnology* 172: 4084–4098.
- 983 Giller K.E. , E. Witter, S.P. Mcgrath Heavy metals and soil microbes .*Soil Biol. Biochem.*,
984 41 (2009), pp. 2031-2037
985
- 986 Gond, SK, Mishra, A, Verma, SK et al. Synthesis and Characterization of Antimicrobial Silver
987 Nanoparticles by an Endophytic Fungus Isolated from *Nyctanthes arbor-tristis*. *Proceedings of*
988 *National Academy of Sciences, India, Section B, Biological Sciences.*
989 <https://doi.org/10.1007/s40011-019-01137-2>
- 990 Goyal, N, Jain, SC, Banerjee, UC (2003) Comparative studies on the microbial adsorption of
991 heavy metals. *Advances in Environmental Research*7: 311–319.
- 992 Graz, M, Pawlikowska-Pawlega, B, Jarosz- Wilkolazka, A, (2011) Growth inhibition and
993 intracellular distribution of Pb ions by the white-rot fungus *Abortiporus biennis*. *International*
994 *Biodeterioration & Biodegradation*, 65: 124-129.
- 995 Griffiths, B, Diaz-Ravina, M, Ritz, K, Mcnicol, J, Ebbelwhite, N, Baath, E (1997) Community
996 DNA hybridisation and communities from heavy metal polluted soils. *FEMS Microbiology*
997 *Ecology*24:103–112.
- 998 Gupta, SK (1992) Mobilizable metal in anthropogenic contaminated soils and its ecological
999 significance. In *Impact of heavy metals on the environment*. (Ed.): J.P. Vernet. Elsevier,
1000 Amsterdam The Netherlands pp: 299–310.
- 1001 Gupta, V, Rastogi, A (2008) Biosorption of Lead (II) from Aqueous Solutions by Non-Living
1002 Algal Biomass *Oedogonium* sp. and *Nostoc* sp.—A Comparative Study. *Colloids and surfaces B:*
1003 *Biointerfaces*64:170–178.

- 1004 Honary, S, Barabadi, H, Gharaei–Fathabad, E, Naghibi, F (2013) Green synthesis of silver
1005 nanoparticles induced by the fungus *Penicillium citrinum*. Tropical Journal of Pharmaceutical
1006 Research12: 7–11.
- 1007 Howe, R, Evans, RL, Ketteridge, SW (1997) Copper–binding proteins in ectomycorrhizal fungi.
1008 The New Phytologist135: 123–131.
- 1009 Hoque, E, Fritscher, J (2019) Multimetal bioremediation and bioimining by a combination of new
1010 aquatic strains of *Mucor hiemalis*. Scientific Reports, 10318
- 1011 Hu, X, Saravanakumar, K, Jin, T, Wang, M (2019) Mycosynthesis, characterization, anticancer
1012 and antibacterial activity of silver nanoparticles from endophytic fungus *Talaromyces*
1013 *purpureogenus*. International Journal of Nanomedicine 2019: 3427–3438.
- 1014 Hulikere, MM, Joshi, CG (2019) Characterization, antioxidant and antimicrobial activity of
1015 silver nanoparticles synthesized using marine endophytic fungus– *Cladosporium*
1016 *cladosporioides*. Process Biochemistry82: 199–204.
- 1017 Igiri, B.E.; Okoduwa, S.I.R.; Idoko, G.O.; Akabuogu, E.P.; Adeyi, A.O.; Ejiogu, I.K. Toxicity
1018 and bioremediation of heavy metals contaminated ecosystem from tannery wastewater: A
1019 review. J. Toxicol. 2018, 2018, 2568038.
- 1020 Ingle, A, Rai, M, Gade, A, Bawaskar, M (2009) *Fusarium solani*: A novel biological agent for
1021 the extracellular synthesis of silver nanoparticles. Journal of Nanoparticle Research11: 2079–
1022 2085.
- 1023 Iram, S, Parveen, K, Usman, J, Nasir, K, Akhtar, N, Arouj, S, Ahmad, I (2012) Heavy metal
1024 tolerance of filamentous fungal strains isolated from soil irrigated with industrial wastewater.
1025 Biologia58: 107–116
- 1026 Iram, S, Zamam, A, Iqbal, Z, Shabbir, R (2013) Heavy metal tolerance of fungus isolted from
1027 soil contaminated with sewage and industrial wastewater. Polish Journal of Environmental
1028 Studies22: 691–697.
- 1029 Iram, S, Abrar, S, (2015) Biosorption of Copper and Lead by Heavy Metal Resistant Fungal
1030 Isolates, International Journal of Scientific and Research Publications, 5: 1
- 1031 Jacob, C, Courbot, M, Brun, A, Steinman, HM, Jacquot, JP, Botton, B, Chalot, M (2001)
1032 Molecular cloning, characterization and regulation by cadmium of a superoxide dismutase from
1033 the ectomycorrhizal fungus *Paxillus involutus*. European Journal of Biochemistry268: 3223–
1034 3232.
- 1035 Jacod, JM, Bardhan, SK, Mohan, R (2013) Selenium and lead tolerance in fungi isolated from
1036 sea water. International Journal of Innovative Research in Science, Engineering and Technology
1037 2: 2975–2982

- 1038 Jarosz–Wilkolazka, A, Gadd, GM (2003) Oxalate production by wood–rotting fungi growing in
1039 toxic metal–amended medium. *Chemosphere*52: 541–547.
- 1040 Javaid, A, Bajwa, R, Javaid, A (2010) Biosorption of heavy metals using dead macro fungus
1041 *Schizophyllum commune* Fries: Evaluation of equilibrium and kinetic models. *Pakistan Journal of*
1042 *Botany* 42: 2105–2118.
- 1043 Kacar, Y, Arpa, C, Tan, S, Denizli, A, Genc, O, Arica, MY (2002) Biosorption of Hg(II) and
1044 Cd(II) from aqueous solutions: comparison of biosorptive capacity of alginate and immobilized
1045 live and heat inactivated *Phanerochaete chrysosporium*. *Process Biochemistry*. 37: 601- 610
1046
- 1047 Kadam, VV, Ettiappan, JP, Balakrishnan, RM (2019) Mechanistic insight into the endophytic
1048 fungus mediated synthesis of protein capped ZnO nanoparticles. *Materials Science &*
1049 *Engineering B243*: 214–221.
- 1050 Kathiresan, K, Manivannan, S, Nabeel, MA, Dhivya, B (2009) Studies on silver nanoparticles
1051 synthesized by a marine fungus, *Penicillium fellutanum* isolated from coastal mangrove
1052 sediment. *Colloids Surfaces B: Biointerfaces*71: 133–137.
- 1053 Kirpichtchikova, TA, Manceau, A, Spadini, L, Panfili, F, Marcus, MA, Jacquet, T (2006)
1054 Speciation and solubility of heavy metals in contaminated soil using X-ray microfluorescence,
1055 EXAFS spectroscopy, chemical extraction, and thermodynamic modeling,” *Geochimica et*
1056 *Cosmochimica Acta*, 70: 2163–2190.
1057
- 1058 Kitching, M, Ramani, M, Marsili, E (2015) Fungal biosynthesis of gold nanoparticles:
1059 mechanism and scale up. *Microbial Biotechnology*8: 904–917.
- 1060 Kumar, SA, Ansary, AA, Ahmad, A, Khan, MI (2007) Extracellular biosynthesis of CdSe
1061 quantum dots by the fungus, *Fusarium oxysporum*. *Journal of Biomedical Nanotechnology*3:
1062 190–194.
- 1063 Kumar, A, Bisht, BS, Joshi, VD (2010) Biosorption of heavy metals by four acclimated
1064 microbial species, *Bacillus spp.*, *Pseudomonas spp.*, *Staphylococcus spp.* and *Aspergillus niger*.
1065 *Journal of Biological & Environmental Sciences* 4: 97–108
- 1066 Landi, L, Renella, G, Moreno, J, Falchini, L, Nannipieri, P (2000) Influence of cadmium on the
1067 metabolic quotient, L–, D–glutamine acid respiration ratio and enzyme activity: microbial
1068 biomass ratio under laboratory conditions. *Biology and Fertility of Soils* 32: 8–16.
- 1069 Lenart A. and K. Wolny-Koladka, “The effects of Heavy Metal Concentration and Soil pH on
1070 the abundance of selected microbial groups within ArcelorMittal Poland Steelworks in Cracow”,
1071 *Bulletin of Environmental Contamination and Toxicology*, 90, 85-90 (2013).

1072 Leonhardt, T, Sacky, J, Simek, P, Santrucek, J, Kotrba, P (2014) Metallothionein-like peptides
1073 involved in sequestration of Zn in the Zn accumulating ectomycorrhizal fungus *Russulaatro*
1074 *purpurea*. *Metallomics*6: 1693–1701.

1075 Levinskaite (2002) Response of soil fungi to chromium (VI). *Ekologija*1: 10.

1076 Li, JF, Rupa, EJ, Hurh, J, Huo, Y, Chen, L, Han, Y, Chan Ahn, J, Park, JK, Lee,
1077 HA, Mathiyalagan, R (2019) *Cordyceps militaris* fungus mediated zinc oxide nanoparticles for
1078 the photocatalytic degradation of methylene blue dye. *Optik* 183: 691–697

1079 Lin Y., Wu Xiao, Yanmei Ye, Cifang Wu, Yiming Hu and Haokun Shi, 2020. Adaption of soil
1080 fungi to heavy metal contamination in paddy fields – a case study in eastern China.
1081 *Environmental Science and Pollution Research* volume 27, pages27819–2783

1082

1083 Litwin, A, Nowak, M, Rozalska, S (2020) Entomopathogenic fungi: unconventional applications.
1084 *Reviews in Environmental Science and Biotechnology* 19: 23–42

1085 Lilly, WW, Wallweber, GJ, Lukefahr, TA (1992) Cadmium absorption and its effects on growth
1086 and mycelial morphology of the basidiomycete fungus, *Schizophyllum commune*. *Microbios*72:
1087 227–237.

1088 Luna, M.A.C., Vieira, E.R., Okada, K., Campos-Takaki, G.M., do Nascimento, A.E., (2015)
1089 Copper-induced adaptation, oxidative stress and its tolerance in *Aspergillus niger* UCP1261.
1090 *Electron. J. Biotechnol.* 18 (6), 418–427.

1091 Luo, J, Xiao, X, Luo, S (2010) Biosorption of cadmium (II) from aqueous solutions by industrial
1092 fungus *Rhizopus cohnii*. *Transactions of Nonferrous Metals Society of China*20:1104–1111

1093 Mahanty, S, Bakshi, M, Ghosh, S, Chatterjee, S, Bhattacharyya, S, Das, P, Das, S, Chaudhuri, P
1094 (2019) Green synthesis of iron oxide nanoparticles mediated by filamentous fungi isolated from
1095 Sundarban mangrove ecosystem, India. *Bionanoscience*. doi:10.1007/s12668–019–00644–w.

1096 Martinez–Juarez, VM, Cardenas–Gonzalez, JF, Torre–Bouscoulet, ME, Acosta–Rodriguez, I
1097 (2012) Biosorption of mercury (II) from aqueous solutions onto fungal biomass. *Bioinorganic*
1098 *Chemistry and Applications* Article ID 156190, 5 pages doi:10.1155/2012/156190.

1099 Mehra, RK, Winge, DR (1991) Metal ion resistance in fungi: Molecular mechanisms and their
1100 regulated expression. *Journal of Cellular Biochemistry*45: 30–40.

1101 Miller W.P. , D.M. Miller A micro-pipette method for soil mechanical analysis. *Commun. Soil*
1102 *Sci. Plant Anal.*, 18 (1987), pp. 1-15

1103

- 1104 Miransari, M. Soybean production and heavy metal stress. In Abiotic and Biotic Stresses in
1105 Soybean Production; Miransari, M., Ed.; Academic Press: Cambridge, MA, USA; Elsevier:
1106 Cambridge, MA, USA, 2016; pp. 197–216
- 1107 Mishra, A, Tripathy, SK, Wahab, R, Jeong, SH, Hwang, I, Yang, YB, Kim, YS, Shin, SH, Yun
1108 SI (2011) Microbial synthesis of gold nanoparticles using the fungus *Penicillium*
1109 *brevicompactum* and their cytotoxic effects against mouse mayo blast cancer C2C12 cells.
1110 Applied Microbiology and Biotechnology92: 617–630.
- 1111 Mishra, A.; Bhattacharya, A.; Mishra, N. Mycorrhizal symbiosis: An effective tool for metal
1112 bioremediation. In New and Future Developments in Microbial Biotechnology and
1113 Bioengineering; Singh, J.S., Ed.; Elsevier: Amsterdam, The Netherlands, 2019; pp. 113–128
1114
- 1115 Mohan, PM, Pratap Rudra, MP, Sastry, KS (1984) Nickel transport in nickel-resistant strains of
1116 *Neurospora crassa*. Current Microbiology10: 125–128.
- 1117 Molnár, Z, Bódai, V, Szakacs, G et al. (2018) Green synthesis of gold nanoparticles by
1118 thermophilic filamentous fungi. Scientific Reports 8: 3943
- 1119 Morselt, AFW, Smits, WTM, Limonard, T (1986) Histochemical demonstration of heavy metal
1120 tolerance in ectomycorrhizal fungi. Plant Soil96: 417–420.
- 1121 Mosallam, FM, Ghariieb, S, El-Sayyad, GS, Fathy, RM, El-Batal, AI (2018) Biomolecules–
1122 mediated synthesis of selenium nanoparticles using *Aspergillus oryzae* fermented Lupin extract
1123 and gamma radiation for hindering the growth of some multidrug-resistant bacteria and
1124 pathogenic fungi. Microbial Pathogenesis122: 108–116.
- 1125 Mugesh, S, Arun, R, Arunkumar, K, Murugan, M (2018) Synthesis of biogenic copper
1126 nanoparticles embedded in graphene oxide–chitosan composite and its anti-bacterial and
1127 cytotoxic activities. Journal of Nanoscience and Nanotechnology19: 2625–2632.
- 1128 Mukherjee, A, Das, D, Mondal, SK, Biswas, R, Das, TK Boujedaini, N, Khuda–Buksh, AR
1129 (2010) Tolerance of arsenate-induced stress in *Aspergillus niger*, a possible candidate for
1130 bioremediation. Ecotoxicology and Environmental Safety73: 172–182.
- 1131 Mukherjee, KK, Das, D, Samal, AC, Santra, SC (2013) Isolation and characterization of Arsenic
1132 tolerant fungal strains from contaminated sites around urban environment of Kolkata. IOSR
1133 Journal Of Environmental Science, Toxicology And Food Technology (IOSR–JESTFT)7:33–37
- 1134 Mukherjee, P, Ahmad, A, Mandal, D, Senapati, S, Sainkar, SR, Khan, MI, Ramani, R, Parischa,
1135 R, Ajayakumar, PV, Alam, M, Sastry, M, Kumar, R (2001a) Bioreduction of AuCl₄– ions by the
1136 fungus *Verticillium* sp. and surface trapping of the gold nanoparticles formed. Angewandte
1137 Chemie – International Edition 40: 3585–3588.

- 1138 Mukherjee, P, Ahmad, A, Mandal, D, Senapati, S, Sainkar, SR, Khan, MI, Parischa, R,
1139 Ajayakumar, PV, Alam, M, Sastry, M, Kumar, R (2001b) Fungus-mediated synthesis of silver
1140 nanoparticles and their immobilization in the mycelial matrix: a novel biological approach to
1141 nanoparticle synthesis. *Nano Letters*1: 515–519.
- 1142 Mukherjee, P, Senapati, S, Mandal, D, Ahmad, A, Khan, MI, Kumar, R, Sastry, M (2002)
1143 Extracellular synthesis of gold nanoparticles by the fungus *Fusarium oxysporum*.
1144 *ChemBioChem*5: 461–463.
- 1145 Mukherjee, P, Roy, M, Mandal, BP, Dey, GK, Mukherjee, PK, Ghatak, J, Tyagi, AK, Kale SP
1146 (2008) Green synthesis of highly stabilized nanocrystalline silver particles by a non-pathogenic
1147 and agriculturally important fungus *Trichoderma asperellum*. *Nanotechnology*19 (7) 075103.
1148 doi:10.1088/0957-4484/19/7/075103
- 1149 Musarrat, J, Dwivedi, S, Singh, BR, Al-Khedhairi, AA, Azam, A, Naqvi, A (2010) Production
1150 of antimicrobial silver nanoparticles in water extracts of the fungus *Amylomycesrouxii* strain
1151 KSU-09. *Bioresource Technology*101: 8772–8776.
- 1152 Narayanan, KB, Sakthivel, N (2011) Facile green synthesis of gold nanostructures by NADPH-
1153 dependent enzyme from the extract of *Sclerotium rolfsii*. *Colloids Surfaces A Physicochemical
1154 and Engineering Aspects*380: 156–161.
- 1155 Nayak, RR, Pradhan, N, Behera, D, Pradhan, KM, Mishra S, Sukla LB, MishraBK, (2011) Green
1156 synthesis of silver nanoparticle by *Penicillium purpurogenum* NPMF: the process and
1157 optimization. *Journal of Nanoparticle Research*13: 3129-3137.
- 1158 Neethu, S, Midhun, SJ, Radhakrishnan, EK, Jyothis, M (2018) Green synthesized silver
1159 nanoparticles by marine endophytic fungus *Penicillium polonicum* and its antibacterial efficacy
1160 against biofilm forming, multidrug-resistant *Acinetobacter baumannii*. *Microbial Pathogenesis*
1161 116: 263–272.
- 1162 Nwuche, CO, Ugoji, EO (2008) Effects of heavy metal pollution on the soil microbial activity.
1163 *International Journal of Environmental Science & Technology*5: 409–414.
- 1164 Oladipo, OG, Awotoye, OO, Olayinka, A, Bezuidenhout, CC, Manoeta, M S (2018) Heavy metal
1165 tolerance traits of filamentous fungi isolated from gold and gemstone mining sites. *Brazilian
1166 Journal of Microbiology*49: 29-37
1167
- 1168 Otto, T, Fritz, E, Polle, A, Schützendubel, A (2002) Characterisation of antioxidative systems in
1169 the ectomycorrhiza-building basidiomycete *Paxillus involutus* (Barsch) Fr. and its reaction to
1170 cadmium. *FEMS Microbiology Ecology*42: 359–366.

- 1171 Ovais, M, Khalil, AT, Ayaz, M, Ahmad, I, Nethi, SK, Mukherjee, S (2018) Biosynthesis of
1172 metal nanoparticles via microbial enzymes: A mechanistic approach. International Journal of
1173 Molecular Sciences19, 4100. doi:10.3390/ijms19124100.
- 1174 Pantidos, N, Horsfall, LE (2014) Biological synthesis of metallic nanoparticles by bacteria, fungi
1175 and plants. Nanomedicine and Nanotechnology5: 233. doi:10.4172/2157-7439.1000233.
- 1176 Pei, X, Qu, Y, Shen, W, Li, H, Zhang, X, Li, S, Zhang, Z, Li X (2017) Green synthesis of gold
1177 nanoparticles using fungus *Mariannaea sp.* HJ and their catalysis in reduction of 4-nitrophenol.
1178 Environmental Science and Pollution Research24: 21649–21659
- 1179 Phanjom, P, Ahmed, G (2017) Effect of different physicochemical conditions on the synthesis of
1180 silver nanoparticles using fungal cell filtrate of *Aspergillus oryzae* (MTCC No 1846) and their
1181 antibacterial effect. Advances in Natural Science: Nanoscience and Nanotechnology8:045016
- 1182 Pradhan N, Nayak RR, Pradhan AK, Sukla LB, Mishra BK,(2011) In situ Synthesis of entrapped
1183 silver nanoparticles by a fungus—*Penicillium purpurogenum*. Nanoscience and Nanotechnology
1184 Letters 3: 659-665
- 1185 Priyadarshini, E, Pradhan, N, Panda, PK, Mishra, BK (2015) Biogenic unmodified gold
1186 nanoparticles for selective and quantitative detection of cerium using UV–vis spectroscopy and
1187 photon correlation spectroscopy (DLS). Biosensors and Bioelectronic68: 598–603.
- 1188 Priyadarshini, E, Pradhan, N, Sukla, LB, Panda, PK (2014a) Controlled synthesis of gold
1189 nanoparticles using *Aspergillus terreus* IF0 and its antibacterial potential against gram negative
1190 pathogenic bacteria. Journal of Nanotechnology2014, Article ID 653198, 9 pages.
1191 doi:10.1155/2014/653198.
- 1192 Priyadarshini, E, Pradhan, N, Sukla, LB, Panda, PK, Mishra, BK (2014b) Biogenic synthesis of
1193 floral-shaped gold nanoparticles using a novel strain, *Talaromyces flavus*. Annals of
1194 Microbiology64: 1055–1063
- 1195 Qian, Y, Yu, H, He, D, Yang, H, Wang, W, Wan, X, Wang, L (2013) Biosynthesis of silver
1196 nanoparticles by the endophytic fungus *Epicoccum nigrum* and their activity against pathogenic
1197 fungi. Bioprocess and Biosystems Engineering36: 1613–1619.
- 1198 Qu, Y, Li, X, Lian, S, Dai, C, Jv, Z, Zhao, Bo, Zhou, H (2018) Biosynthesis of gold
1199 nanoparticles using fungus *Trichoderma sp.* WL-Go and their catalysis in degradation of
1200 aromatic pollutants. IET Nanobiotechnology13: 12–17
- 1201 Rajakumar, G, Rahuman, AA, Roopan, SM, Khanna, VG, Elango, G, Kamaraj, C, Zahir, AA,
1202 Velayutham, K (2012) Fungus-mediated biosynthesis and characterization of TiO₂ nanoparticles
1203 and their activity against pathogenic bacteria. Spectrochimica Acta Part A: Molecular and
1204 Biomolecular Spectroscopy 91: 23–29.

- 1205 Ramasamy, RK, Congeevaram, S, Thamaraiselvi, K (2011) Evaluation of isolated fungal strain
1206 from e-waste recycling facility for effective sorption of toxic heavy metal Pb (II) ions and fungal
1207 protein molecular characterization– a mycoremediation approach. *Asian Journal of Experimental*
1208 *Biological Sciences*2: 342–347
- 1209 Rao, PR, Bhargavi, C (2013) Studies on biosorption of heavy metals using pretreated biomass of
1210 fungal species. *International Journal of Chemistry and Chemical Engineering*3:171–180
- 1211 Rao, KR, Rashmi, K, Latha, JNL, Mohan, PM (2005) Bioremediation of toxic metal ions using
1212 biomass of *Aspergillus fumigates* from fermentative waste. *Indian Journal of Biotechnology*4:
1213 139–143.
- 1214 Remacle, J (1990) The cell wall and metal binding. In: B. Volesky (ed.). *Biosorption of Heavy*
1215 *Metals*. CRC Press, Boca Raton, Florida, USA, pp. 83–92.
- 1216 Rifkind, JM, Shin, YA, Hiem JM, Eichorn, GL (2001) Cooperative disordering of single–
1217 stranded polynucleotides through copper crosslinking. *Biopolymers*15: 1879.
- 1218 Rodríguez-Serrano, C, Guzmán-Moreno, J, Ángeles-Chávez, C, Rodríguez-González, V, Ortega-
1219 Sigala, JJ, Ramírez-Santoyo, RM, et al. (2020) Biosynthesis of silver nanoparticles by *Fusarium*
1220 *scirpi* and its potential as antimicrobial agent against uropathogenic *Escherichia coli* biofilms.
1221 *PLoS ONE*15(3): e0230275. <https://doi.org/10.1371/journal.pone.0230275>
- 1222 Romero, MC, Reinoso, EH, Urrutia, MI, Kiernan, AM (2006) Biosorption of heavy metals by
1223 *Talaromyces helicus*: a trained fungus for copper and biphenyl detoxification. *Electronic Journal*
1224 *of Biotechnology*9, Special Issue
- 1225 Rózalska, S, Soliwoda, K, Dlugonski, J (2016) Synthesis of silver nanoparticles from
1226 *Metarhizium robertsii* waste biomass extract after nonylphenol degradation, and their
1227 antimicrobial and catalytic potential *RSC Advances* 6: 21475–21485
- 1228
- 1229 Sánchez-Castro I, Gianinazzi-Pearson V, Cleyet-Marel JC, Baudoin E, van Tuinen D.
1230 Glomeromycota communities survive extreme levels of metal toxicity in an orphan mining site.
1231 *Sci Total Environ*. 2017 Nov 15;598:121-128. doi: 10.1016/j.scitotenv.2017.04.084. Epub 2017
- 1232 Sanghi, R, Verma, P, Puri, S (2011) Enzymatic Formation of Gold Nanoparticles Using
1233 *Phanerochaete chrysosporium*. *Advances in Chemical Engineering and Science*1: 154–162
- 1234 Sanghi, R, and Verma, P, (2009) Biomimetic synthesis and characterization of protein capped
1235 silver nanoparticles. *Bioresource Technology* 100: 501–504

- 1236 Saravanakumar, K, Wang, MH, (2018) *Trichoderma* based synthesis of anti-pathogenic silver
1237 nanoparticles and their characterization, antioxidant and cytotoxicity properties. *Microbial*
1238 *Pathogenesis*114: 269–273.
- 1239 Shaligram, NS, Bule, M, Bhambure, R, Singhal, RS, Singh, SK, Szakacs, G, Pandey, A (2009)
1240 Biosynthesis of silver nanoparticles using aqueous extract from the compactin producing fungal
1241 strain. *Process Biochemistry*44: 939–943.
- 1242 Sharma, D, Kanchi, S, Bisetty, K, (2019) Biogenic synthesis of nanoparticles: a review. *Arabian*
1243 *Journal of Chemistry* 12: 3576–3600
- 1244 Shen, W, Qu, Y, Pei, X, Li, S, You, S, Wang, J, Zhang, Z, Zhou J (2017) Catalytic reduction of
1245 4-nitrophenol using gold nanoparticles biosynthesized by cell-free extracts of *Aspergillus sp.*
1246 WL-Au. *Journal of Hazardous Materials* 321: 299–306.
- 1247 Siddiqi, KS, Husen, A (2016) Fabrication of metal nanoparticles from fungi and metal salts:
1248 scope and application. *Nanoscale Research Letters* 11: 98
- 1249 Sing, C, Yu, J (1998) Copper adsorption and removal from water by living mycelium of white-
1250 rot fungus *Phanerochaete chrysosporium*. *Water Research*32: 2746–2752.
- 1251 Singh, D, Rathod, V, Ninganagouda, S, Hiremath, J, Singh, AK, Mathew, J (2014) Optimization
1252 and characterization of silver nanoparticle by endophytic fungi *Penicillium sp.* isolated from
1253 *Curcuma longa* (Turmeric) and application studies against MDR *E. coli* and *S. aureus*.
1254 *Bioinorganic Chemistry and Applications* 2014, Article ID 408021, 8 pages.
1255 doi:10.1155/2014/408021
- 1256 Singh, P, Kim, Y, Zhang, D, Yang, D (2016) Biological Synthesis of Nanoparticles from Plants
1257 and Microorganisms. *Trends in Biotechnology* 34: 588–599
- 1258 Sintuprapa, W, Thiravetyan, P, Tanticharoen, M, (2000) A possible mechanism of Zn²⁺ uptake
1259 by living cells of *Penicillium sp.* *Biotechnology Letters*22: 1709–1712.
- 1260 Sobolev, D, Begonia, MFT (2008) Effects of heavy metal contamination upon soil microbes:
1261 lead-induced changes in general and denitrifying microbial communities as evidenced by
1262 molecular markers. *International Journal of Environmental Research and Public Health*5: 450–
1263 456.
- 1264 Spagnoletti, FN, Spedalieri, C, Kronberg, F, Giacometti, R (2019) Extracellular biosynthesis of
1265 bactericidal Ag/AgCl nanoparticles for crop protection using the fungus *Macrophomina*
1266 *phaseolina*. *Journal of Environmental Management*231: 457–466.
- 1267 Suh, JH, Yun JW, Kim, DS (1999) Effect of extracellular polymeric substances (EPS) on Pb²⁺
1268 accumulation by *Aureobasidium pullulans*. *Bioprocess Engineering*21: 1–4.

- 1269 Syed, A, Ahmad, A (2012) Extracellular biosynthesis of platinum nanoparticles using the fungus
1270 *Fusarium oxysporum*. Colloids Surfaces B: Biointerfaces201: 27–31.
- 1271 Syed, A, Saraswati, S, Kundu, GC, Ahmad, A (2013a) Biological synthesis of silver
1272 nanoparticles using the fungus *Humicolasp.* and evaluation of their cytotoxicity using normal and
1273 cancer cell lines. Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy114:
1274 144–147.
- 1275 Tan, T, Hu, B, Su, H (2004) Adsorption of Ni²⁺ on amine–modified mycelium of *Penicillium*
1276 *chrysogenum*. Enzyme and Microbial Technology35: 508–513.
- 1277 Tan, TW, Chen, P (2003) Biosorption behavior of metal ions with *Penicillium chrysogenum*.
1278 Applied Biochemistry and Biotechnology104:119–28.
- 1279 Thippeswamy, B, Shivakumar, CK, Krishnappa, M (2012) Bioaccumulation potential of
1280 *Aspergillus niger* and *Aspergillus flavus* for removal of heavy metals from paper mill effluent.
1281 Journal of Environmental Biology 33:1063–1068.
- 1282 Tripathi, AK, Harsh, NSK, Gupta, N (2007) Fungal treatment of industrial effluents: a mini–
1283 review. Life Science Journal4: 78–81.
- 1284 Tsekova, K, Ilieva, S (2001) Copper removal from aqueous solution using *Aspergillus niger*
1285 mycelia in free and polyurethane–bound form. Applied Microbiology Biotechnology55:636–637.
- 1286 Uddin, I, Adyanthaya, S, Syed, A, Selvaraj, K, Ahmad, A, Poddar, P (2008) Structure and
1287 microbial synthesis of sub–10 nm Bi₂O₃ nanocrystals. Journal of Nanoscience Nanotechnology8:
1288 3909–3913.
- 1289 Ulla, AJ, Patrick, AWV, Ulla, SL, Roger, DF (2000) Organic acids produced by mycorrhizal
1290 *Pinus sylvestris* exposed to elevated aluminium and heavy metal concentrations. New
1291 Phytologist146: 557–567.
- 1292 Vabahi, K, Mansoori, GA, Karimi S (2011) Biosynthesis of silver nanoparticles by fungus
1293 *Trichoderma reesei*. Insciences Journal1: 65–79.
- 1294 Vacchina, V, Baldrian, P, Gabriel, J, Szpunar, J (2002) Investigation of the response of wood–
1295 rotting fungi to copper stress by size–exclusion chromatography and capillary zone
1296 electrophoresis with ICP MS detection. Analytical & Bioanalytical Chemistry372:453–456.
- 1297 Vala, AK (2015) Exploration on green synthesis of gold nanoparticles by a marine–derived
1298 fungus *Aspergillus sydowii*. Environmental Progress & Sustainable Energy34: 194–197.
- 1299 Verma, J, Bhatt, A, Agarwal, PK (2016) In-vitro study on Bioaccumulation and Tolerance of
1300 heavy metals by endophytic fungi *Alternaria alternate* isolated from *Cupressus torulosa*D.Don.
1301 Octa Journal of Environmental Research 4: 146-154

- 1302 Verma, VC, Kharwar, RN, Gange, AC (2010) Biosynthesis of antimicrobial silver nanoparticles
1303 by the endophytic fungus *Aspergillus clavatus*. *Nanomedicine* 5: 33–40.
- 1304 Verma, R.; Tapwal, A.; Kumar, D.; Parkash, V.; Puri, S. Vesicular arbuscular mycorrhizal
1305 diversity in some important ethnomedicinal plants of Western Himalaya. *Med. Plants* 2019, 11,
1306 279–285
1307
- 1308 Vigneshwaran, N, Ashtaputre, NM, Varadarajan, PV, Nachane, RP, Paralikar, KM,
1309 Balasubramanya, RH (2007) Biological synthesis of silver nanoparticles using the fungus
1310 *Aspergillus flavus*. *Materials Letters* 61: 1413–1418.
- 1311 Vigneshwaran, N, Kathe, AA, Varadarajan, PV, Nachane, RP, Balasubramanya, RH (2006)
1312 Biomimetics of silver nanoparticles by white rot fungus, *Phaenerochaete chrysosporium*.
1313 *Colloids Surfaces B: Biointerfaces* 53: 55–59.
- 1314 Vijayanandan, AS, Balakrishnan, RM (2018) Biosynthesis of cobalt oxide nanoparticles using
1315 endophytic fungus *Aspergillus nidulans*. *Journal of Environmental Management* 218: 442–450.
- 1316 Vijayanandan, AS, Balakrishnan, RM (2020) Photostability and electrical and magnetic
1317 properties of cobalt oxide nanoparticles through biological mechanism of endophytic fungus
1318 *Aspergillus nidulans*. *Applied Physics A* 126: 234
- 1319 Vivas A, B. Biró, J. M. Ruíz-Lozano, J. M. Barea, and R. Azcón, “Two bacterial strains isolated
1320 from a Zn-polluted soil enhance plant growth and mycorrhizal efficiency under Zn-
1321 toxicity,” *Chemosphere*, vol. 62, no. 9, pp. 1523–1533, 2006.
1322
- 1323 Wang A. S., J. S. Angle, R. L. Chaney, T. A. Delorme, and R. D. Reeves, “Soil pH effects on
1324 uptake of Cd and Zn by *Thlaspi caerulescens*,” *Plant and Soil*, vol. 281, no. 1-2, pp. 325–337,
1325 2006
- 1326 WHO. Guidelines for drinking-water quality - 4th ed. (2011) ISBN 9789241548151 pp 472-47.
1327 (https://apps.who.int/iris/bitstream/handle/10665/44584/9789241548151_eng.pdf?sequence=1)
- 1328 Wilson, D, Citiulo, F, Hube, B (2012) Zinc Exploitation by Pathogenic Fungi. *PLOS*
1329 *Pathogens* 8:12 e1003034. doi: 10.1371/journal.ppat.1003034.
- 1330 Xie, J, Lee, JY, Wang, DIC, Ting, YP (2007) High-yield synthesis of complex gold
1331 nanostructures in a fungal system. *The Journal of Physical Chemistry C* 111: 16858–16865.

- 1332 Xu, X, Xia, L, Huang, Q, Gu, J, Chen, W (2012) Biosorption of cadmium by a metal-resistant
1333 filamentous fungus isolated from chicken manure compost. *Environmental Technology*33:1661–
1334 70.
- 1335 Xu, X, Xia, L, Zhang, Z, Huang, Q, Chen, W (2015) Role of *Penicillium chrysogenum* XJ-1 in
1336 the Detoxification and Bioremediation of Cadmium. *Frontiers in Microbiology*6: 1422.
- 1337 Yalcinkaya, Y, Soysal, L, Denizli, A, Arica, MY, Bektas, S, Genc, O(2002) Biosorption of
1338 cadmium from aquatic systems by carboxy methyl cellulose and immobilized *Trametes*
1339 *versicolor*. *Hydrometallurgy* 63: 31–40
- 1340 Yamaji, K.; Watanabe, Y.; Masuya, H.; Shigeto, A.; Yui, H.; Haruma, T. Root fungal
1341 endophytes enhance heavy-metal stress tolerance of *Clethra barbinervis* growing naturally at
1342 mining sites via growth enhancement, promotion of nutrient uptake and decrease of heavy-metal
1343 concentration. *PLoS ONE* 2016, 11, e0169089
- 1344 Yan, G, Viraraghavam, T (2003) Heavy Metal Removal from Aqueous Solution by Fungus *Mucor*
1345 *rouxii*. *Water Research*37: 4486–4496.
- 1346 Yang, L, Lubeck, M, Lubeck, PS (2016) *Aspergillus* as a versatile cell factory for organic acid
1347 production. *Fungal Biology Reviews*. 1-17. doi.org/10.1016/j.fbr.2016.11.001
1348
- 1349 Zafar, S, Aqil, F, Ahmad, I (2006) Metal tolerance and biosorption potential of filamentous fungi
1350 isolated from metal contaminated agricultural soil. *Bioresource Technology*98: 2557–2561.
- 1351 Zaidi, J, Pal, A (2017) Review on heavy metal pollution in major lakes of India: Remediation
1352 through plants. *African Journal of Environmental Science and Technology*11: 255–265.
- 1353 Zapotoczny, S, Jurkiewicz, A, Tylko, G, Anielska, T, Turnau, K (2007) Accumulation of copper
1354 by *Acremonium pinkertoniae*, a fungus isolated from industrial wastes. *Microbiological Research*
1355 162:219–228.
- 1356 Zare, B, Babaie, S, Setayesh, N, Shahverdi, AR (2013) Isolation and characterization of a fungus
1357 for extracellular synthesis of small selenium nanoparticles. *Nanomedicine Journal*1: 13–19.
- 1358 Zhang, H, Zhou, H, Bai, J, Li, Y, Yang, J, Ma, Q, Qu, Y (2019) Biosynthesis of selenium
1359 nanoparticles mediated by fungus *Mariannaea sp.* HJ and their characterization. *Colloids and*
1360 *Surfaces A* 571: 9–16
- 1361 Zhang, D, Yin C, Abbas, N, Mao, Z, Zhang, Y, (2020) Multiple heavy metal tolerance and
1362 removal by an earthworm gut fungus *Trichoderma brevicompactum* QYCD-6. *Scientific*
1363 *Reports*10: 6940

1364 Zhang, Q., Zeng, G., Chen, G. et al. The Effect of Heavy Metal-Induced Oxidative Stress on the
1365 Enzymes in White Rot Fungus *Phanerochaete chrysosporium* . *Appl Biochem Biotechnol* 175,
1366 1281–1293 (2015). <https://doi.org/10.1007/s12010-014-1298-z>

1367 Zhang, Y., Yu, X., Zhang, W. et al. Interactions between Endophytes and Plants: Beneficial
1368 Effect of Endophytes to Ameliorate Biotic and Abiotic Stresses in Plants. *J. Plant Biol.* 62, 1–13
1369 (2019). <https://doi.org/10.1007/s12374-018-0274-5>

1370 Zhao, X, Zhou, L, Rajoka, MSR, Yan, L, Jiang, C, Shao, D, Zhu, J, Shi, J, Huang, Q, Yang,
1371 H, Jin, M (2018) Fungal silver nanoparticles: synthesis, application and challenges. *Critical*
1372 *Reviews in Biotechnology* 38: 817–835.

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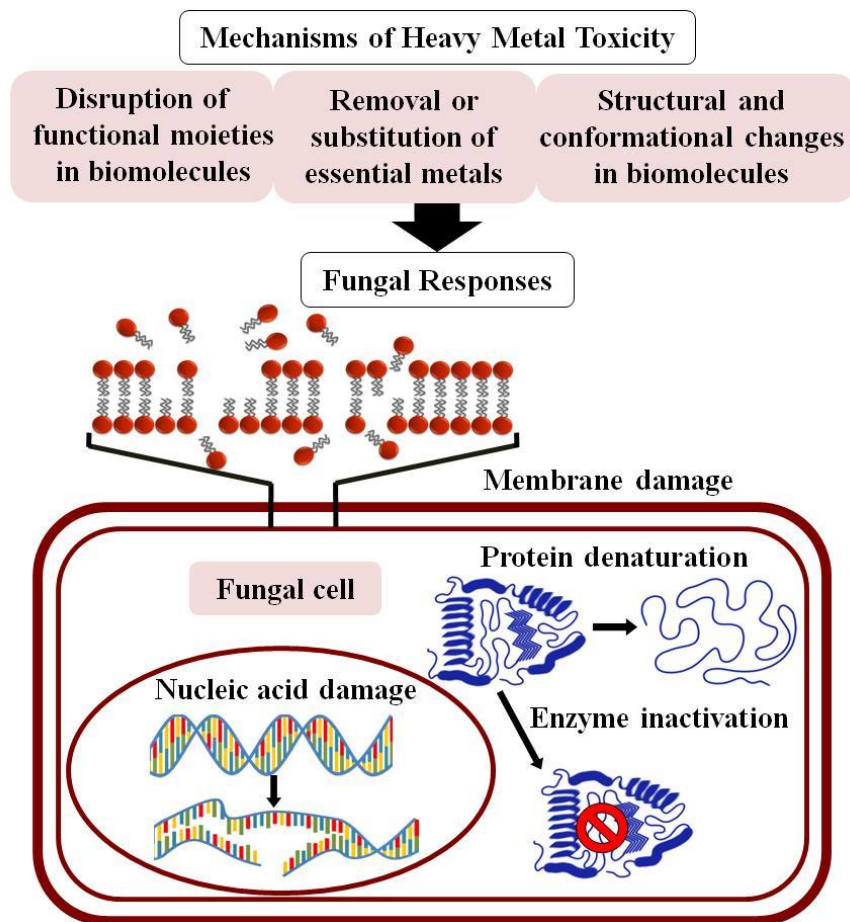
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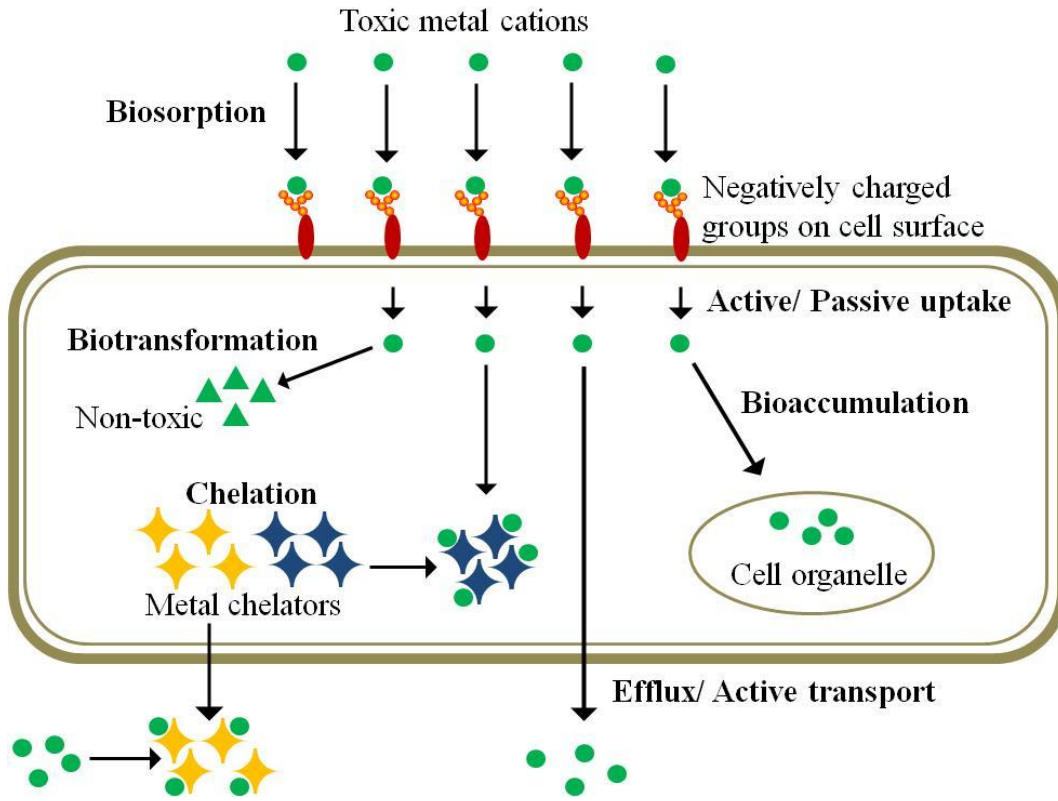
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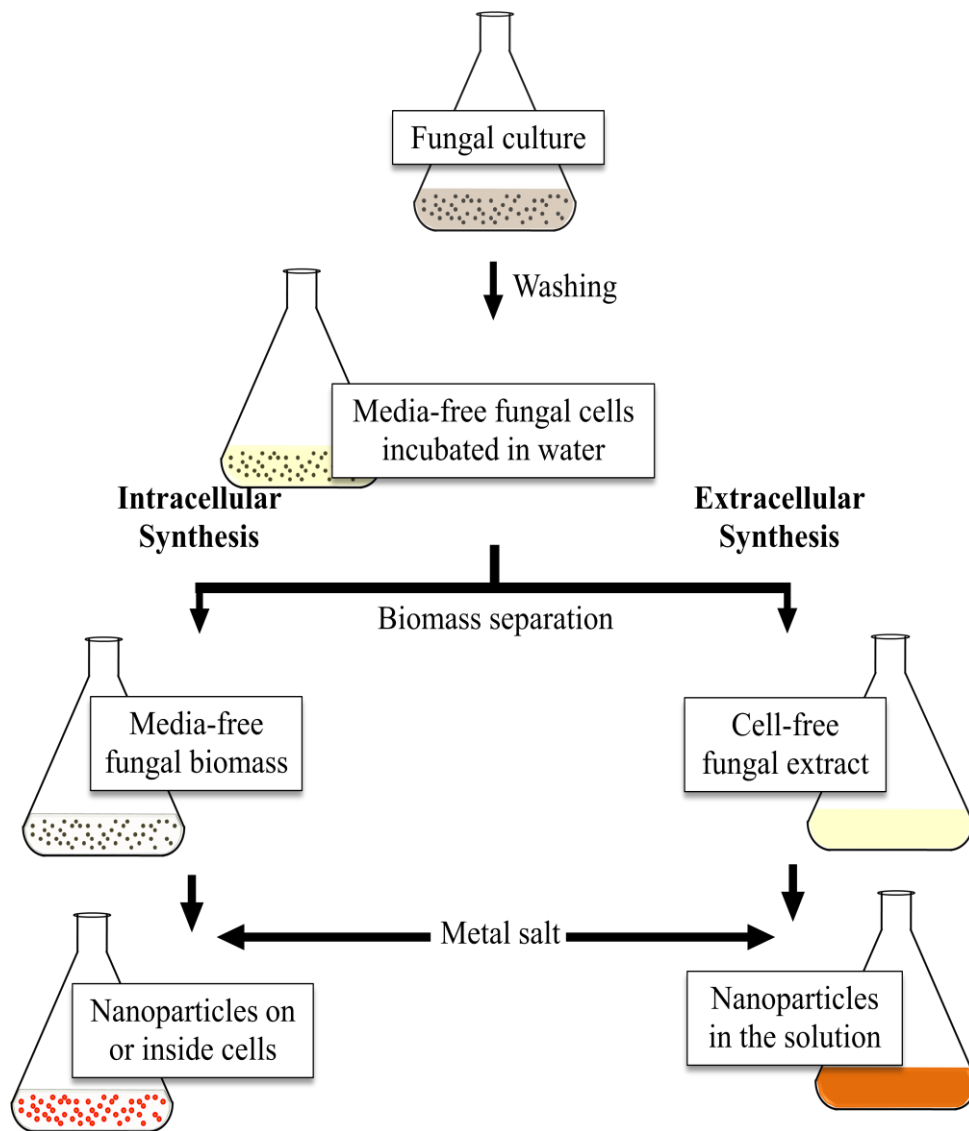
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Figure 2: Cellular mechanism of heavy metal tolerance by fungal cell

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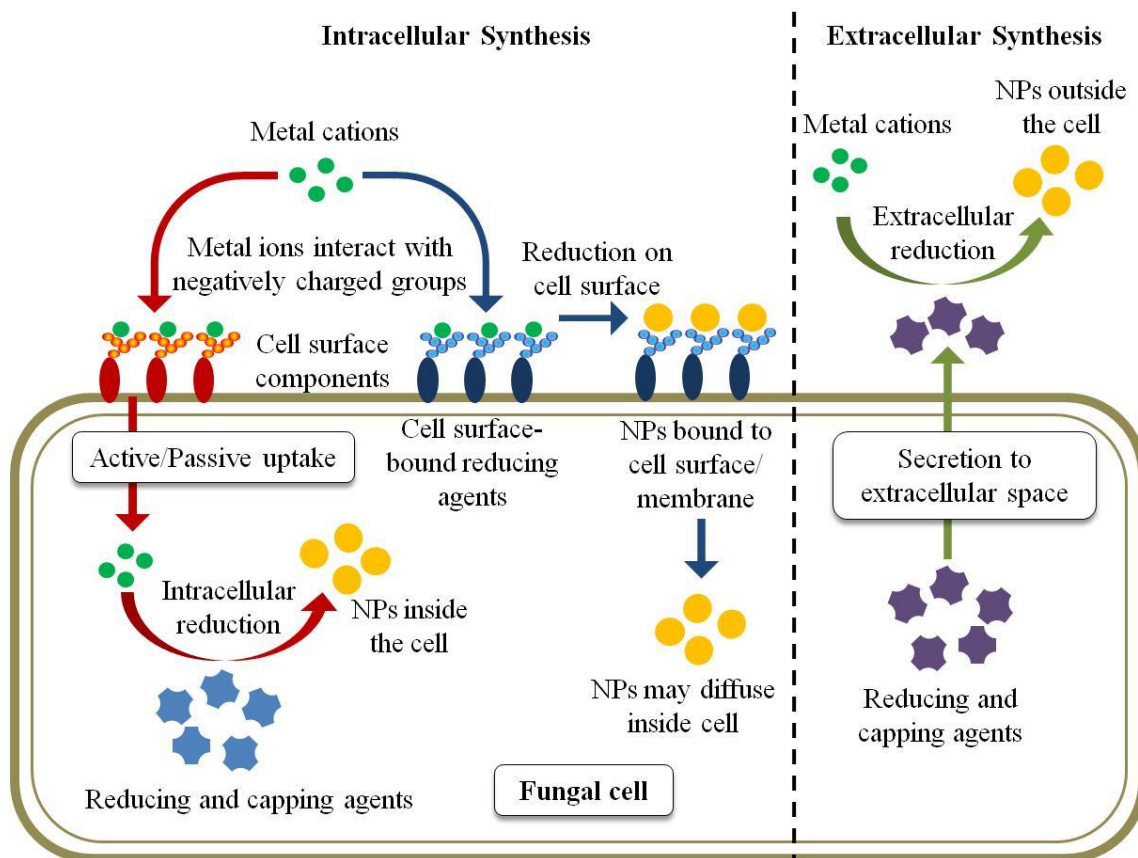
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Figure 3: General protocol for fungal mediated nanoparticles synthesis



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1406 **Figure 4: Schematic representation of cellular processes involved in intracellular and**
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Table 1: Different cellular sites that assist in binding of heavy metals to fungus

Location	Functional groups involved in metal uptake	Reference
Extracellular	OH/NH ₂ and CH-OH functional groups, e.g. <i>Aspergillus fumigates</i> .	Rao et al. 2005
	-C=O and -OH groups, e.g. <i>Penicillium chrysogenum</i> XJ-1.	Xu et al. 2015
	Amino group of chitosan, e.g. <i>Penicillium chrysogenum</i> .	Tan and Chen 2003
	Phosphate binding ligands, e.g. <i>Mucor hiemalis</i> .	Hoque and Fritscher, 2019
	Electronegative interaction with outer surface of spores, e.g. <i>Mucor hiemalis</i> .	Hoque and Fritscher, 2019
Cytoplasm	Phosphate precipitates, e.g. <i>Penicillium</i> sp PT1.	Sintuprapaet al. 2000
	Arsenate and copper precipitates, e.g. <i>Aspergillus foetidus</i> .	Ge et al. 2011
	Metal oxalates, e.g. <i>Beauveria caledonica</i> .	Fominaet al. 2005
Cell organelles	Transport to vacuoles by Cot1/Zrc1 transporters, e.g. <i>Saccharomyces cerevisiae</i> .	Wilson et al., 2012
	Vesicle formation (Zincosomes), e.g. <i>S. cerevisiae</i> .	Devirgiliset al. 2004
Other chelators /peptides	Cysteine-containing peptides RaZBP1 and RaZBP2, e.g. <i>Russulaatropurpurea</i> PRM 858109	Leonhardt et al.2014
	Reduced glutathione, e.g. <i>Aspergillus</i> sp. P37; <i>A.niger</i> .	Canovas et al. 2004 Mukherjee et al. 2010
	Thiol compounds (glutathione, phytochelatins, or metallothioneins), e.g. <i>Paxillus involutus</i> .	Courbotet al. 2004
	Metallothionein, e.g. <i>Pisolithustinctorius</i>	Morseltet al. 1986
	Dihydroxynaphthalene melanin, e.g. <i>Gaeumannomycesgraminis</i> .	Caesar-Tonthatet al. 1995

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Table 2: Maximum tolerance limit of some fungal strains for different metal ions.

Metal	Conc (mg/l)	Fungus	Reference
Cr	1000	<i>Aspergillus</i> sp.	Congeevaram et al. 2007
	800	<i>Micrococcus</i> sp.	Congeevaram et al. 2007
	600	<i>Penicillium chrysogenum</i>	Levinskaite, 2002
	600	<i>Trichoderma viride</i>	Levinskaite, 2002
	400	<i>Aspergillus flavus</i>	Iramet al. 2013
	300	<i>Trichoderma brevicompactum</i> QYCD-6	Zhang et al. 2020
	100	<i>Fusarium solani</i>	Iramet al. 2013
	100	<i>Penicillium chrysogenum</i>	Iramet al. 2013
	100	<i>Aspergillus niger</i>	Thippeswamy et al. 2012
	3.9	<i>Neurospora sp SG1</i>	Joshi 2014
Pb	1200	<i>Alternaria alternata</i>	Verma et al. 2016
	1600	<i>Trichoderma brevicompactum</i> QYCD-6	Zhang et al. 2020
	1000	<i>Aspergillus niger</i>	Thippeswamy et al. 2012
	1000	<i>Aspergillus flavus</i>	Thippeswamy et al. 2012
	600	<i>Aspergillus niger</i>	Iramet al. 2013
	400	<i>Geotrichum candidum</i>	Falih 1998
	400	<i>Rhizopus microsporus</i>	Oladipo et al, 2018
	400	<i>Fomitopsis meliae</i>	Oladipo et al, 2018
	4.5	<i>Neurospora sp SG1</i>	Joshi 2014
Cu	1716	<i>Aspergillus niger</i> (SF-5)	Akhtar et al. 2013
	1000	<i>Rhizopus microsporus</i>	Oladipo et al, 2018
	1000	<i>Fomitopsis meliae</i>	Oladipo et al, 2018
	1000	<i>Alternaria alternata</i>	Verma et al. 2016
	700	<i>Pithium sp. (SF-1)</i>	Akhtar et al. 2013
	500	<i>Aspergillus niger</i>	Thippeswamy et al. 2012
	400	<i>Geotrichum candidum</i>	Falih 1998
	100	<i>Aspergillus flavus</i>	Thippeswamy et al. 2012
	5	<i>Neurospora sp SG1</i>	Joshi 2014
Cd	9218	<i>Aspergillus</i> sp.	Akhtar et al. 2013
	5732	<i>Curvularia sp. (GF-6)</i>	Akhtar et al. 2013
	1600	<i>Aspergillus</i> sp.	Akhtar et al. 2013
	600	<i>Talaromyces helices</i>	Romero et al. 2006
	250	<i>Trichoderma brevicompactum</i> QYCD-6	Zhang et al. 2020
	293	<i>Curvularia sp. (GF-6)</i>	Akhtar et al. 2013
Zn	1000	<i>Aspergillus flavus</i>	Thippeswamy et al. 2012
	450	<i>Trichoderma brevicompactum</i> QYCD-6	Zhang et al. 2020
	250	<i>Aspergillus niger</i>	Thippeswamy et al. 2012
	80	<i>Penicillium sp GK1</i>	Joshi 2014
As	500	<i>Rhizopus microsporus</i>	Oladipo et al, 2018
	100	<i>Aspergillus niger</i>	Mukherjee et al. 2010
Ni	1000	<i>Aspergillus flavus</i>	Thippeswamy et al. 2012

	100	<i>Aspergillus niger</i>	Thippeswamy et al. 2012
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Table 3: Biosorption uptake capacity of different metal ions by fungus

Metal	Organism	Biomass type	Uptake efficiency (mg/l)	Reference
Cr	<i>Aspergillus niger</i>	Live Mycelium	100.3	Goyal et al. 2003
	<i>Aspergillus flavus</i>		0.25	Chandrakaret al. 2014
	<i>Rhizopus sp.</i>		9.50	Ahmad et al. 2005
	<i>Fusarium sp.</i>		0.24	Chandrakaret al. 2014
	<i>Cladosporium sp.</i>		0.44	Chandrakaret al. 2014
	<i>Aspergillus sp.</i>	Dead biomass	6.20	Ahmad et al. 2005
	<i>Rhizopus sp.</i>		2.3	Ahmad et al. 2005
	<i>Schizophyllum commune</i> Fries		18.54	Javaidet al. 2010
Pb	<i>Aspergillus fumigates</i>	Live Mycelium	85.65	Ramasamy et al. 2011
	<i>Penicillium simplicissimum</i>		65.60	Fan et al. 2008
	<i>Rhizopus arrhizus</i>		2.64	Bahadiret al. 2007
	<i>Mucor rouxii</i>		7.75 mg/g	Yan and Viraraghavan, 2003
	<i>Sarcinella sp.</i>		0.32	Chandrakaret al. 2014
	<i>Oedogonium sp.</i>	Dead biomass	145	Gupta and Rastogi, 2008
	<i>Nostoc sp.</i>		93.5	Gupta and Rastogi, 2008
	<i>Mucor rouxii</i>		6.34 mg/g	Yan & Viraraghavan, 2003
	<i>Trametes versicolor</i>	Immobilized biomass (live)	0.85 mmol/g	Bayramogluet al. 2003
	Immobilized biomass (inactivated)	1.11 mmol/g		
Cu	<i>Aspergillus niger</i> 405	Live Mycelium	4.4	Filipovic-Kovacevic et al. 2000
	<i>Aspergillus niger</i>		20.75 -93.65 mg/g	Iram and Abrar, 2015
	<i>Mucor rouxii</i>		2.6	Mullen et al 1992
	<i>P. chrysosporium</i>		3.9	Sing and Yu 1998
	<i>Schizophyllum commune</i> Fries	Dead biomass	21.27	Javaidet al. 2010
	<i>Trametes versicolor</i>	Immobilized biomass (live)	1.51 mmol/g	Bayramogluet al. 2003
	Immobilized biomass (inactivated)	1.84 mmol/g		
Cd	<i>Penicillium simplicissimum</i>	Live Mycelium	52.50	Fan et al. 2008
	<i>Penicillium chrysogenum</i> XJ-1		100.41	Xu et al. 2012
	<i>Rhizopus cohnii</i>		40.5	Luo et al. 2010
	<i>Rhizopus sp.</i>		8.21	Ahmad 2005
	<i>Mucor rouxii</i>		35.69 mg/g	Yan and Viraraghavan, 2003

	<i>Aspergillus</i> sp.	Dead biomass	9.5	Ahmad 2005
	<i>Rhizopus</i> sp.		8.21	Ahmad 2005
	<i>Funaliatrogii</i>		191.6	Arica et al. 2004
	<i>Mucor rouxii</i>		25.22 mg/g	Yan and Viraraghavan, 2003
	<i>Trametes versicolor</i>	Immobilized biomass	153	Yalcinkaya et al., 2002
	<i>Funaliatrogii</i>		164.8	Arica et al. 2004
Zn	<i>Penicillium</i> sp PT1	Live Mycelium	16	Sintuprapaet al. 2000
	<i>Penicillium simplicissimum</i>		76.90	Fan et al. 2008
	<i>Mucor rouxii</i>		11.09 mg/g	Yan and Viraraghavan, 2003
	<i>Penicillium</i> sp PT1	Dead biomass	10	Sintuprapaet al. 2000
	<i>Funaliatrogii</i>		54.0	Arica et al. 2004
	<i>Schizophyllum commune</i> Fries		4.83	Javaidet al. 2010
	<i>Mucor rouxii</i>		16.62 mg/g	Yan and Viraraghavan, 2003
	<i>Funaliatrogii</i>	Immobilized biomass	42.1	Arica et al. 2004
	<i>Trametes versicolor</i>	Immobilized biomass (live)	1.33 mmol/g	Bayramogluet al. 2003
	Immobilized biomass (inactivated)	1.67 mmol/g		
Ni	<i>Aspergillus niger</i> 405	Live Mycelium	2	Filipovic-Kovacevic et al. 2000
	<i>Aspergillus niger</i>		23.5 mg/g	Magyarosy et al. (2002)
	<i>Rhizopus nigiricans</i>		1.0	Holan and Volesky 1995
	<i>Mucor rouxii</i>		8.46 mg/g	Yan and Viraraghavan, 2003
	<i>Schizophyllum commune</i> Fries	Dead biomass	9.0	Javaidet al. 2010
	<i>Mucor rouxii</i>		8.36 mg/g	Yan and Viraraghavan, 2003
Hg	<i>Funaliatrogii</i>	Dead biomass	403.2	Arica et al. 2004
	<i>Funaliatrogii</i>	Immobilized biomass	333.0	Arica et al. 2004
	<i>Coprinus comatus</i>	Live mycelium	0.78 – 6.7 mg/kg	Falandysz, 2016
	<i>Phanerochaetechryosporium</i>	Heat inactivated	30 -50	Kacar et al, 2002

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Table 4: Bioaccumulation of different heavy metals by fungus

Metal	Organism	Bioaccumulation capacity	Reference
Cr	<i>Aspergillus</i> sp.	92 %	Congeevaramet al. 2007
	<i>Aspergillus niger</i>	25 %	Thippeswamyet al. 2012
	<i>Micrococcus</i> sp	90 %	Congeevaramet al. 2007
	<i>Trichoderma brevicompactum QYCD-6</i>	31.83 %	Zhang et al. 2020
Pb	<i>Trichoderma brevicompactum QYCD-6</i>	80 %	Zhang et al. 2020
	<i>Aspergillus niger</i>	75 %	Thippeswamyet al. 2012
	<i>Aspergillus flavus</i>	82 %	Thippeswamyet al. 2012
	<i>Aspergillus flavus</i>	89 %	Bano et al. 2018
	<i>S. halophilus</i>	60 %	Bano et al. 2018
Cu	<i>Acremonium pinkertoniae</i>	70-280 mg/g	Zapotocznyet al. 2007
	<i>Trichoderma brevicompactum QYCD-6</i>	64 %	Zhang et al. 2020
	<i>Aspergillus niger</i>	45 %	Thippeswamyet al. 2012
	<i>Aspergillus flavus</i>	34 %	Thippeswamyet al. 2012
	<i>Calvatia excipuliformis</i>	226.52 mg/kg	Elekes and Busuioc, 2011
Cd	<i>Aspergillus niger</i>	0.01-0.303 mg/g	Kumar et al. 2010
	<i>T. brevicompactum QYCD-6</i>	8.45 – 20.13 %	Zhang et al. 2020
Zn	<i>Aspergillus niger</i>	3.399 – 6.783 mg/g	Kumar et al. 2010
	<i>Aspergillus niger</i>	49 %	Thippeswamyet al. 2012
	<i>Aspergillus flavus</i>	40 %	Thippeswamyet al. 2012
	<i>Calvatia excipuliformis</i>	124.30 mg/kg	Elekes and Busuioc, 2011
	<i>T. brevicompactum QYCD-6</i>	2.47 – 4.43 %	Zhang et al. 2020
	<i>A. flavus</i>	84 %	Bano et al. 2018
	<i>S. halophilus</i>	90 %	Bano et al. 2018
Ni	<i>Aspergillus</i> sp.	90 %	Congeevaramet al. 2007
	<i>Aspergillus niger</i>	41 %	Thippeswamyet al. 2012
	<i>Aspergillus flavus</i>	20 %	Thippeswamyet al. 2012
	<i>Aspergillus niger</i>	98 %	Magyarosy et al. 2002
	<i>Micrococcus</i> sp	55 %	Congeevaramet al. 2007

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Table 5: Synthesis of different nanoparticles by fungus

Nanoparticle	Organism	Application	Reference
Ag	<i>Aspergillus clavatus</i>	Antibacterial and fungicidal activity	Verma et al. 2010
	<i>Alternaria alternata</i>	Enhancement of antifungal activity of flucanazole	Gajbhiye et al. 2009
	<i>Amylomycesrouxii</i>	Antimicrobial activity	Mussarat et al. 2010
	<i>Aspergillus flavus</i>		Vigneshwaran et al. 2007
	<i>Aspergillus fumigatus</i>		Bhainsa et al. 2006
	<i>Aspergillus niger</i>	Antibacterial activity	Gade et al. 2008
	<i>Botryosphaeria rhodina</i>	Anticancer activity	Akther et al. 2019
	<i>Cladosporium cladosporioides</i>		Balaji et al. 2009
	<i>Cladosporium cladosporioides</i>	Antimicrobial and Antioxidant activity	Hulikere et al. 2019
	<i>Cryphonectria sp.</i>	Antibacterial activity	Dar et al. 2013
	<i>Duddingtonia flagrans</i>	Nematicidal activity	Barbosa et al. 2019
	<i>Epicoccum nigrum</i>	Antifungal activity	Qian et al. 2013
	<i>Fusarium oxysporum</i>		Ahmad et al. 2003
	<i>Fusarium oxysporum</i>		Ingle et al. 2008
	<i>Fusarium scirpi</i>	Antimicrobial activity	Rodríguez-Serrano et al. 2020
	<i>Fusarium oxysporum</i>		Birla et al. 2013
	<i>Humicola sp.</i>	Cytotoxicity of nanoparticles	Syed et al. 2013
	<i>Macrophomina phaseolina (Tassi) Goid</i>	Antibacterial activity against MDR	Choudhury et al. 2014
	<i>Penicillium brevicompactum</i>		Shaligram et al. 2009
	<i>Penicillium citrinum</i>		Honary et al. 2013
	<i>Penicillium fellutanum</i>		Kathiseran et al. 2009
	<i>Penicillium polonicum</i>	Antibacterial activity against MDR strains	Neethu et al. 2018
	<i>Penicillium sp</i>	Antibacterial activity against MDR strains	Singh et al. 2014
	<i>Phaenerochaete chryso sporium</i>		Vighneshwaran et al. 200
	<i>Phoma golemrata</i>	Antibacterial activity	Birla et al. 2008
	<i>Piriformo sporaindica</i>	Anticancer activity	Aziz et al. 2019
	<i>Rhizopus stonililifer</i>		AbdelRahim et al. 2016
	<i>Talaromyces purpureogenus</i>	Antibacterial and anti-proliferation activity against lung cancer cells	Hu et al. 2019
	<i>Trichodermaatroviride</i>	Antibacterial activity	Saravanakumar et al. 2018
	<i>Trichoderma</i>		Elawami et al. 2018

	<i>longibraciatum</i>		
	<i>Trichoderma reesei</i>		Vabahi et al. 2011
	<i>Trichoderma asperellum</i>		Mukherjee et al. 2008
	<i>Verticillium sp.</i>		Mukherjee et al. 2001b
	<i>Aspergillus clavatus</i>	Antibacterial and fungicidal activity	Verma et al. 2010
	<i>Phomopsis helianthi</i>	Antimicrobial activity	Gond et al. 2019
	<i>Metarhizium robertsii</i>	Antimicrobial and catalytic activity	Rozalska et al. 2016
	<i>Alternaria alternate</i>	Enhancement of antifungal activity of flucanazole	Gajbhiye et al. 2009
Ag/AgCl	<i>Macrophomina phaseolina</i>	Antibacterial activity, soybean seed protection	Spagnoletti et al. 2019
Au	<i>Verticillium sp.</i>		Mukherjee et al. 2001a
	<i>Aspergillus candidus</i>	Cerium detection	Priyadarshini et al. 2015
	<i>Aspergillus niger</i>	Synthesis of different anisotropic nanoparticles using different parts of fungal system	Xie et al. 2007
	<i>Aspergillus niger</i>		Bhambure et al. 2009
	<i>Aspergillus sydowii</i>		Vala 2015
	<i>Aspergillus terreus</i>	Antibacterial activity	Priyadarshini et al. 2014
	<i>Aspergillus oryzae</i> var. <i>viridis</i>		Binupriya et al. 2010
	<i>Aspergillus sp. WL-Au</i>	Catalytic reduction of p-Nitrophenol	Shen et al. 2017
	<i>Candida ablicans</i>	Cell-specific conjugation for liver cancer detection	Chauhan et al. 2011
	<i>Fusarium oxysporium</i>		Ahmad et al. 2002
	<i>Fusarium oxysporium</i>		Mukherjee et al. 2002
	<i>Mariannaea sp. HJ</i>	Catalysis of p-Nitrophenol reduction	Pei et al. 2017
	<i>Penicillium berricompactum</i>	Cytotoxic effect against mouse mayoblast cancer cells	Mishra et al. 2011
	<i>Sclerotiumrolfsii</i>		Narayanan and Sakthivel 2011
	<i>Talaromyces flavus</i>		Priyadarshini et al. 2013
	<i>Trichotheciumsp</i>		Ahmad et al. 2005
	<i>Trichoderma sp. WL-Go</i>	Catalysis in degradation of aromatic pollutants	Qu et al. 2018

	<i>Yarrowia lipolytica</i>		Agnihotri et al. 2009
CdS	<i>Fusarium oxysporium</i>		Ahmad et al. 2002
BaTiO ₃	<i>Fusarium oxysporium</i>	Ferroelectric property	Bansal et al. 2006a
SiO ₂	<i>Fusarium oxysporium</i>	Biotransformation of amorphous silica to nanocrystalline form in rice husk	Bansal et al. 2006b
CdSe	<i>Fusarium oxysporium</i>		Kumar et al. 2007
ZrO ₂	<i>Fusarium oxysporium</i>		Bansal et al. 2004
Fe ₂ O ₃	<i>Fusarium incarnatum</i>		Mahanty et al. 2019
Fe ₃ O ₄	<i>Fusarium oxysporium</i>		Bharde et al. 2006
	<i>Phialemoniopsis ocularis</i>		Mahanty et al. 2019
	<i>Trichoderma asperellum</i>		Mahanty et al. 2019
Pt	<i>Fusarium oxysporium</i>		Syed and Ahmad 2012
	<i>Verticillium sp.</i>		Bharde et al. 2006
TiO ₂	<i>Aspergillus flavus</i>	Antibacterial activity	Rajakumar et al. 2012
CoO	<i>Aspergillus nidulans</i>		Vijayanandan and Balakrishnan 2018
CoFe ₂ O ₄	<i>Monascus purpureus</i>	Antioxidant, anticancer and antimicrobial property	El-Sayed et al. 2020
Se	<i>Aspergillus terreus</i>		Zare et al. 2013
	<i>Mariannaea sp HJ</i>		Zhang et al. 2019
ZnO	<i>Aspergillus oryzae</i>	Antibacterial activity	Mosallam et al 2018
	<i>Cochliobolus geniculatus</i>		Kadam et al. 2019
	<i>Alternaria tenuissima</i>	Antimicrobial, anticancer, antioxidant band photocatalytic activity	Abdelhakim et al. 2020
	<i>Cordyceps militaris</i>	Photocatalytic degradation of Methylene blue dye	Li et al. 2019
Cu	<i>Colletotrichum gloeosporiodes</i>	Antibacterial and cytotoxic property against human breast cancer cells	Mugesh et al. 2019
Bi ₂ O ₃	<i>Fusarium oxysporium</i>		Uddin et al. 2008
Ag-Au	<i>A. niger</i> <i>T. longibrachiatum</i>	Antibacterial, Anticoagulant, and Antioxidant activity	Elegbede et al. 2019
Pb	<i>Aspergillus sp</i>		Pavani et al. 2012

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