Biolife
AN INTERNATIONAL QUARTERLY JOURNAL OF BIOLOGY & LIFE SCIENCES
3(1):77-108
ISSN (online): 2320-4257
www.biolifejournal.com
BIOLIFE REVIEW ARTICLE

Role of myco-communities in the field of heavy metal remediation

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ABSTRACT

Heavy metals have been reported as priority pollutants, due to their mobility in natural ecosystems and due to their toxicity. Bioremediation is cost effective, efficient and environmentally friendly alternative for removal of heavy metals. The ubiquitous presence of fungi has allowed acclimation to most types of wastes. During the last decade, fungi have been used in the treatment of a wide variety of wastes, and the role of fungi in the bioremediation of various hazardous and toxic compounds in soils and sediments has been established. The properties of fungi to absorb and accumulate heavy metals give potential for cheap alternative method of heavy metal removal from soil and waste water. Therefore, this review has been made to discuss about the heavy metal removal from contaminated sources by fungi of different groups like Zygomycotina, Ascomycotina, Basidiomycotina and Deuteromycotina. In this review we found, species of *Aspergillus, Penicillium, Trichoderma, Saccharomyces, Mucor, Rhizopus* and *Pleurotus* represented the best remediation agents for different heavy metals.

Key words: Heavy metals; Biosorption; Bioaccumulation.

INTRODUCTION

Contamination of natural resources especially soil and water by heavy metals has become a major concern worldwide. The conventional methods of remediating heavy metals are less effective and costly. Conventional methods can remove only up to certain minimum level of metal ions, whereas, bioremediation is cost effective, efficient and environmentally friendly alternative for removing heavy metals from contaminated habitats. Among the microbes the fungi have been widely used in bioremediation. Fungi are ubiquitous, present in aquatic sediments, terrestrial habitats as well as water surfaces and play a significant role in natural remediation of heavy metals (Dugal and Gangawane, 2012).

Various mechanisms of metal removal by microbes have been reported and have been classified according to various criteria.

According to the dependence on the cell's metabolism, mechanisms of metal removal can be divided into: (1) Biosorption: which is a metabolism-independent uptake of metals by living and non-living biomass (Arica et al., 2004). Biosorption involves a combination of different processes, namely, electrostatic attraction, complexation, ion exchange, covalent binding, Van der Waals' forces, adsorption and precipitation (Nabizadeh et al., 2005) and (2) Bioaccumulation: which is an active process dependent upon metabolic energy of microorganisms. In other words, bioaccumulation is an energy-dependent heavy metal transport system (Gadd, 1988). In metabolically active living cells intracellular metal uptake occur in combination with extra cellular adsorption. Metal accumulation is carried out by initial rapid binding of metal ions on to the negatively charged cell wall followed by penetration in to the cytoplasm and get

accumulated inside the cell (Thippeswamy et al., 2012b).

The process of bioremediation by microorganisms involve enzymatic attack on pollutants and convert them into harmless products. As bioremediation can be effective only where environmental conditions permit microbial growth and activity, its application often involves the manipulation of environmental parameters to allow microbial growth and degradation to proceed at a faster rate (Karigar and Rao, 2011).

Fungal cell walls can act as a cation exchanger due to their negative charge originating from the presence of different functional groups, e.g. carboxylic, phosphate, amine or sulfhydryl, in different wall components (hemicelluloses, pectin, lignin, etc.) (Fomina et al., 2007) having excellent metal binding properties (Mann, 1990; Luef et al., 1991; Muraleedharan et al., 1991). Cell walls of fungi are rich in polysaccharides and glycoproteins such as glucans, chitin, mannans and phospho-mannans. These polymers provide abundant sources of metal binding ligands (Farkas, 1980). Metals and their compounds can interact with fungi in various ways depending on the type of metal, organism and environment (Aung and Ting, 2005). Moreover the use of fungal biomasses as biosorption materials is very convenient because of their inexpensive production methods (Maurya et al., 2006). Therefore, the cost of a biosorbent will be significantly lowered as compared to the cost of the conventional adsorbent. Therefore, the aim of this review is to discuss about the heavy metal removal from contaminated sources and aqueous solutions involving the two mechanisms i.e., biosorption and bioaccumulation by fungi of different groups.

Heavy metal remediation by fungi of Zygomycotina:

The fungi included in this group are terrestrial and are mainly found in soil and dung. There are various examples of fungi of Zygomycotina those have been used for heavy metal removal. These are (Table 1):

Circinella

Circinella sp. was employed as a biosorbent for removal of Ni from aqueous solutions (Alpat et al., 2010). The effect of several parameters, such as biosorbent dosage, contact time, initial concentration of metals, pH and temperature, on biosorption process was evaluated. The results of the biosorption of Ni by *Circinella* sp. showed that temperature and initial concentration of metal ion greatly influenced the uptake capacity. The biosorption capacity increased with an increase, both in temperature up to 40ºC and in concentration of the metal ions up to 3.0 mM (Alpat et al., 2010).

Cunninghamella

Cunninghamella echinulata was chosen for biosorption studies by El Morsy-El Sayed (2004) and Shoaib et al. (2012). They found that free and immobilized biomass of *C. echinulata* sequestered ions from polluted water in the descending order of Pb > Cu > Zn. The effects of biomass concentration, pH and time of contact were also investigated. The level of ion uptake rose with increasing biomass concentration; and pH up to 4 in the case of Pb and 5 in the case of Cu and Zn. Maximum uptake for all metals was achieved after 15 min. Results revealed a marked increase in uptake of all tested metals by the alkali-treated, alginate-immobilized biomass over free biomass. Treatment of *C. echinulata* biomass with NaOH improved biosorbent capacity by 25-30 %, as did immobilization with alginate.

Mucor

Live and dead biomass of *Mucor rouxii* has been found to uptake heavy metals from aqueous solution (Yan and Viraraghavan, 2003). The highest biosorption capacity of live biomass was found for Pb followed by Ni, Cd and Zn, whereas dead biomass adsorbed metal ions in the order of Zn>Pb>Ni>Cd. At pH 4.0 little biosorption occurred and almost no biosorption

was observed at pH 2.0 (except for nickel). A sharp increase in biosorption capacity took place in the pH range of 4.0–5.0. Above pH 5.0, biosorption of lead was found to be relatively

Table 1. Heavy metal remediation by the different fungi of group Zygomycotina (TEM=Temperature, CT=Contact time, BC=Biomass concentration, PRT=Pretreatment, ET=Equilibrium time, IP= Incubation period, -- = Not available)

Fungi	Heavy metal	Initial concentra-tion of metal	Metal uptake by biomass and other conditions	Process involved	References
Circinella sp.	Ni	_	18.66 mg/g	Biosorption	Alpat *et al*., 2010
			pH 6		
Cunnighamella echinulata	Pb	_	45 mg/g	Biosorption	El-Morsy El-Sayed, 2004
			pH 4, 15 min CT, 200 mg/l BC		
	Cu	_	20 mg/g	Biosorption	El-Morsy El-Sayed, 2004
			pH 5, 15 min CT, 200 mg/l BC		
	Cu	50mg/l	20%	Biosorption	Shoaib *et al.*, 2012
	Ni	50mg/l	20%	Biosorption	Shoaib *et al.*, 2012
	Zn	_	18.8 mg/g	Biosorption	El-Morsy El-Sayed, 2004
			pH 5, 15 min CT, 200 mg/l BC		
Mucor hiemalis	Cd	10-50 mg/l	85.47 mg/g	Biosorption	Srivastava and Hasan, 2011
			pH 6, 35 min CT, 25^{o}C TEM		
	Cr	50 mg/l	4.3 mg/g	Biosorption	Pillichshammer *et al*., 1995
			pH 1, 30^{o}C TEM, 1000 min CT		
	Cr	_	22 mg/g	Biosorption	Ebner *et al*., 2002
			pH 5, 25^{o}C TEM, 30 min CT		
Mucor rouxii	Pb	10 mg/l	53.75 mg/g	Biosorption	Yan and Viraraghvan, 2003
			pH 6, NaOH PRT		
	Pb	100 mg/l	90%	Biosorption	Majumdar *et al*., 2010
			pH 5-6, 30^{o}C TEM		
	Pb	10 mg/l	17.13 mg/g	Biosorption	Yan and Viraraghvan, 2000
			Live biomass, pH 5, 15 hrs CT		
	Cd	10 mg/l	20.31 mg/g	Biosorption	Yan and Viraraghvan, 2003
			pH 6, NaOH PRT		
	Cd	10 mg/l	6.94 mg/g	Biosorption	Yan and Viraraghvan, 2000

			Live biomass, pH 5, 15 hrs CT		
	Ni	10 mg/l	20.49 mg/g	Biosorption	Yan and Viraraghvan, 2003
			pH 6, NaOH PRT		
	Ni	10 mg/l	5.24 mg/g	Biosorption	Yan and Viraraghvan, 2000
			Live biomass, pH 5, 15 hrs CT		
	Zn	10 mg/l	53.85 mg/g	Biosorption	Yan and Viraraghvan, 2003
			pH 6, NaOH PRT		
	Zn	10 mg/l	4.89 mg/g	Biosorption	Yan and Viraraghvan, 2000
			Live biomass, pH 5, 15 hrs CT		
Mucor sp.	Cu	3 mM	94.6 mg/g	Biosorption	Tahir, 2012
	Cu	90 mg/l	38 mg/g	Biosorption	Khan *et al*., 1998
Rhizopus arrhizus	Pb	1 µg/mg	154.41± 11.64 µg/g	Bioaccumulation	Pal *et al*., 2010
			28°±2°C TEM, 5 days IP		
	Pb	10-600 mg/l	55.6 mg/g	Biosorption	Fourest and Roux, 1992
			pH 5-7, 3-5 hrs ET		
	Pb	150 mg/l	68.8 mg/g	Biosorption	Sag *et al*., 1995
			pH 5, 25°C TEM, 30 min CT		
	Pb	300 mg/l	50 mg/g	_	Volesky, 1992
			pH 3.5, 26°C TEM		
	Cr	0-100 mg/l	8.40 mg/g/min	_	Prakasham *et al*., 1998
			pH 1-2, 35°C TEM, 60 min CT		
	Cr	25-400 mg/l	4.5 mg/g	_	Nourbakhsh *et al*., 1994
			pH 1-2, 25°C TEM		
	Cr	5-15 mg/l	70%	Biosorption	Shoaib *et al.,* 2012
	Cd	10-600 mg/l	26.8 mg/g	Biosorption	Fourest and Roux, 1992
			pH 6-7, 3-5 hrs ET		
	Cd	10-400 mg/l	25 mg/g	_	Volesky, 1992
			pH 3.5, 26°C TEM		
	Cu	_	9.5 mg/g	Biosorption	Gadd *et al*., 1988
			pH 5.5, 25°C TEM		
	Ni	10-600 mg/l	18.7 mg/g	Biosorption	Fourest and Roux, 1992
			pH 6-7, 3-5 hrs ET		
	Ni	300 mg/l	46.67%	Biosorption	Shoaib *et al.,* 2012
	Zn	10-600 mg/l	13.5 mg/g	Biosorption	Fourest and Roux, 1992

			pH 6-7, 3-5 hrs ET		
Rhizopus cohnii	Cd	_	40.5 mg/g	Biosorption	Luo *et al*., 2010
			pH > 2		
Rhizopus nigricans	Cr	100 mg/l	80%	Biosorption	Bai and Abraham, 2001
			pH 2, 4 hrs CT		
	Cr	_	47 mg/g	_	Volesky and Holan, 1995
	Pb	_	13-105 mg/g	_	Volesky and Holan, 1995
	Zn	5-200 mg/l	14 mg/g	_	Volesky, 1992
Rhizopus oryzae	Cu	5 mg/l	2.3 mg/l	Biosorption	El-Gendy *et al*., 2011
			pH 6±0.1, 30°C TEM, 3 hrs CT		
	Cd	3.5 mg/l	1.7 mg/l	Biosorption	El-Gendy *et al*., 2011
			pH 6±0.1, 30°C TEM, 3 hrs CT		
Rhizopus sp.	Cu	3 mM	98.8 mg/g	Biosorption	Tahir, 2012
	Cd	6 mM	2.72 mg/g	Biosorption	Zafar *et al*., 2006
			25°C TEM, 4 hrs CT		
	Cd	6 mM	8.21 mg/g	Biosorption	Ahmad *et al*., 2005b
			pH 4.5, 18 hrs CT, 5 N NaOH PRT		

constant; whereas that of cadmium and nickel still increased but to a lesser extent (Yan and Viraraghavan, 2003). Other species *M. hiemalis* was investigated for biosorption of Cr by their whole cells and isolated cell walls. A fast initial sorption of Cr on the cell wall was found, reaching 80% of the calculated maximum load after 30 min contact time. From the Langmuir-fitted biosorption isotherms theoretical maximum biosorption capacities of 132 and 22 mg Cr/g dry weight were calculated for cell wall and whole cells, respectively. The major components of cell wall involve in the process were chitosan and chitin (Ebner et al., 2002). In another study, *M. hiemalis* was studied for the removal of cadmium from aqueous solution in a batch system (Srivastava and Hasan, 2011). Effects of various parameters such as pH, biomass dosage, contact time, and initial metal concentrations were also investigated (Srivastava and Hasan, 2011).

Rhizopus

Rhizopus sp. was tested for their metal biosorption potential of Cr and Cd in vitro. Biosorption experiments were conducted with initial metal concentrations of 2, 4, 6 and 8 mM with a contact time of 4 h and wet fungal

biomass (1-5 g) at 25°C. Maximum biosorption of Cr and Cd ions was found at 6 mM initial metal concentration (Zafer et al., 2007). Similarly another strain of this fungal species,

Rhizopus (RSH 9) was selected for the biosorption potential for Cr and Cd (Ahmad et al., 2005b). The results obtained by them varied with respect to initial concentration of heavy metals and other factors like temperature and pH than those obtained previously (Ahmad et al., 2005b). A Lead tolerant strain, *R. arrhizus* (M1) was investigated for accumulation of Pb in the mycelia in comparison to wild type (Pal et al., 2010). Accumulation of Pb in cell wall of M1 strain was more than wild type strain. Optimum incubation period and temperature were also evaluated in this study. The results indicated that the cell surface functional groups of the fungus might act as ligands for metal sequestration resulting in removal of the metals from the aqueous culture (Pal et al., 2010). *R.*

cohnii was used as an efficient biosorbent for removing cadmium from wastewater (Luo et al., 2010). The sorption conditions, such as pH, the dose of biomass and the initial concentration of cadmium were also examined. The uptake of cadmium was higher in weak acid condition than in strong acid condition. Nearly no sorption of cadmium occurred when the pH value was lower than 2.0 (Luo et al., 2010). Work of the other researchers has been summarized in table 1.

Heavy metal remediation by fungi of group *Ascomycotina*

Fungi of this group occur in a wide range of habitats: in soil, dung, marine and fresh waters. This group of fungi mainly encompasses filamentous fungi and yeasts. There are various examples of fungi of Ascomycotina those show excellent bioremediation capacity for different metals. These are (Table 2):

Aspergillus

Aspergillus sp. was evaluated as a metal resistant species for bioaccumulations of Cr and Ni (Congeevaram et al., 2007; Sen and Dastidar, 2010; Shoaib et al., 2012) and was characterized to assess its applicability for heavy metal removal from industrial wastewaters. The optimum pH and temperature for both the growth and heavy metal removal were also determined. The observed effect of pH was attributable mainly to organism-specific physiology because in all the tested cases the cellular growth was positively correlated with heavy metal removal (Congeevaram et al., 2007). Ahmad et al., (2005b) conducted an experiment in which NaOH pretreated dead biomass of *Aspergillus* (ASH 1) was selected for the biosorption potential of Cr and Cd. It was influenced by initial metal concentration (2-8 mM), nature of organism and other factors like temperature, pH, contact time and agitation rate. Similarly, Zafer et al. (2007) tested *Aspergillus sp*. for their biosorption potential of Cr and Cd *in vitro* with initial metal concentrations of 2, 4, 6 and 8 mM with a contact time of 4 h and wet fungal biomass (1-5 g) at 25^{o} C. Maximum biosorption was found at 6 mM initial metal concentration. Ramasamy et al. (2012) found that *Aspergillus* sp. has good potential to be used as biosorbent for Cd ions from contaminated wastewater. The optimal parameters for removal of Cd such as metal concentration, pH, temperature and time were studied. In the controlled conditions it was demonstrated that the maximum of 88% Cd was removed from aqueous solution by *Aspergillus* sp. at pH 4 and temperature 30°C. In batch mode, NaOH pretreated *A. niger* biomass was investigated for cadmium biosorption (Amini et al., 2009). The effect of three independent variables, initial pH of solution (1.3–8.7), biomass dosage (0.1–7.5 g/l) and initial cadmium ion concentration (0.5–37.5 mg/l) on the biosorption process was determined (Amini et al., 2009). In another experiment, *A. niger* was tested for their Cr, Ni and Cd biosorption potential using alkali treated, dried and powdered mycelium. It was found to adsorb metals from single and multi-metal solutions in the order of Ni > Cd > Cr (Ahmad et al., 2005a). Isolate of *A. niger*, Ni27 has been observed to uptake maximum Ni at initial metal concentration of 50 ppm (Joshi et al., 2011). Besides a cadmium tolerant strain *A. niger* (AB10) was studied for accumulated Cd in the mycelia in comparison to wild type strains and was found to accumulate maximum amount of cadmium after optimum incubation period and temperature in a synthetic medium. Accumulated cadmium in the cell wall fractions of cadmium tolerant *A. niger* was more than the wild type strain. Cytosolic fraction contained the next highest load of metal. The results indicated contribution of the surface property of the fungus in metal bioaccumulation. Involvement of the cellular metabolism during metal bioaccumulation and distribution in the sub-cellular compartments was substantiated by the use of some metabolic inhibitors during growth in presence of metals (Pal et al., 2010). Moreover, *A. niger* has found to tolerate and accumulate toxic metals namely Ni, Zn, Cd, Pb, Cr and Cu from synthetic medium and Paper mill effluent with maximum accumulation of Pb followed by Zn > Cu > Cr > Ni at 100 mg/l of metal solution, whereas metal accumulation

from 250 and 500 mg/l of metal solution was found in following order: Pb > Cu > Zn and Pb >Cu (Thippeswamy et al., 2012b). Furthermore, It was investigated for their potential abilities to accumulate arsenic from salt medium and found to uptake 64.20±18.60 nmol/mg arsenic from the medium (Adeyemi, 2009). *A. fumigatus* was found to be suitable biosorbent for Pb ions, especially when the metal content in the water system was in the concentration of 100 mg/l. Factors like pH, temperature, time and ionic concentration showed significant effects on lead biosorption (Ramasamy et al., 2011). A significant differential expression of some polypeptides was seen in lead pre-exposed fungi than unexposed one. This was probably attributed due to a higher degree of functional diversity among the fungi (Ramasamy et al., 2011).

Table 2. Heavy metal remediation by the different fungi of group Ascomycotina (TEM=Temperature, CT=Contact time, BC=Biomass concentration, PRT=Pretreatment, ET=Equilibrium time, IP= Incubation period, -- = Not available)

Fungi	Heavy metal	Initial concentr -ation of metal	Metal uptake by biomass and other conditions	Process involved	References
Aspergillus flavus	Zn	0.45 mg/l	0.40 mg/l	Biosorption	Chandrakar *et al.*, 2012
			5 days IP		
	Zn	100 mg/l	49%	Bioaccumul -ation	Thippeswamy *et al*., 2012a
	Cu	100 mg/l	45%	Bioaccumul -ation	Thippeswamy *et al*., 2012a
	Cu	300 mg/l	23%	Biosorption	Shoaib *et al*., 2012
	Cu	0.6625 mg/l	0.62 mg/l	Biosorption	Chandrakar *et al.*, 2012
			5 days IP		
	Ni	100 mg/l	25%	Bioaccumul -ation	Thippeswamy *et al*., 2012a
	Ni	50-100 mg/l	16%	Biosorption	Shoaib *et al.*, 2012
	Pb	100 mg/l	75%	Bioaccumul -ation	Thippeswamy *et al*., 2012a
Aspergillus foetidus	Cr	5 mg/l	97%	Biosorrption	Prasenjit and Sumathi, 2005
			pH 7, 92 hrs CT		
Aspergillus fumigatus	Cu	25 mM	72%	Biosorption	Rao *et al*., 2005
	Cd	25 mM	61%	Biosorption	Rao *et al*., 2005
	Co	25 mM	49%	Biosorption	Rao *et al.,* 2005
	Ni	25 mM	37%	Biosorption	Rao *et al.*, 2005
	Pb	100 ppm	85.25%	Biosorption	Ramasamy, 2011
			pH 4, 30^{o}C TEM		
Aspergillus luchuensis	Cu	5 mg/l	3.1 mg/l	Biosorption	El-Gendy *et al.*, 2011
			pH 6±0.1, 30^{o}C TEM, 3 hrs CT		
	Cd	3.5 mg/l	1.3 mg/l	Biosorption	El-Gendy *et al*., 2011

			pH 6±0.1, 30°C TEM, 3 hrs CT		
Aspergillus nidulans	As	500 mg/l	84.35%	Biosorption	Maheshwari and Murugesan, 2009
			pH 4, 35°C TEM, After 11 days		
Aspergillus niger	Cd	4 µg/ml	243.20±18.17 µg/g	Bioaccumul-ation	Pal *et al*., 2010
			8 days IP, 28°±2°C TEM		
	Cd	_	26.72 mg/g	Biosorption	Junior *et al*., 2003
			pH 5, 6 hrs IP		
	Cd	30 mg/l	10.14 mg/g	Biosorption	Amini *et al*., 2009
			pH 5.96, 1440 min CT		
	Cd	4 mM	19.4 mg/g	Biosorption	Ahmad *et al.*, 2005a
			25°C TEM, 18 hrs CT		
	Cd	50-250 µg/ml	0.01-0.303 mg/g	_	Kumar *et al*., 2011
			30-35°C±2°C TEM, 48 hrs CT		
	Pb	100 mg/l	82%	Bioaccumul-ation	Thippeswamy *et al*., 2012a
	Pb	1000 mg/l	209.33 mg/g	Biosorption	Faryal *et al*., 2007
			pH 9.5, 28°C TEM		
	Zn	100 mg/l	40%	Bioaccumul-ation	Thippeswamy *et al*., 2012a
	Zn	50-250 µg/ml	3.399-6.783 mg/g	Biosorption	Kumar *et al.*, 2011
			30-35°C±2°C TEM, 48 hrs CT		
	Cu	100 mg/l	34%	Bioaccumul-ation	Thippeswamy *et al.*, 2012a
	Cu	50 mg/l	36%	Biosorption	Shoaib *et al.*, 2012
			pH 4.5, 25°C TEM, 3 hrs CT		
	Cu	0.5 mM	7.22 mg/g	Biosorption	Rao *et al*., 1993
			pH 5, 41 g/l BC		
	Cu	100 mg/l	4 mg/g	_	Venkobacher, 1990
	Ni	100 mg/l	20%	Bioaccumul-ation	Thippeswamy *et al.,* 2012a
	Ni	50 ppm	0.55 mg/g	Bioaccumul-ation	Joshi *et al*., 2011
	Ni	50-100 mg/l	20%	Biosorption	Shoaib *et al.*, 2012
			pH 4.5, 25°C TEM, 3 hrs CT		
	Ni	4 mM	25.05 mg/g	Biosorption	Ahmad *et al*., 2005a
			25°C TEM, 18 hrs CT		
	Cr	100 mg/l	41%	Bioaccumul-ation	Thippeswamy *et al*., 2012a
	Cr	4 mM	18.05 mg/g	Biosorption	Ahmad *et al*., 2005a
			25°C TEM, 18 hrs CT		

	Cr	35 mg/l	51%	Biosorption	Shoaib *et al*., 2012
			pH 4.5, 25°C TEM, 3 hrs CT		
	As	0.40%	64.20±18.60 nmol/mg	Bioaccumul -ation	Adeyemi, 2009
Aspergillus ochraceous	Cr	20 ppm	94.10%	Biosorption	Seshikala and Charya, 2012
			pH 3-7		
Aspergillus oryzae	Cr	240 mg/l	97%	_	Nasseri *et al.*, 2002
			pH 5, 30°C TEM		
	Cd	_	7.22 mg/g	Biosorption	Rao *et al.*, 1993
Aspergillus sp.	Cd	100 mg/l	88%	Biosorption	Kumar *et al.,* 2011
			pH 4, 30°C TEM, 24 hrs IP		
	Cd	150 mg/l	57 mg/g	Biosorption	Khan *et al.*, 1998
			25°C TEM, 3 hrs CT		
	Cd	6 mM	2.72 mg/g	Biosorption	Zafar *et al*., 2006
			25°C TEM, 4 hrs CT		
	Cd	4 mM	6 mg/g	Biosorption	Ahmad *et al*., 2005b
			pH 4.5, 18 hrs CT, 0.5 N NaOH PRT		
	Cr	100 mg/l	92%	Bioaccumul -ation	Congeevaram *et al*., 2007
			pH 5, 35°C TEM, 18 hrs IP		
	Cr	0-500 mg/l	34.8 mg/g	Biosorption	Sen and Dastidar, 2007
			pH 2, 30°C TEM, 36 hrs CT		
	Cr	50-500 mg/l	10-27.5 mg/g	_	Sen and Dastidar, 2010
			pH 2, 30°C TEM, 2 hrs CT		
	Pb	150 mg/l	42 mg/g	Biosorption	Khan *et al*., 1998
			25°C TEM, 3 hrs CT		
	Zn	150 mg/l	67 mg/g	Biosorption	Khan *et al*., 1998
			25°C TEM, 3 hrs CT		
	Cu	3 mM	254.7 mg/g	Biosorption	Tahir, 2012
			pH 3, 30°C TEM, 24 hrs IP		
Aspergillus terrus	Pb	50 ppm	59.67 mg/g	Bioaccumul -ation	Joshi *et al*., 2011
	Cu	50 mg/l	21%	Biosorption	Shoaib *et al.*, 2012
	Cu	22.57 mg/l	7.77 mg/g	Biosorption	Varshney *et al*., 2010
			pH 4, 27°C TEM		
	Ni	100 mg/l	21%	Biosorption	Shoaib et al., 2012
	Cr	20 ppm	94.30%	Biosorption	Seshikala and Charya, 2012
Aspergillus tubingensis	Cu	5 mg/l	2.5 mg/l	Biosorption	El-Gendy et al., 2011

			pH 6±0.1, 30°C TEM, 3 hrs CT		
	Cd	3.5 mg/l	0.9 mg/l	Biosorption	El-Gendy *et al*., 2011
			pH 6±0.1, 30°C TEM, 3 hrs CT		
Aspergillus ustus	Zn	0.45 mg/l	0.42 mg/l	Biosorption	Chandrakar *et al*., 2012
			5 days IP		
	Cu	0.6625 mg/l	0.62 mg/l	Biosorption	Chandrakar *et al*., 2012
			5 days IP		
Aspergillus versicolor	Pb	100 mg/l	30.6 mg/g	Biosorption	Cabuk *et al*., 2004
			pH 5.5, 180 min CT,		
			DMSO (Dimethyl sulphoxide) PRT		
Ascohyta betae	Cr	20 ppm	85%	Biosorption	Seshikala and Charya, 2012
			pH 3-7		
Candida sp.	Cu	0.082 ppm	0.079 ppm	Biosorption	Anaemene, 2012
			2 hrs CT, 0.5 N NaOH PRT		
	Zn	0.075 ppm	0.074 ppm	Biosorption	Anaemene, 2012
			2 hrs CT, 0.5 N NaOH PRT		
	Fe	0.091 ppm	0.088 ppm	Biosorption	Anaemene, 2012
			2 hrs CT, 0.5 N NaOH PRT		
Candida tropicalis	Zr	1 g/l	179 mg/g	Biosorption	Akhtar *et al*., 2008
			pH 3.5, 28±2°C TEM, 24 hrs CT		
Candida utilis	Cr	50 µm	90%	–	Pattanapipitpaisal *et al*., 2001
Cladosporium resinae	Cu	1-320 mg/l	25.4 mg/g	Biosorption	Gadd and de Rome, 1988
			pH 5.5, 25°C TEM		
Cladosporium sp.	Zn	0.45 mg/l	0.44 mg/l	Biosorption	Chandrakar *et al.*, 2012
			5 days IP		
	Cu	0.6625 mg/l	0.66 mg/l	Biosorption	Chandrakar *et al*., 2012
			5 days IP		
	Cu	90 mg/l	37 mg/g	Biosorption	Khan *et al.,* 1998
Curvularia lunata	Cu	5 mg/l	1.04 mg/l	Biosorption	El-Gendy *et al*., 2011
			pH 6±0.1, 30°C TEM, 3 hrs CT		
	Cd	3.5 mg/l	1 mg/l	Biosorption	El-Gendy et al., 2011
			pH 6±0.1, 30°C TEM, 3 hrs CT		
	Cr	20 ppm	58%	Biosorption	Seshikala and Charya, 2012

			pH 3-7		
Dactylosporium	Cr	20 ppm	74%	Biosorption	Seshikala and Charya, 2012
			pH 3-7		
Drechslera hawaiiensis	Cu	5 mg/l	4.18 mg/l	Biosorption	El-Gendy *et al.*, 2011
			pH 6±0.1, 30°C TEM, 3 hrs CT		
	Cd	3.5 mg/l	0.9 mg/l	Biosorption	El-Gendy *et al.,* 2011
			pH 6±0.1, 30°C TEM, 3 hrs CT		
Drechslera rostrata	Cr	20 ppm	74%	Biosorption	Seshikala and Charya, 2012
			pH 3-7		
Gliocladium sp.	Cu	3 mM	474.5 mg/g	Biosorption	Tahir, 2012
			pH 3, 30°C TEM, 24 hrs IP		
Metarrhizium anisopliae	Pb	100 mg/l	23.3 mg/g	Biosorption	Cabuk *et al*., 2004
			pH 5.5, 180 min CT, autoclave PRT		
Monacrosporium elegans	Cu	5 mg/l	3.5 mg/l	Biosorption	El-Gendy *et al*., 2011
			pH 6±0.1, 30°C TEM, 3 hrs CT		
	Cd	3.5 mg/l	1.6 mg/l	Biosorption	El-Gendy *et al.*, 2011
			pH 6±0.1, 30°C TEM, 3 hrs CT		
Neurospora elegans	Pb	200 mg/l	49.06 mg/g	Biosorption	Ismail *et al*., 2005
			pH 4, 15 min ET, Detergent treated		
	Cu	200 mg/l	12.28 mg/g	Biosorption	Ismail *et al*., 2005
			pH 4, 15 min ET, Detergent treated		
Penicillium canescens	Cd	_	102.7 mg/g	_	Say *et al*., 2003
			pH 5		
	Pb	_	213.2 mg/g	_	Say *et al*., 2003
			pH 5		
	As	_	26.4 mg/g	_	Say *et al*., 2003
			pH 5		
	Hg	_	54.8 mg/g	_	Say *et al.,* 2003
Penicillium chrysogenum	Cr	_	27.2 mg/g	Biosorption	Tan and Cheng, 2003
	Ni	_	19.2 mg/g	Biosorption	Tan and Cheng, 2003
	Cu	_	13 mg/g	_	Skowronski *et al.*, 2001
			pH 6, 21°C TEM		
	U	_	70 mg/g	Biosorption	Tsezos and Volesky, 1981
			pH 4-5, 23°C TEM		

	Th	_	142 mg/g	Biosorption	Tsezos and Volesky, 1981
			pH 4-5, 23°C TEM		
	Zn	_	24.5 mg/g	Biosorption	Tan and Cheng, 2003
	Zn	_	6.5 mg/g	Biosorption	Niu *et al*., 1993
			pH 4-5		
	Zn	_	13 mg/g	_	Skowronski *et al*., 2001
			pH, 21°C TEM		
	Pb	2-20 mg/l	11.6 mg/g	Biosorption	Niu *et al*., 1993
			pH 4-5, 23°C TEM		
	Pb	_	96 mg/g	_	Skowronski *et al*., 2001
			pH 6, 21°C TEM		
	Cd	_	11 mg/g	_	Niu *et al*., 1993
			pH 4-5		
	Cd	_	21.5 mg/g	_	Skowronski *et a*l., 2001
Penicillium cyclopium	Cu	15 mg/l	50 mg/g	_	Ianis *et al.*, 2006
			pH 4.5		
Penicillium decumbens	Cd	0.1-3 mM	83%	Biosorption	Levinskaite, 2001
	Ni	0.1-3 mM	29.40%	Biosorption	Levinskaite, 2001
	Cr	0.1-3 mM	77.80%	biosorption	Levinskaite, 2001
Penicillium digitatum	Cd	10-50 mg/l	3.5 mg/g	_	Galun *et al*., 1987
			pH 5.5, 25°C TEM		
	Cu	10-50 mg/l	3 mg/g	_	Galun *et al*., 1987
			pH 5.5, 25°C TEM		
	Pb	10-50 mg/l	5.5 mg/g	_	Galun *et al.*, 1987
			pH 5.5, 25°C TEM		
Penicillium duclauxi	Cu	5 mg/l	1.4 mg/l	Biosorption	El-Gendy *et al.*, 2011
	Cd	3.5 mg/l	1.5 mg/l	Biosorption	El-Gendy *et al*., 2011
Penicillium lilacium	Cu	5 mg/l	4.27 mg/l	Biosorption	El-Gendy *et al*., 2011
	Cd	3.5 mg/l	1.1 mg/l	Biosorption	El-Gendy *et al*., 2011
Penicillium notatum	Cr	25 ppm	94.10%	Biosorption	Seshikala and Charya, 2012
Penicillium pupurogenum	Cr	_	36.5 mg/g	_	Say *et al*., 2003
			pH 6, 20°C TEM		
Penicillium simplicissimum	Cd	200 mg/l	52.50 mg/g	Biosorption	Fan et al., 2008
			pH 5, 28°C TEM		
	Zn	250 mg/l	65.60 mg/g	Biosorption	Fan et al., 2008
			pH 5, 28°C TEM		
	Pb	250 mg/l	76.90 mg/g	Biosorption	Fan et al., 2008
			pH 5, 28°C TEM		

Penicillium sp.	Cr	4 mM	18.05 mg/g	Biosorption	Ahmad *et al*., 2005a
			25°C TEM, 18 hrs CT		
	Cd	4 mM	19.4 mg/g	Biosorption	Ahmad *et al.*, 2005a
			25°C TEM, 18 hrs CT		
	Cd	120 mg/l	58 mg/g	Biosorption	Khan *et al.*, 1998
			25°C TEM, 3 hrs CT		
	Cd	350 mg/l	95%	Biosorption	Dugal and Gangawane, 2012
			pH 6, 37°C TEM, 96 hrs IP		
	Ni	4mM	25.05 mg/g	Biosorption	Ahmad *et al*., 2005a
			25°C TEM, 18 hrs CT		
	Ni	150 mg/l	62 mg/g	Biosorption	Khan *et al*., 1998
			25°C TEM, 3 hrs CT		
	Zn	150 mg/l	70 mg/g	Biosorption	Khan *et al*., 1998
			25°C TEM, 3 hrs CT		
	Cu	3mM	254.7 mg/g	Biosorption	Tahir, 2012
			pH 3, 30°C TEM, 24 hrs IP		
	Pb	0.15 g/l	72.5 mg/g	Biosorption	Velmurugan *et al.,* 2010
			pH 6-10, 20-60°C TEM		
Penicillium spinulosum	Zn	_	0.2 mg/g	_	Townsley and Ross, 1985
	Cu	_	0.4-2 mg/g	_	Townsley and Ross, 1985
Penicillium verrucosum	Pb	100 mg/l	23.3 mg/g	Biosorption	Cabuk *et al.,* 2004
			pH 5.5, 180 min CT, autoclaved PRT		
Pestalotiopsis clavispora	Cu	5 mg/l	4.01 mg/l	Biosorption	El-Gendy *et al*., 2011
	Cd	3.5 mg/l	1.1 mg/l	Biosorption	El-Gendy *et al*., 2011
Pyrenocheta cajani	Cr	20 ppm	71.50%	Biosorption	Seshikala and Charya, 2012
			pH 3-7		
Saccharomyces cerevisae	Cd	2000 mg/l	52%	Bioaccumul -ation	Thippeswamy *et al*., 2012b
	Cd	30 ppm	79%	Biosorption	Damodaran *et al*., 2011
			pH 5.5, 30 days IP,		
			1.5 % glucose, 6.5 LPM aeartion		
	Cd	5.6 mg/l	1 mg/g	_	Huang *et al.*, 1990
			pH 5, 25°C TEM		
	Ni	2000 mg/l	43%	Bioaccumul -ation	Thippeswamy *et al.*, 2012b
	Ni	50 mg/l	0.468 mg/g	Biosorption	Mihova and Godjevargova, 2001
			48 hrs CT		
	Pb	2000 mg/l	45%	Bioaccumul -ation	Thippeswamy *et al.*, 2012b

	Pb	5 ppm	82%	Biosorption	Damodaran *et al*., 2011
			pH 5.5, 30 days IP,		
			1.5 % glucose, 6.5 LPM aeartion		
	Pb	50 mg/l	1.146 mg/g	Biosorption	Mihova and Godjevargova, 2001
			48 hrs CT		
	Pb	_	2.7 mg/g	_	Huang *et al*., 1990
			pH 5, 25^{o}C TEM		
	Cr	2000 mg/l	41%	Bioaccumul -ation	Thippeswamy *et al*., 2012b
	Cr	0-100 mg/l	4.30 mg/g/min	_	Prakasham *et al*., 1998
			pH 1-2, 35^{o}C TEM, 60 min CT		
	Zn	2000 mg/l	38%	Bioaccumul -ation	Thippeswamy *et al.*, 2012b
	Zn	5-200 mg/l	17 mg/g	_	Volesky, 1992
	Cu	2000 mg/l	37%	Bioaccumul -ation	Thippeswamy *et al.*, 2012b
	Cu	50 mg/l	0.246 mg/g	Biosorption	Mihova and Godjevargova, 2001
			48 hrs CT		
	Cu	3.2 mg/l	0.8 mg/g	_	Huang *et al*., 1990
			pH 4, 25^{o}C TEM		
Sarcinella sp.	Zn	0.45 mg/l	0.43 mg/l	Biosorption	Chandrakar *et al.*, 2012
			5 days IP		
	Cu	0.6625 mg/l	0.58 mg/l	Biosorption	Chandrakar *et al*., 2012
			5 days IP		
Talaromyces helicus	Cu	600 ppm	52%	Biosorption	Romero *et al*., 2006
			pH 5		
Trichoderma atroviride	Zn	500 mg/l	18.1 mg/g	Biosorption	Yazdani *et al*., 2010
Trichoderma harzianum	Cu	50-500 mg/l	24%	Biosorption	Shoaib *et al*., 2012
	Ni	50 mg/l	46%	Biosorption	Shoaib *et al.*, 2012
	Ni	50 mg/l	90.20%	Biosorption	Sarkar *et al*., 2010
			pH 4-5, 30^{o}C TEM, 7 days IP		
	Cr	5 mg/l	76%	Biosorption	Shoaib *et al.*, 2012
Trichoderma longbrachiatum	Cr	50 ppm	0.55 mg/g	Bioaccumul -ation	Joshi *et al.*, 2011
Trichoderma sp.	Cu	90 mg/l	43 mg/g	Biosorption	Khan *et al*., 1998
			25^{o}C TEM, 3 hrs CT		
	Pb	150 mg/l	60 mg/g	Biosorption	Khan *et al.*, 1998
			25^{o}C TEM, 3 hrs CT		
	Cr	100 ppm	97.39%	Biosorption	Vankar and Bajpai, 2007

			pH 5.5		
Trichoderma virde	Pb	10 mg/l	90%	Biosorption	Prasad *et al.*, 2013
			pH 6, 30°C TEM, 90 min CT		
	Ni	0.1-3 mM	58.20%	Bioaccumul -ation	Levinskaite, 2001
	Cd	0.1-3 mM	94.40%	Bioaccumul -ation	Levinskaite, 2001
	Cd	50 ppm	16.25 mg/g	Bioaccumul -ation	Joshi *et al*., 2011
	Cr	0.1-3 mM	81.90%	Bioaccumul -ation	Levinskaite, 2001
	Cr	20 ppm	67%	Biosorption	Seshikala and Charya, 2012
	Cr	175 mg/l	4.66 mg /g	Biosorption	Hala and Eman, 2009
			pH 6, 45 min CT, 3.7 mg/l BC		
Trichosporon cutaneum	Cr	1 mM	24.08%	Biosorption	Bajgai *et al.*, 2011
			120 min IP		
Verticillium fungicola	Cu	5 mg/l	1.7 mg/l	Biosorption	El-Gendy *et al.*, 2011
	Cd	3.5 mg/l	1.2 mg/l	Biosorption	El-Gendy *et al*., 2011

A. terreus has been found to uptake Pb excellently at initial metal concentration of 50 ppm (Joshi et al., 2011). *A. versicolor* biomass subjected to dimethyl sulfoxide had maximum Pb biosorption capacity of 30.6 mg g-1 at pH 5.5 and contact time of 180 min (Cabuk et al., 2005).

A. nidulans isolated from arsenic-contaminated soil, had the potential to remove arsenic from soil (Maheshwari and Murugesan, 2009). The isolated resistant strain showed resistance up to 500 ppm and the mean weight was found to be 1.309 g. The effect of different concentrations of nutrients such as carbon as dextrose, nitrogen as yeast extract and phosphate as K_2HPO_4 on improvement of the remediation of arsenic-contaminated soil was also studied (Maheshwari and Murugesan, 2009). The effect of ionic strength on *A. nidulans* was optimized by NaCl at 0.12–0.30% (Maheshwari and Murugesan, 2009). *A. ustus* has been investigated to biosorb Zn and Cu from waste water and at 50% concentration *A. ustus* was found to absorb the high amount of Zn ion (Chandrakar et al., 2012). *A. flavus* was evaluated for absorption of Zn and Cu from municipal waste water with high removal rate of Cu than Zn (Chandrakar et al., 2012), moreover it has been found to tolerate and accumulate toxic metals namely Ni, Zn, Cd, Pb, and Cu from synthetic medium and paper mill effluent with maximum accumulation of Pb followed by Zn, Cu, Ni (Thippeswamy et al., 2012a).

Candida

Candida sp. effectively biosorbed Cu, Fe and Zn ions from industrial effluent (Anaemene, 2012). Iron removal was the highest by *Candida* biomass followed by copper and the zinc. Time was found an important factor because with increase of time 80% metal absorption was found with even the untreated biomass for all the metal ions in the effluent. The highest amount of metal was absorbed by *Candida* sp. biomass treated by the NaOH, followed by overnight oven dried biomass than the untreated biomass as against the control (Anaemene, 2012). Akhtar et al. (2008) used *C. tropicalis* as biosorbent to remove zirconium (Zr) from dilute aqueous solutions. The process was found to be highly dependent on initial pH and concentration of metal solution. At optimized

experimental parameters, the maximum zirconium biosorption capacity of *Candida tropicalis* was 179 mg Zr g−1 dry weight of biosorbent. Mata et al. (2013) observed removal of Zn, Cu, Mn and Fe from mining effluents poured in San Pedro River in Sonara, Mexico. They found that two yeast species were able to reduce 81.5% Zn, 76.5 % Cu, 95.5% Mn and 99.8% Fe after 40 days of experiment from effluent reactor.

Gliocladium

Gliocladium viride was found to be highly copper tolerant fungus isolated from electroplating tanning effluent (Tahir, 2012). It has been exposed to Cu metal ions up to 3mM to study metal tolerance. Whole mycelium and cell wall components were analyzed for Cu biosorption and it was found that cell wall components were responsible for Cu biosorption. Amino groups were found to be abundant in the cell wall of *Gliocladium* sp. These examinations indicated the involvement of amines in metal uptake. This finding also indicated direct relationship between level of metal resistance and biosorption capacity (Tahir, 2012).

Neurospora

The sorption of Pb and Cu ions from aqueous solutions by raw and pretreated *Neurospora crassa* fungal biomass was investigated (Ismail et al., 2005). The influence of solution pH, equilibrium time and initial metal ion concentration using dried *N. crassa* cells as well as pretreatment on the sorption capacity of the biomass at optimum conditions were studied. These studies indicated that biosorption capacity of biomass decreased with increasing the competing metal ion concentration (Ismail et al., 2005).

Penicillium

Penicilium sp. was tested for their Cr, Ni and Cd biosorption potential using alkali treated, dried and powdered mycelium. It was found to adsorb metals from single and multi-metal solutions in the order of Cr > Cd > Ni (Ahmad et al., 2005a). A strain of this fungus *Penicillium* (MRF-1) was found as one of the best lead resistant fungus. Effects of pH, temperature and contact time on adsorption of Pb by this strain was studied and it was observed that sorption gradually increased with pH from 2.0 to 5.0; then stabilized at pH 6.0 and also increased with increasing temperature. The maximum removal of Pb by biosorbent was observed after two hours of exposure between the metal ion and the fungal biomass, and the equilibrium of metal removal was reached after 3 hours in all concentrations (Velmurugan et al., 2010). A cadmium resistant *Penicillium* sp. was obtained by carrying out successive enrichments from soil samples and screening for resistance to other heavy metals showed significant tolerance to zinc, lead, nickel and copper. The fungal culture demonstrated resistance to 1.4 mg/ml cadmium. Optimum pH, temperature and growth conditions for the isolate were determined (Dugal and Gangawane, 2012). Study of growth pattern of this culture revealed a low specific growth rate, with an extended lag period in the presence of cadmium. The isolate was found to remove 67%, 84% and 95% of cadmium from solution after 48, 72 and 96 hours respectively. The order of resistance to heavy metal concentration was Zn > Pb > Cd > Cu = Hg > Ni > Cr (Dugal and Gangawane, 2012).

P. chrysogenum has been studied for biosorption of Cd, Zn and Pb from aqueous solution with high capacity of Pb removal over Cd and Zn (Niu et al., 1993; Skowronski et al., 2001). In the same way the biosorption potential of *P. simplicissimum* to remove Cd, Zn and Pb from aqueous solutions was reported by Fan et al. (2008) and it was found that initial pH significantly influenced Cd, Zn and Pb uptake. The sorption capacities of metal ions increased as temperature increased, but decreased with increased in biomass dose. The maximum removal capacity was higher for Pb followed by Zn and Cd. *P. canescence* was investigated to remove the Cd, Pb, Hg and As ions from aqueous solutions by biosorption. The binding of heavy metal ions to *P. canescens* was pH-dependent and it showed preference to binding of Pb over Cd, Hg and As ions (Say et al.,

2003). Live cells of *P. cyclopium* has been studied for Cu biosorption and it was found to dependent strongly on pH, time, biomass and Cu ion concentrations in the solutions. The biosorption process was rapid, and in the first five minutes up to 75% of total Cu ions were deposited in the *P. cyclopium* surface (Ianis et al., 2006).

P. purpurogenum was reported to bind high amounts of chromium which was clearly dependent on pH, and sorption capacity increased with increasing pH. Time was also found as an important factor because adsorption capacity increased with time during the first four hours and then levels off toward the equilibrium (Say et al., 2004). Likewise, *P. notatum* was also found as good absorbent for high chromium concentrations and was found to adsorb about 94% Cr at 20 ppm concentration (Seshikala and Charya, 2012). Other species of *Penicillium*, *P. lilacinum* was found to remove Cu (85.4%) brilliantly and cadmium in relatively less amount (31.43 %) (El-Gendy et al., 2011). *P. decumbens* (102 ML) showed highest accumulation rate for Cd followed by Cr and Ni from soil and for Cd it was more sensitive as compared to Ni and Cr (Levinskaite, 2001). *P. verrucosum* biomass subjected to autoclave pretreatment has maximum biosorption capacity for Pb i.e., 23.3 mg/g at pH 5.5 and at contact time 180 min (Cabuk et al., 2005).

Saccharomyces

Damodaran et al. (2011) revealed that *S. cerevisiae* has good potential of accumulating Pb and Cd from metal contaminated soil. The parameters affecting the biosorption of heavy metals; such as time, carbon source, aeration, metal concentration and biomass concentrations have been investigated. The time taken for maximum sorption of Pb and Cd was 30 days for soil containing 100 and 300 ppm of Pb and Cd respectively. A better growth of *S. cerevisiae* was observed in soil samples, which is continuously aerated at 6.5 LPM and soil pH was maintained at 5.5. The availability of glucose as carbon source was found to facilitate the bioaccumulation process indirectly by increasing the biomass. An optimum concentration of 1.5 % glucose was proved to support the biosorption to a maximum level. The effect of Cu concentration on sorption and growth of this strain was studied and it was found that the biomass concentration decreased with the increase of Cu concentration. Cuprous ions with concentration of 50 mg/l exert a weak inhibiting effect while inhibiting effect was more (period of cells adaptation was longer) with concentrations higher than 250 mg/l and its growth was slower (Mihova and Godjevargova, 2001). Toxic metals Cu, Zn, Ni, Cr, Cd and Pb have also been efficiently removed by *S. cerevisiae* in both aqueous medium and effluent (Thippeswamy et al., 2012b). Obtained results showed high Cd accumulation followed by Pb, Ni, Cr, Zn and Cu in aqueous medium. The efficiency of heavy metals accumulation in *Saccharomyces* sp. decreased with increase in metal concentration due to saturation of biosorbent. *Saccharomyces* sp. accumulated high cadmium and lead among all treated metals due to presence of cysteine rich metallothionein. This protein shows higher affinity towards Cd and Pb as compared with other metals. Outer mannan layer on the cell wall favors the heavy metals accumulation by *Saccharomyces*. Result also indicated that metal removal capability in *Saccharomyces* sp. increased with decrease in their biomass. The low biomass of *Saccharomyces* sp. causes high surface area-to-volume ratio and holds maximum heavy metals in both soluble and particular forms. Low biomass also leads to exhaustion of heavy metal ions in the medium and cause increased interaction of metals with active binding sites of the cell surface (Thippeswamy et al., 2012b).

Talaromyces

Talaromyces helicus, an efficient strain was trained with high copper levels, and became also tolerant to cobalt, lead and cadmium when was cultured in their presence (Romero et al., 2006). They have reported that copper adaptation was the result of physiological mechanisms, and the activated biochemical processes conferred resistance to Cu as well as to other heavy

metals. Interestingly, they find metals combinations were less toxic than single ones, and co-tolerance development indicated that the cellular mechanisms that conferred resistance were non-specific, so the mycobiota isolated from co-contaminated environments often exhibited resistance to more than one ions. These results emphasized the detoxification abilities of *T. helicus* and the adaptation to heavy metals compounds (Romero et al., 2006).

Trichoderma

Biosorption of the chromium ion onto the cell surface of *Trichoderma* fungal species in aerobic condition was investigated (Vankar and Bajpai, 2007). Batch experiments were conducted with various initial concentrations of chromium ions to obtain the sorption capacity. The results of FTIR analysis suggested that the chromium binding sites on the fungal cell surface were most likely carboxyl and amine groups. Best results for sorption were obtained at 5.5–5.8 pH, at low or high pH values, Cr uptake was significantly reduced (Vankar and Bajpai, 2007). *T. longibrachiatum* has also been reported to uptake maximum (0.55 mg/g) of Cr and Cd (16.25 mg/g) at initial metal concentration of 50 ppm (Joshi et al., 2011). It was also found as suitable adsorbent for the removal of Pb from effluents. The adsorption was strongly dependent on pH and contact time (Prasad et al., 2013). It was reported to accumulate the highest amount of Ni, Cr and Cd from soil and showed highest resistance to all these metals (Levinskaite, 2001).

Siddiquee et al. (2013) determined the resistance levels of different concentrations of heavy metals (Pb, Ni, Zn and Cu) using three different species of this fungus namely *T. aureoviride*, *T. harzianum*, and *T. virens.* The accumulation and uptake capacity was determined by the maximum removal of Pb, Cu, and Ni by a *T. harzianum* in liquid medium when compared to other fungi. The metal removal occurred at a concentration of 500 mg/L and was 13.48 g/g for Pb, 3.1254 g/g for Cu and 0.8351 g/g for Ni. For Zn, the highest tolerance and uptake capacity of metal was recorded as 3.1789 g/g by *T. virens.* Dry biomass of *T. harzianum*, *T. virens* and *T. aureo-viride* decreased with increasing initial concentrations of heavy metals (Ni, Zn, Pb and Cu) for 7 days at temperature of 28°C ± 2°C. In another study, it was found that *T. harzianum* had tolerance capacity to different nickel concentrations (Sarkar et al., 2010). It was noticed that *T. harzianum* was moderately tolerant up to 60 mg/L of Ni, where the inhibition of mycelial growth was 33.3 %. Further increase in Ni concentration decreased the growth and total inhibition was observed at 200 mg/L. The metal residues were analyzed at different day's interval (4, 5, 6, 7 and 8 days) and effect of different pH and temperature on metal removal was also investigated (Sarkar et al., 2010; Shoaib et al., 2012).

Trichosporon

The adsorption data obtained from the experiments conducted by Bajgai et al. (2012) have showed the applicability of *Trichosporon cutaneum* (R57) in the remediation of heavy metals particularly Cr. The removal efficiency of this strain increased with the decrease in the concentration of metal ions up to certain minimum level; it removes 20.89% Cr from 1 mM of ions in the culture medium while only 14.01% from 10 mM of Cr ions in 30 minutes. Removal efficiency also increased with the contact time between the metal ions and fungal biomass in lower concentrations.

Heavy metal remediation by fungi of group Basidiomycotina

Most Basidiomycota are found in terrestrial habitats, a few are marine. This group comprises macro-fungi. There are various examples of fungi of Basidiomycotina those have been used for heavy metal removal. They are as follows (Table 3):

Agaricus

Agaricus bisporus has been found to accumulate heavy metals from soil in decreasing sequence of Zn > Mn > Cu > Ni > Pb > Cd (Ita et al.,

2008) while Sesli and Tuzen (1999) find the trend as Fe>Zn>Cu>Mn>Cd>Pb>Hg from East black sea region of Turkey. Nagy et al. (2013) have conducted an experiment in which biosorption of Cd ions from aqueous solutions onto immobilized fruiting bodies of cultivated *A. bisporus* was investigated in batch system. The biosorption of Cd ions was carried out at different concentrations ranging from 45 to 265 mg/l. The operating parameters: initial metal ion concentration, contact time and pH were considered to describe the biosorption efficiency on the removal of Cd ions. The adsorption capacity increases with an increase of metal concentration, pH up to 5.6–5.8 favored the biosorption process and a contact time between 90 and 120 min was necessary to reach the equilibrium (89.5% absorption). The adsorption capacity was found to increase with the increase of initial concentration but a decrease in the removal efficiency was observed with further increase in concentration (Table 3). *A. bitorquis* has been found to remediate highest Cd concentration (98.97%) followed by Zn 98.02% (Table 3) (Lamrood and Relegankar, 2013).

Lactarius

The ability of cultivated wild *Lactarius* sp. for Cd, Cr, Cu, Pb and Zn biosorption from aqueous solution was investigated in batch conditions (Cayer et al., 2010; Nagy et al., 2013). The biosorption of Cd ions was carried out at different concentrations ranging from 45 to 265 mg/l. Initial metal ion concentration, contact time and pH were considered to describe the biosorption efficiency on the removal of Cd ions (Nagy et al., 2013).

Phanerochaete

The adsorption capacity of dead fungal biomass of *Phanerochaete chrysosporium* on waste was studied to remove cadmium, copper, zinc and iron from synthetic water and leachate (Mamun et al., 2011). The effects of biomass dosage, contact time, pH and agitation speed were also observed for optimal adsorption. The fungal species has also been used by Mihova and Godjevargova (2001) for decontamination of waste waters containing Cu ions. The sorption of Cu by this fungal strain was proved to be a fast process. Up to 75% of the Cu content were absorbed during the first 6 hours. The effect of the type of metal on the sorption process was also studied and the following order of sorption was observed: Pb > Ni > Cu.

Pleurotus

Biosorption of Cu, Zn, Fe, Cd, Pd, Ni, Mn, Cr, Hg by *Pleurotus* spent mushroom compost has been investigated (Mitra, 1994; Tuzen, et al., 1998; Demirbas, 2001; Ita et al., 2008; Tay et al., 2010; Javaid et al., 2011; Arbanah et al., 2012; Kuzhali, 2012; Lamrood and Ralegankar, 2013; Prasad et al., 2013). In addition, *P. sapidus* has been reported to accumulate heavy metals from soil in decreasing sequence of Zn > Cu > Mn > Pb > Ni > Cd, while *P. ostreatus* has been reported to accumulate these metal in decreasing order of Cu > Zn > Mn > Ni > Pb > Cd (Ita et al., 2008). The adsorption potential of *P. ostreatus* was also explored to remove copper, nickel, zinc and chromium from water (Javaid et al., 2011). Different operational parameters such as the effect of pH, biomass dose, equilibrium time, stirring intensity, temperature and initial metal ion concentrations were studied (Javaid et al., 2011). In another experiment, *P. ostreatus* was found to remove the highest concentration of Fe followed by Cu, Cr and Zn (Arbanah et al., 2012). The results showed that pH, temperature and contact time played an important role in biosorption capacity of the fungus (Arbanah et al., 2012). Furthermore, it was found to remove Cd excessively from wastewater (Talib, 2013) at optimum conditions of initial pH 6, 10 minutes contact time, 10 mg/l cadmium concentration in 50 ml solution at room temperature (Talib, 2013).

Mycelial biomass of cultivated *P. florida*, has been evaluated for biosorption of heavy metals such as Cr, Zn and Ni from tannery effluent (Kuzhali et al., 2012). It showed the maximum biosorption for Cr than Zn and Ni. The biomass of this fungal species was also observed for adsorption of Pb from effluents (Prasad et al. 2013),

Table 3. Heavy metal remediation by the different fungi of group Deuteromycotina (TEM=Temperature, CT=Contact time, ET=Equilibrium time, -- = Not available)

Fungi	Heavy metal	Initial concentr-ation of metal	Metal uptake by biomass and other conditions	Process involved	References
Agaricus biosporous	Ni	14.31 µg/g	2.87 µg/g	Bioaccumul-ation	Ita *et al.*, 2008
	Cu	66.57 µg/g	23.18 µg/g	Bioaccumul-ation	Ita *et al*., 2008
	Cu	_	13.5 µg/g	_	Sesli and Tuzen, 1999
	Pb	26.55 µg/g	1.33 µg/g	Bioaccumul-ation	Ita *et al.*, 2008
	Pb	_	0.28 µg/g	_	Sesli and Tuzen, 1999
	Mn	_	3.61 µg/g	_	Sesli and Tuzen, 1999
	Mn	82.31 µg/g	40.01 µg/g	Bioaccumul-ation	Ita *et al*., 2008
	Cd	8.34 µg/g	0.83 µg/g	Bioaccumul-ation	Ita *et al*., 2008
	Cd	_	89.50%	Biosorption	Nagy *et al*., 2013
			pH 5.6-5.8, 296 K TEM,		
			90-120 min CT		
	Cd	_	0.74 µg/g	_	Sesli and Tuzen, 1999
	Zn	213.53 µg/g	50.22 µg/g	Bioaccumul-ation	Ita *et al.*, 2008
	Zn	_	22.5 µg/g	_	Sesli and Tuzen, 1999
	Hg	_	0.03 µg/g	_	Sesli and Tuzen, 1999
	Fe	_	31.3 µg/g	_	Sesli and Tuzen, 1999
Agaricus bitorquis	Cu	796.19 mg/l	93.53%	Biosorption	Lamrood and Ralegankar, 2013
			pH6, 32^{o}C TEM, 180 min CT		
	Zn	729.69 mg/l	98.02%	Biosorption	Lamrood and Ralegankar, 2013
			pH6, 32^{o}C TEM, 180 min CT		
	Fe	401.71 mg/l	88.92%	Biosorption	Lamrood and Ralegankar, 2013
			pH6, 32^{o}C TEM, 180 min CT		
	Cd	1226.34 mg/l	98.97%	Biosorption	Lamrood and Ralegankar, 2013
			pH6, 32^{o}C TEM, 180 min CT		
	Pb	1251.21 mg/l	88.76%	Biosorption	Lamrood and Ralegankar, 2013
			pH6, 32^{o}C TEM, 180 min CT		
	Ni	493.84 mg/l	97.22%	Biosorption	Lamrood and Ralegankar, 2013

			pH6, 32°C TEM, 180 min CT		
Armillariella mellea	Ni	14.31 µg/g	0.64 µg/g	Bioaccumul-ation	Ita *et al.*, 2008
	Cu	66.57 µg/g	30.18 µg/g	Bioaccumul-ation	Ita *et al.*, 2008
	Pb	26.55 µg/g	1.42 µg/g	Bioaccumul-ation	Ita *et al.*, 2008
	Mn	82.31 µg/g	41.11 µg/g	Bioaccumul-ation	Ita *et al*., 2008
	Cd	8.34 µg/g	0.49 µg/g	Bioaccumul-ation	Ita *et al.*, 2008
	Zn	213.53 µg/g	82.47 µg/g	Bioaccumul-ation	Ita *et al.*, 2008
Calocybe indica	Cr	_	55%	Biosorption	Kuzhali, 2012
	Zn	_	37.90%	Biosorption	Kuzhali, 2012
	Ni	_	49.10%	Biosorption	Kuzhali, 2012
Ganoderma lucidum	Cu	0.2-2 mM	0.383 mM/g	Biosorption	Muraleedharan *et al.*, 1995
			pH 4, 3 hrs CT		
	Cu	5-50 mg/l	24 mg/g	_	Venkobacher, 1990
			pH 5		
Lactarius piperatus	Cd	_	95.73%	Biosorption	Nagy *et al.*, 2013
			pH 5.6-5.8, 296 K TEM,		
			90-120 min CT		
Lentinus edodes	Cd	20-1000 mg/l	58 mg/g	Biosorption	Chen *et al.*, 2005
			pH 6.95		
	Pb	20-1000 mg/l	82.48 mg/g	Biosorption	Chen *et al.*, 2005
			pH 6.04		
	Cr	20-1000 mg/l	12.61 mg/g	Biosorption	Chen *et al.*, 2005
			pH 4.82		
Phanerochaete chysosporium	Cu	50 mg/l	0.348 mg/g	Biosorption	Mihova and Godjevargova, 2001
	Cu	4.77 mg/l	41.29%	Biosorption	Mamun *et al.*, 2011
			pH 5, 5 hrs CT		
	Ni	50 mg/l	0.398 mg/g	Biosorption	Mihova and Godjevargova, 2001
	Pb	50 mg/l	1.144 mg/g	Biosorption	Mihova and Godjevargova, 2001
	Cd	0.295 mg/l	28.81%	Biosorption	Mamun *et al.*, 2011
			pH 5, 18 hrs CT		
	Zn	1.985 mg/l	58.94%	Biosorption	Mamun *et al.*, 2011
			pH 5, 5 hrs CT		
	Fe	4.67 mg/l	52.03%	Biosorption	Mamun *et al.*, 2011
			pH 5, 5 hrs CT		
Pleurotus florida	Cr	_	88.50%	Biosorption	Kuzhali, 2012

	Zn	_	68.40%	Biosorption	Kuzhali, 2012
	Ni	_	58.80%	Biosorption	Kuzhali, 2012
	Pb	10 mg/l	100%	Biosorption	Prasad *et al*., 2013
			pH 7, 30°C TEM, 60 min CT		
Pleurotus floridianus	Cu	796.19 mg/l	93.53%	Biosorption	Lamrood and Ralegankar, 2013
			pH6, 32°C TEM, 180 min CT		
	Zn	729.69 mg/l	98.02%	Biosorption	Lamrood and Ralegankar, 2013
			pH6, 32°C TEM, 180 min CT		
	Fe	401.71 mg/l	85.02%	Biosorption	Lamrood and Ralegankar, 2013
			pH6, 32°C TEM, 180 min CT		
	Cd	1226.34 mg/l	98.93%	Biosorption	Lamrood and Ralegankar, 2013
			pH6, 32°C TEM, 180 min CT		
	Pb	1251.21 mg/l	98.14%	Biosorption	Lamrood and Ralegankar, 2013
			pH6, 32°C TEM, 180 min CT		
	Ni	493.84 mg/l	97.22%	Biosorption	Lamrood and Ralegankar, 2013
			pH6, 32°C TEM, 180 min CT		
Pleurotus ostreatus	Ni	14.31 µg/g	1.03 µg/g	Bioaccumul -ation	Ita *et al*., 2008
	Ni	_	20.40 mg/g	Biosorption	Javaid *et al*., 2011
			pH 4.5-5, 150 min ET		
	Cu	66.57 µg/g	57.45 µg/g	Bioaccumul -ation	Ita *et al.,* 2008
	Cu	_	8.06 mg/g	Biosorption	
			pH 4.5-5, 150 min ET		Javaid *et al*., 2011
	Cu	_	5 mg/kg	_	Tuzen *et al*., 1998
	Cu	_	13.6 mg/kg	_	Demirbas, 2001
	Cu	_	45.20%	Biosorption	Arbanah *et al*., 2012
			pH 6, 25°C TEM		
	Cu	50 mg/l	4.6 mg/g	Biosorption	Tay et al., 2010
			pH 5.5, 10 min CT		
	Pb	26.55 µg/g	0.78 µg/g	Bioaccumul -ation	Ita et al., 2008
	Pb	_	0.11 mg/kg	_	Tuzen et al., 1998
	Pb	_	3.24 mg/kg	_	Demirbas, 2001
	Mn	82.31 µg/g	45.98 µg/g	Bioaccumul -ation	Ita et al., 2008
	Mn	_	10.3 mg/kg	_	Tuzen et al., 1998
	Mn	_	6.27 mg/kg	_	Demirbas, 2001

	Cr	_	10.75 mg/g	Biosorption	Javaid *et al.*, 2011
			pH 2.5, 150 min CT		
	Cr	_	12.47%	Biosorption	Arbanah *et al.*, 2012
			pH 5, 25°C TEM		
	Cd	8.34 µg/g	0.54 µg/g	Bioaccumul-ation	Ita *et al*., 2008
		_	0.55 mg/kg	_	Tuzen *et al*., 1998
	Cd	_	1.18 mg/kg	_	Demirbas, 2001
	Cd	10 mg/l	85%	Biosorption	Talib, 2013
			pH 6, 26±1°C TEM, 10 min CT		
	Zn	213.53 µg/g	52.23 µg/g	Bioaccumul-ation	Ita *et al.*, 2008
	Zn	_	3.22 mg/g	Biosorption	Javaid *et al*., 2011
			pH 4.5-5, 150 min ET		
	Zn	_	19.3 mg/kg	_	Tuzen *et al.*, 1998
	Zn	_	29.8 mg/kg	_	Demirbas, 2001
	Zn	_	5.04%	Biosorption	Arbanah *et al.*, 2012
			pH 5, 25°C TEM		
	Fe	_	48.6 mg/kg	_	Tuzen *et al*., 1998
	Fe	_	86.1 mg/kg	_	Demirbas, 2001
	Fe	_	80.52%	Biosorption	Arbanah *et al*., 2012
			pH 6, 25°C TEM		
	Hg	_	0.31 mg/kg	_	Tuzen *et al*., 1998
	Hg	_	0.42 mg/kg	_	Demirbas, 2001
Pleurotus sajor-caju	Hg	0.150-3 mmol/dm-3	0.660±0.019 mmol/g	Biosorption	Arica *et al.*, 2003
	Pb	_	7 mg/kg	_	Mitra, 1994
	Pb	1251.21 mg/l	94.73%	Biosorption	Lamrood and Ralegankar, 2013
	Cd	_	33 µg/g	_	Mitra, 1994
	Cu	796.19 mg/l	93.50%	Biosorption	Lamrood and Ralegankar, 2013
			pH6, 32°C TEM, 180 min CT		
	Zn	729.69 mg/l	98.00%	Biosorption	Lamrood and Ralegankar, 2013
			pH6, 32°C TEM, 180 min CT		
	Fe	401.71 mg/l	88.15%	Biosorption	Lamrood and Ralegankar, 2013
			pH6, 32°C TEM, 180 min CT		
	Cd	1226.34 mg/l	98.94%	Biosorption	Lamrood and Ralegankar, 2013
			pH6, 32°C TEM, 180 min CT		
	Pb	1251.21 mg/l	94.73%	Biosorption	Lamrood and Ralegankar, 2013

			pH6, 32°C TEM, 180 min CT		
	Ni	493.84 mg/l	97.22%	Biosorption	Lamrood and Ralegankar, 2013
			pH6, 32°C TEM, 180 min CT		
Pleurotus sapidus	Ni	14.31 µg/g	0.52 µg/g	Bioaccumul -ation	Ita *et al.*, 2008
	Cu	66.57 µg/g	24.66 µg/g	Bioaccumul -ation	Ita *et al.*, 2008
	Pb	26.55 µg/g	0.55 µg/g	Bioaccumul -ation	Ita *et al.*, 2008
	Mn	82.31 µg/g	22.56 µg/g	Bioaccumul -ation	Ita *et al.*, 2008
	Cd	8.34 µg/g	0.41 µg/g	Bioaccumul -ation	Ita *et al*., 2008
	Zn	213.53 µg/g	60.45 µg/g	Bioaccumul -ation	Ita *et al.*, 2008
Polyporus frondosis	Ni	14.31 µg/g	20.98 µg/g	Bioaccumul -ation	Ita *et al*., 2008
	Cu	66.57 µg/g	22.56 µg/g	Bioaccumul -ation	Ita *et al*., 2008
	Pb	26.55 µg/g	1.42 µg/g	Bioaccumul -ation	Ita *et al.*, 2008
	Mn	82.31 µg/g	20.54 µg/g	Bioaccumul -ation	Ita *et al*., 2008
	Cd	8.34 µg/g	0.61 µg/g	Bioaccumul -ation	Ita *et al*., 2008
	Zn	213.53 µg/g	42.34 µg/g	Bioaccumul -ation	Ita *et al.*, 2008
Polyporus sulphureus	Ni	14.31 µg/g	1.78 µg/g	Bioaccumul -ation	Ita *et al*., 2008
	Cu	66.57 µg/g	46.77 µg/g	Bioaccumul -ation	Ita *et al.*, 2008
	Pb	26.55 µg/g	0.91 µg/g	Bioaccumul -ation	Ita *et al.*, 2008
	Mn	82.31 µg/g	34.88 µg/g	Bioaccumul -ation	Ita *et al.*, 2008
	Cd	8.34 µg/g	0.52 µg/g	Bioaccumul -ation	Ita *et al*., 2008
	Zn	213.53 µg/g	38.12 µg/g	Bioaccumul -ation	Ita *et al.*, 2008
Rhizoctonia solani	Cr	25 ppm	94.10%	Biosorption	Seshikala and Charya, 2012
Serpula himantioides	As	0.40%	112.80±28.80 mmol/mg	–	Adeyemi, 2009
Volvariella diplasia	Cu	796.19 mg/l	93.59%	Biosorption	Lamrood and Ralegankar, 2013
			pH6, 32°C TEM, 180 min CT		
	Zn	729.69 mg/l	98.04%	Biosorption	Lamrood and Ralegankar, 2013
			pH6, 32°C TEM, 180 min CT		
	Fe	401.71 mg/l	84.52%	Biosorption	Lamrood and Ralegankar, 2013
			pH6, 32°C TEM, 180 min CT		

	Cd	1226.34 mg/l	98.90%	Biosorption	Lamrood and Ralegankar, 2013
			pH6, 32°C TEM, 180 min CT		
	Pb	1251.21 mg/l	98.18%	Biosorption	Lamrood and Ralegankar, 2013
			pH6, 32°C TEM, 180 min CT		
	Ni	493.84 mg/l	96.92%	Biosorption	Lamrood and Ralegankar, 2013
			pH6, 32°C TEM, 180 min CT		
Volvariella volvacea	Cu	796.19 mg/l	93.59%	Biosorption	Lamrood and Ralegankar, 2013
			pH6, 32°C TEM, 180 min CT		
	Zn	729.69 mg/l	98.02%	Biosorption	Lamrood and Ralegankar, 2013
			pH6, 32°C TEM, 180 min CT		
	Fe	401.71 mg/l	84.92%	Biosorption	Lamrood and Ralegankar, 2013
			pH6, 32°C TEM, 180 min CT		
	Cd	1226.34 mg/l	98.91%	Biosorption	Lamrood and Ralegankar, 2013
			pH6, 32°C TEM, 180 min CT		
	Pb	1251.21 mg/l	98.69%	Biosorption	Lamrood and Ralegankar, 2013
			pH6, 32°C TEM, 180 min CT		
	Ni	493.84 mg/l	96.94%	Biosorption	Lamrood and Ralegankar, 2013
			pH6, 32°C TEM, 180 min CT		

The optimum conditions of pH and contact time for biosorption were determined. Furthermore, *P. sajur-caju* mycelium immobilized in Ca-alginate beads was used for the removal of mercuric ions from aqueous solutions (Arica et al., 2003). The sorption of Hg ions by alginate beads and both, immobilized live and heat-killed fungal mycelia of *P. sajur-caju* was studied in the concentration range of 0.150–3.00 mmol dm−3. The biosorption of Hg increased as the initial concentration of Hg ions increased in the medium. Biosorption capacities for live and heat-killed *P. sajur-caju* were 0.450 ± 0.014 mmol Hg/g and 0.660 ± 0.019 mmol Hg/g respectively. Biosorption equilibrium was established in about 1 h and maximum adsorption was observed between pH 4.0 and 6.0 (Arica et al., 2003). The details of remediation of other heavy metals by the species of this fungus have been given in table 3.

Polyporus

According to Ita et al. (2008), *Polyporus frondosis* revealed maximum bioaccumulation of Zn (60.45 µg/g) followed by Cu, Mn, Pb, Ni and Cd from soil, while *P. sulphureus* had the ability to accumulate these metals in decreasing sequence of Cu (46.77 µg/g) > Zn > Mn > Ni > Pb > Cd.

Trametes

Trametes versicolor was investigated for their potential abilities to accumulate arsenic from an agar environment consisting of non-buffered mineral salts media amended with 0.2, 0.4, 0.6 and 0.8% (w/v) arsenopyrite (FeAsS) (Adeyemi, 2009). Growth rates, dry weights and arsenic accumulation by the fungi as well as the pH of the growth media were assessed during this study. *T. versicolor* showed higher accumulation of As at 0.4% arsenopyrite and least at 0.6% (Adeyemi, 2009). Immobilization of this fungus with Ca-alginate was found effective in removal of mercuric ions from aqueous solutions. The sorption of Hg ions by alginate beads and both immobilized live and heat-killed fungal mycelia of *T. versicolor* was studied in the concentration range of 0.150–3.00 mmol dm−3. Maximum biosorption capacities for alginate beads were 0.144 ± 0.005 mmol Hg/g; for immobilized live and heat-killed fungal mycelia of *T. versicolor* were 0.171 ± 0.007 mmol Hg/g and 0.383 ± 0.012 mmol Hg/g respectively. Maximum adsorption was observed between pH 4.0 and 6.0 and equilibrium was established in about 1 h (Arica et al., 2003).

Heavy metal remediation by fungi of group Deuteromycotina

The vast majority of these organisms are terrestrial, although a good number have been reported from marine and fresh water habitats. Following fungi of Deuteromycotina had been shown as biosorbents for heavy metals remediation (Table 4):

Alternaria

Alternaria alternata has found to accumulate Cd, Cr, Ni and Cu from soil and exhibited the highest resistance to chromate and sensitive to nickel (Levinskaite, 2001; Shoaib et al., 2012) (Table 4) whereas, Seshikala and Charya (2012) found the highest absorption of Cr (70.5%) at 20 ppm initial concentration of Cr.

Fusarium

Fusarium sp. has been investigated to biosorb Zn and Cu from waste water with maximum biosorption of Cu (Chandrakar et al., 2012). The potential of the resting cells of the *F. solani* has also been evaluated for Cr removal from aqueous solution. The effects of pH, initial Cr concentration, biomass concentration and age of the culture on Cr removal from aqueous solutions were studied using synthetic Cr solution in batch bioreactors (Sen and Dastidar, 2011). Amatussalam et al. (2011) obtained maximum efficiency of *F. oxysporum* for Cr removal (90%) achieved at the end of 5th day (120 min contact time) for 100 and 200 ppm concentration of Cr with pH ranging from 5.8 and 5.6 respectively. Furthermore, nonliving cells of *F. solani* has been used for biosorption of zinc and nickel from wastewaters (Sen, 2013). The specific metal removal increased with increase in initial metal ion concentration up to 500 mg/l for both zinc and nickel (Sen, 2013).

Table 4. Heavy metal remediation by the different fungi of group Deuteromycotina (CT= Contact time, ET= Equilibrium time, TEM=Temperature, IP= Incubation period)

Fungi	Heavy metal	Initial concentration of metal	Metal uptake by biomass and other conditions	Process involved	References
Alternaria alternate	Cd	0.1-3 mM	86.90%	Bioaccumulation	Levinskaite, 2001
	Cr	0.1-3 mM	67.80%	Bioaccumulation	Levinskaite, 2001
	Cr	20 ppm	70.50%	Biosorption	Seshikala and Charya, 2012
	Ni	0.1-3 mM	43.60%	Bioaccumulation	Levinskaite, 2001
	Ni	50 mg/l	20%	Biosorption	Shoaib *et al.*, 2012
	Cu	50-100 mg/l	20%	Biosorption	Shoaib *et al.*, 2012

	Ni	50 mg/l	20%	Biosorption	Shoaib *et al.*, 2012
	Cu	50-100 mg/l	20%	Biosorption	Shoaib *et al*., 2012
Fusarium oxysporum	Cr	100 ppm	90%	Bioaccumulation	Amatussalam *et al.*, 2011
			pH 5.8, 120 hrs CT		
	Cr	20 ppm	95%	Biosorption	Seshikala and Charya, 2012
			pH 3-7		
Fusarium solani	Cr	500 mg/l	60 mg/g	Biosorption	Sen and Dastidar, 2011
			pH 4, 30^{o}C TEM, 24 hrs CT		
	Zn	500 mg/l	60 mg/g	Biosorption	Sen, 2013
			pH 6, 2 hrs ET		
	Ni	500 mg/l	54.5 mg/g	Biosorption	Sen, 2013
Fusarium sp.	Zn	0.45 mg/l	0.45 mg/l	Biosorption	Chandrakar *et al*., 2012
			5 days IP		
	Cu	0.6625 mg/l	0.60 mg/l	Biosorption	Chandrakar *et al.*, 2012
			5 days IP		

DISCUSSION

This review highlighted the abilities of certain fungi for remediation of heavy metals. Present review indicated that heavy metal remediation is effective by fungi of Ascomycotina followed by Basidiomycotina, Zygomycotina and Deuteromycotina. Among Ascomycotina species of *Aspergillus* were found more effective followed by species of *Penicillium, Trichoderma* and *Saccharomyces.* Besides, species of *Mucor* and *Rhizopus* represent best bioremediator among Zygomycotina, species of *Pleurotus* among Basidiomycotina and species of *Fusarium* among Deuteromycotina.

It is evident from the above examples that fungi have found higher ability to remove high concentrations of heavy metals (Table 1, 2, 3 & 4). Biosorption was found to be most effective and has been found to be advantageous over bioaccumulation as in biosorption as it do not require live biomass and nutrients for growth of fungi hence it is cost effective than bioaccumulation (Iqbal and Edyvean, 2004).

Furthermore, the absorbed metals on the cell surfaces could be desorb easily and facilitate metal recovery (Yetis et al., 2000). The most limiting factor of bioaccumulation process is the reduction in metal uptake capacity due to metal toxicity (Dursun et al., 2003).

Further studies should be accompanied for those fungi which are least known for sorption/accumulation abilities of heavy metals for more and more application of fungi in the field of bioremediation. The use of fungi is cost effective than other conventional biosorbents, their cell wall components show outstanding metal binding properties as well as they play important role in decomposition, a knowledge of their response to detoxify the metal polluted habitats may be particularly relevant for heavy metal remediation (Adeyemi, 2009). More specific and accurate methodology has to be developed for the recovery of metals from fungal biomass and removal of biomass from contaminated soil and water systems.

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