



A Review on Microbial Treatments of Metal Pollution

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ABSTRACT

Heavy metals like zinc, copper, nickel, mercury, cadmium, lead and chromium are the elements that have atomic masses between 63.5 and 200.6, and their specific gravity is greater than 5.0. These toxic metals are released from metal plating facilities, mining operations, fertilizer industries, tanneries, batteries, paper industries and pesticides, and directly or indirectly become part of environment. Heavy metals are non biodegradable and are carcinogenic in nature, become permanent part of food chains. Conventional treatments used for metal removal are cost effective, sludge produced is non-biodegradable and require much cost for its disposal. Microbial treatment of metal pollution is an alternative, innovative, and economically more suitable method. Microbial biomass used can be obtain naturally, from fermentation industries or can be culture on simple media. Microorganisms can mobilise heavy metals by autotrophic and heterotrophic leaching, siderophores, chelation by microbial metabolites and methylation. However, immobilisation can result from sorption to cell components or exopolymers, transport into cells and intracellular separation or precipitation as insoluble organic and inorganic compounds. Microbiological processes have significant role in determining environmental metal mobility and have actual or potential applications in bioremediation. Metallic pollution is increasing day by day and it is suggested to use microbial remediation to protect our environment from toxic effects of heavy metals.

Keyword: *Microorganisms, Toxic metals, Metallic pollution, Biological biomass, Heavy metals.*

INTRODUCTION

Heavy metals are elements that have atomic masses between 63.5 and 200.6, and their specific gravity is greater than 5.0 [1]. Toxic heavy metals are zinc, copper, nickel, mercury, cadmium, lead and chromium. In the developing countries, with the rapid development of industrialization, the primary sources of heavy metals are metal plating facilities, mining operations, fertilizer industries, tanneries, batteries, paper industries and pesticides etc., which are discharged directly or indirectly as waste waters into the surrounding environment and their number is increasing day by day. Heavy metals are not biodegradable and tend to accumulate in living organisms and many heavy metal ions are known to be toxic or carcinogenic. It is of particular concern to treat industrial waste waters before their discharge into surrounding environment [2].

Heavy metal pollution has become one of the most serious environmental problems nowadays. Recently, various methods for removal of heavy metals from waste water have been extensively studied. In 2010, Fenglian and Wang reviewed the current methods that had been used for treatment of heavy metal wastewater. These technologies include chemical precipitation, adsorption, ion exchange, coagulation flocculation, membrane filtration, electrochemical and flotation methods. It is obvious from the literature review that adsorption, membrane filtration and ion exchange are the most frequent methods for the treatment of heavy metal wastewater [3].

It is evident that conventional treatment technologies for the removal of heavy metals from aqueous solution are not economical and produce huge quantity of toxic chemical sludge, whose disposal is highly expensive. Removal of heavy metals by biosorption of metabolically inactive non-living microbial biomass is an innovative, inexpensive and alternative technology for removal of pollutants from aqueous solution. Unique chemical composition of biomass segregates metal ions by formation of

metal complexes from solution and obviate the requirement for maintenance of special growth supporting conditions. Biomass of different species of *Aspergillus niger*, *Penicillium chrysogenum*, *Rhizopus nigricans*, *Ascophyllum nodosum*, *Sargassum natans*, *Chlorella fusca*, *Oscillatoria angustissima*, *Bacillus firmus* and *Streptomyces* have highest capacities of metal adsorption, ranging from 5-641 mg g⁻¹ primarily for Pb, Cr, Cu, Ni Zn and Cd. Biomass produced as a by product from fermentation industries offers great potential for adoption of an economical metal recovery system [4]. The use of biological biomass is an effective method for removal and recovery of heavy metals from contaminated waste waters. According to Zouboulis, microbial treatment has appeared as a potential alternative method to conventional treatment techniques. In 2003, Zouboulis studied biosorption of toxic metals from aqueous solution by the application of microorganisms such as *Bacillus laterosporus* or *Bacillus licheniformis*, which was isolated from polluted soil burdened with metal. Two toxic metals were selected as typical examples, chromium which is an oxyanion cadmium which is a cation and promising results were obtained, under optimized conditions. Microorganisms have a high surface area to volume ratio, due their small size they have a large contact interface, and provide interaction with metals from the surrounding environment. During recent years, microbial metal accumulation has gained much attention, because of the potential use of microorganisms for treatment of wastewater streams or metal polluted water [5].

In 2001, Goyal described a procedure of competitive biosorption of Cr(VI) and Fe(III) ions on *Streptococcus equisimilis*, *Saccharomyces cerevisiae* and *Aspergillus niger* and compared to single metal ion adsorption in solution. The ability of these three microorganisms to adsorb metal ions wCr(VI) and Fe(III)x, was shown as a function of metal concentration, growth medium composition, culture age, contact time, pH and temperature with the biosorbents. The effect of addition of an extra energy source in

the form of glucose, fructose and sucrose in the adsorption medium was studied for the biosorption of metal ions by microorganisms [6].

Microorganisms can mobilise radionuclides or metals by autotrophic and heterotrophic leaching, siderophores, chelation by microbial metabolites and methylation, which can result in evaporation. In contrast, immobilisation can result from sorption to cell components or exopolymers, transport into cells and intracellular separation or precipitation as insoluble organic and inorganic compounds, for example, oxalates [7,8], sulfides or phosphates [9,10,11]. Additionally, the reduction of certain redox sensitive radionuclides or metals to a lower valency can be mediated by some microorganisms, which may also help in mobilisation e.g., Mn(IV) reduces to the more soluble form of Mn(II) or immobilisation e.g., U(VI) reduces to the less soluble U(IV) or Tc(VII) to Tc(IV) [12,13,14].

Mechanism of metal uptake

The mechanism by which microorganisms effect modifications in metal mobility and speciation is an important part of biogeochemical cycles for metals [15,16]. The capability of microorganisms to affect metal speciation is based on their effectiveness to mediate mobilization or immobilization procedures that has influence on the balance of metal species between soluble and insoluble stages. Metals can be mobilized by protonation, chemical transformation and chelation and immobilization can be achieved by precipitation or crystallization of insoluble organic or inorganic compounds, by means of sorption, uptake and intracellular separation. Metals can also be mobilizing or immobilize by redox reactions that depends on the metal species involved [15,16,17,18,19,20,21,22,23,24,25,26].

Mostly all metal and microbial interactions have been observed as a means for removal, recovery, detoxification of inorganic and organic metal or radionuclide pollutants [27,28,29,30]. Solubilization may enable the removal from solid materials such as from soils, sediments, dumps and industrial wastes. While immobilization procedures may change metals from in situ into insoluble and chemically inert forms and are also applicable for removal of metals from aqueous solution. However, mostly research is laboratory based, while there are many developments to pilot scale with some procedures evidently in successful commercial operation. It should also be noted that metal removal or transformation processes are inherent although these are less appreciated components of traditional means of water or sewage treatment as well as lagoon, reed bed and wetlands technologies [29,31]

Molecular and genetic analysis is now understanding microbial metal metabolism, including those aspects which are relevant to environmental and biotechnological aspects [32,33]. The objective of this review is to highlight some of the more important microbiological processes which have significance in determining environmental metal mobility and which have actual or potential applications in bioremediation.

Mobilization

Microorganisms can mobilize metals by autotrophic and heterotrophic leaching, chelation by microbial metabolites, siderophores and methylation which can leads to volatilization. Such processes result in the dissolution of insoluble metal compounds, minerals, oxides, phosphates, sulfides, complex mineral ores and desorption of metal species from their exchange sites, for example, minerals clay or organic matter in the soil [34].

Heterotrophic or chemoorganotrophic leaching

Microorganisms can acidify their environment by efflux of proton through plasma membrane i.e; H⁺-ATPases, and maintains the charge balance as a result of accumulation of respiratory carbon

dioxide. Acidification leads to the release of metal through various routes, i.e; competition between protons and the metal in a metal anion complex that result in the release of free metal cations. Heterotrophic metabolism leads to the leaching by means of efflux of organic acids and siderophores. Organic acids can provide both protons and metal complexing anions [15,35,36].

Anions like citrate and oxalate can form stable complexes along with a large number of metals. Mostly metal citrates are highly mobile and not degraded easily [37]. Oxalic acid also acts as a leaching agent for those metals like Al and Fe that form soluble oxalate complexes [38]. Effective methods of leaching of wastes and minerals of soil, mud, filter dust, lateritic ores, copper converter slag, fly ash and electronic waste materials has been demonstrated [15,35,39,40,41,42].

A strain of *Penicillium simplicissimum* has been used for leaching of Zn from insoluble ZnO present in the industrial filter dust. In the filter dust, the production of citric acid less than 100 mM was introduced [43,44,45]. In biogenic chemical weathering and soil formation, organic acid production is also an important agent of mineral deterioration [15]. In 1999, Sayer demonstrated that heterotrophic solubilization is also used for remedial treatments of contaminated soils. Pyromorphite is a stable lead mineral present in urban and industrially contaminated soils. The formation of pyromorphite has been suggested as a remediation technique for lands contaminated with lead by addition of phosphate. However, pyromorphite can be solubilized through phosphate solubilizing fungi, *Aspergillus niger*, and during fungal transformation of pyromorphite, biogenic production of lead oxalate dihydrate takes place [46].

Autotrophic leaching

Mostly autotrophic leaching is carried out by means of chemolithotrophic or acidophilic bacteria which fix the carbon dioxide and obtain energy from oxidation of ferrous iron or reduced sulfur compounds by the solubilization of metals leading to the production of Fe(III) and H₂SO₄ [47,48]. The microorganisms involved are sulfur oxidizing bacteria e.g., *Thiobacillus thiooxidans*, iron and sulfur oxidizing bacteria e.g., *Thiobacillus ferrooxidans* and iron oxidizing bacteria e.g., *Leptospirillum ferrooxidans* [49,50].

As a result of sulfur and iron oxidation, metal sulfides are solubilized and pH of their contiguous environment is decreased, that results in the solubilization of other metal compounds. Such leaching of metal sulfides by *Thiobacillus* species and other acidophilic bacteria is well established for industrial scale biomining [47,49,50,51]. In a bioremediation context, autotrophic production of sulfuric acid has also been used to solubilize metals from sewage sludge and soils [23,52]. In a two stage process, sulfur oxidizing bacteria were used to acidify soil and solubilize toxic metals before metal removal from the metal contaminated liquid leachate using sulfate reducing bacteria [22,23].

In 1994, a study was conducted on the bioremediation of red mud which is the main waste product of aluminium extraction from bauxite. Autotrophic leaching by indigenous *Thiobacillus* spp. was more efficient than heterotrophic leaching within range of fungal strains, and results in decreasing the toxicity of waste products [53]. In 1999, *T. Ferrooxidans* has also been used to treat air pollution control residues, APCR contains fly ash and used lime which contain high amounts of toxic metals. Although growth of the *thiobacilli* was poor but removal of about 95 percent of Cd from APCR of 270mg Cd kg⁻¹ was achieved along with 69 percent of removal of Pb from APCR of 5g Pb kg⁻¹ [54].

Siderophores

Siderophores are highly specific Fe(III) ligands and their formation constants are often less than 10³⁰. The extractions of

these low molecular weight coordination molecules are helpful in iron assimilation [55]. Such assimilation may be improved by attachment to solid Fe minerals, e.g., Fe oxides facilitate contact with the Fe substrate. However, primarily produced iron, siderophores are also able to bind with other metals such as magnesium, manganese, chromium(III), gallium(III) and radionuclides such as plutonium (IV) [56].

According to Diels, one method for the treatment of metal contaminated sandy soil depends on the siderophore mediated metal solubilization by *Alcaligenes eutrophus*. Solubilized metals were adsorbed to the biomass or precipitated with biomass got separated from a soil slurry by flocculation. This results in a complete decline in the bioavailability of Cd, Zn and Pb [57].

Biomethylation

Methylation of Hg, As, Se, Sn, Te and Pb can be obtained by means of bacteria and fungi under aerobic and anaerobic conditions. Methyl groups are enzymatically transferred to the metal, and given species of bacteria or fungi may transform a number of different metals. Methylated metal compounds formed by these processes differ in their solubility, volatility and toxicity. Volatile methylated species, like $(\text{CH}_3)_2\text{Se}$ and $(\text{CH}_3)_2\text{Se}_2$ are often lost from the soil [17,58].

Many environmental and soil factors of organic reformations and frequent tillage, can be optimized to enhance diffusive transport through soil and increase Se volatilization [59,60]. According to Thompson-Eagle and Frankenberger, at Kesterson Reservoir, California, microbial methylation of selenium results in volatilization has been used successfully for in situ bioremediation of selenium containing land and water, that reduced the selenium concentrations to acceptable levels [61]. Several bacterial and fungal species can methylate arsenic compounds such as arsenate, arsenite and methylarsonic acid to volatile dimethyl- $(\text{CH}_3)_2\text{HAs}$ or trimethylarsine [62].

Redox transformations

Microorganisms can mobilize metals, metalloids and organometallic compounds by redox processes [17,63,64]. For example, metal solubilities increases reduction of Fe(III) to Fe(II) and Mn(IV) to Mn(II) [27,64,65]. Most iron reduction is carried out by means of specialized anaerobic bacteria that use iron(III) as a terminal electron acceptor. Dissimilation by metal reducing bacteria can use a variety of metalloids with an appropriate redox couple, includes Fe(III), Mn(IV), Se(IV), Cr(VI) and U(VI) [66,67]. While on reduction Fe and Mn increase their solubility and decrease the solubility of other metals such as U(VI) to U(IV) and Cr(VI) to Cr(III), that results in immobilization [68,69]. Reduction of Hg(II) to Hg(0) by bacteria and fungi results in diffusion of elemental Hg out of cells [70,71,72].

In 1999, a study was conducted by Chang in which mercuric reductase from a recombinant *Escherichia coli* strain was immobilized on a chemically modified diatomaceous earth support with immobilization enhancing stability and reusability whose maximal activity was $1.2 \text{ nmol Hg mg}^{-1} \text{ protein s}^{-1}$ at an initial Hg^{2+} of 50 umol dm^{-3} [73]. Fe(III) and Mn(IV) oxides strongly absorb metals and this may hinder metal extraction from contaminated soils. Microbial reduction of Fe(III) and Mn(IV) may be one way for releasing such metals and this process may be enhanced with the addition of important soil polymers like humic materials or related compounds. Such compounds act as electron shuttles for U(VI) and Cr(VI), especially if located in tight pore spaces away from activity of microbes [27]. Bacterial Fe(III) reduction resulted in release of Mn and Co from goethite where 5 percent of the iron was substituted by these metals [74].

Immobilization

There are a number of processes that result in immobilization of

metals. Although immobilization reduces the external free metal species it may also promote solubilization in some circumstances that shift the equilibrium to release more metal into solution [34].

Biosorption and intracellular accumulation

Biosorption can be defined as the microbial uptake of organic and inorganic metal species both soluble and insoluble by physiochemical mechanisms of adsorption. Within living cells metabolic activities may also influence the process due to alterations in pH, Eh, organic, inorganic nutrients and metabolites. Biosorption also provides nucleation sites for the formation of stable minerals [26,75,76]. As well as sorption to cellular surfaces, some cationic species can be accumulated within cells through membrane transport systems having various affinity and specificity. Within cells, metal species may be bound, precipitated, localized within intracellular structures or organelles, translocated to specific structures depending on the concern element and the organism [18,22,36].

Peptidoglycan carboxyl groups are the main binding site for cations in Gram positive bacterial cell walls along with phosphate groups that contribute significantly in Gram negative species [26,75]. Chitin is an important structural component of fungal cell walls and this is an effective biosorbent for radionuclides, as are chitosan and other chitin derivatives [77]. In *Rhizopus arrhizus*, U biosorption involves coordination to the amine N of chitin, adsorption in the cell wall chitin structure and further precipitation of hydroxylated derivatives [78]. Fungal phenolic polymers and melanins contain various binding sites for potential metal along with oxygen containing groups that include carboxyl, phenolic and alcoholic hydroxyl, carbonyl and methoxyl groups [79].

Freely suspended and immobilized biomass from bacteria, cyanobacteria, algae and fungal species have attained much attention with the immobilized systems that appear to have several advantages including higher mechanical strength, easier biomass or liquid separation and increased metal tolerance of living cells [77,80,81,82]. Immobilized living biomass has primarily taken the form of bacterial biofilms on inert supports and is used in a variety of bioreactor configurations that includes rotating biological contactors, fixed bed reactors, trickle filters, fluidized beds and air lift bioreactors [21,80,83,84].

Metal binding peptides, proteins, polysaccharides and other biomolecules

Microorganisms produce a range of specific and nonspecific metal binding compounds. Nonspecific metal binding compounds are simple organic acids, alcohols and macromolecules such as polysaccharides, humic and fulvic acids [56,85,86,87]. Extracellular polymeric substances are a mixture of polysaccharides, proteins and mucopolysaccharides are produced by bacteria, algae and fungi and bind potentially to the toxic metals [13,85,88]. Extracellular polysaccharides can also adsorb or entrap particular matter like precipitated metal sulfides and oxides [89,90].

In 1994, Bender demonstrated a process used floating cyanobacterial mats for removal of metals from water by the metal binding process of polysaccharides [91]. In response of toxic metals, specific low molecular weight metal binding proteins, termed as metallothioneins are produced by animals, plants and microorganisms [92]. Other metal binding proteins, phytochelatins and related peptides possess glutamic acid and cysteine at the terminal amino position and have been identified in plants, algae and several microorganisms [93].

Eukaryotic metallothioneins and other metal binding peptides have been expressed in *E. coli* fused to membrane or membrane associated proteins such as LamB which is an outer membrane protein. In vivo expression of metallothioneins provide a mean of

designing biomass with specific metal binding properties [33,94,95].

Metal precipitation by metal and sulfate reducing bacteria

Reduction of a metal to a lower redox state by mobility and toxicity offer bioremediation applications [96,97]. Such processes include indirect reductive metal precipitation mechanisms, e.g., in sulfate reducing bacterial reduction of Cr(VI) obtain by indirect reduction by Fe^{2+} . Aerobic or anaerobic reduction of Cr(VI) to Cr(III) is common in microorganisms [69,98] and it has been documented in both ex situ reactor systems and in situ treatment approaches [27,99]. Certain Fe(III) dissimilatory microorganisms are used for reduction of U(VI) to U(IV) and this leads to the reduction of U removal from contaminated waters and leachates [27,96,97].

In 1998, Aubert demonstrated sulfur and sulfate reducing bacteria are geochemically important in reductive precipitation of toxic metals, e.g., U(VI) and Cr(VI), a process mediated by multiheme cytochrome c proteins [100]. *Desulfovibrio desulfuricans* can couple the oxidation of a range of electron donors to reduction of Tc(VII), which is precipitated as an insoluble oxide at cell peripheries. Resting cells immobilized in a flow through membrane bioreactor accumulated substantial quantities of Tc when supplied with formate as electron donor, that suggest the potential of this organism for treatment of Tc contaminated wastewater [101,102]. *D. desulfuricans* can also use for reduction of Pd(II) to cell bound Pd(0), with hydrogen dependent reduction being O_2 insensitive thus provide a mean of Pd recovery under oxic conditions [14]. Some sulfate reducing bacteria, like *Desulfotomaculum reducens* share physiological properties of both sulfate and metal reducing groups of bacteria, and can grow with Cr(VI), Mn(IV), Fe(III) and U(IV) as sole electron acceptors [103].

Oremland described the reduction of Se(VI) to elemental insoluble Se (0), employed to rectify contaminated waters and soils. In situ removal of SeO_4^{2-} by reduction to Se^0 by sediment bacteria in agricultural drainage regions of Nevada [104,61]. Flooding of exposed sediments at Kesterson Reservoir with water to create anoxic conditions has resulted in the reduction and immobilization of large quantities of selenium that was present in the sediment [105]. Some bacteria can use such reduction to support growth making this a natural process for in situ applications.

Although reduction of oxyanions of As and Se can occur by different mechanisms, the most environmentally significant process is dissimilatory reduction. Oxyanions of arsenic and selenium can be used in microbial anaerobic respiration as terminal electron acceptors providing enough energy for growth and metabolism. Their reduction can be coupled to a variety of organic substrates e.g., lactate, acetate and aromatics with the bacteria found in a range of habitats and not confined to any specific genus. These organisms and even the enzymes themselves may have applications for bioremediation of selenium and arsenic contaminated environments [67,106]. The incidental ability of a variety of microorganisms from all major groups to reduce Se(VI) and Te(VI) by additional often uncharacterised mechanisms offers additional scope for bioreactor based approaches [63].

Sulfate reducing bacteria oxidize organic compounds or hydrogen coupled with the reduction of sulfate producing sulfide [10,11,107]. The solubility products of most heavy metal sulfides are very low, in the range of 4.65×10^{-14} (Mn) to 6.44×10^{-53} (Hg) so that even a moderate output of sulfide can remove metals to levels permitted in the environment with metal removal being directly related to sulfide production [13,108]. Sulfate reducing bacteria can also create extremely reducing conditions which can chemically reduce metals such as uranium(VI) [108].

In addition, sulfate reduction partially eliminates acidity from the system as a result of the shift in equilibrium when dissociated sulfate is converted to largely protonated sulfide. This results in the further precipitation of metals as hydroxides as well as increase the efficiency of sulfide precipitation. Sulfate reduction can provide both in situ [109] and ex situ metal removal from contaminated wastes [110,111,112,113,114] and contribute to removal of metals and acidity in artificial and natural wetlands [115,116].

A process integrating bacterial sulfate reduction with bioleaching by sulfur oxidizing bacteria has been developed to remove contaminating toxic metals from soils. In this process, sulfur and iron oxidizing bacteria were employed to liberate metals from soils by the breakdown of sulfide minerals and production of sulfuric acid [10,11,22,23]. Metals are liberated in the form of an acid sulfate solution which enables both a large proportion of the acidity and almost the entirety of the metals to be removed by bacterial sulfate reduction [23,107]. Sulfate reducing bacterial biofilm reactors may offer a means of process intensification and entrap or precipitate metals, e.g., Cu and Cd, at the biofilm surface. Mixed sulfate reducing bacterial cultures were more effective than pure cultures with metal removal being enhanced by the production of exopolymers [13,117].

Bacterial and fungal oxidation

Bacterial Fe oxidation is ubiquitous in environments with sufficient Fe^{2+} and conditions to support bacterial growth, such as drainage waters and tailings piles in mined areas, pyritic and hydric soils (bogs and sediments), drain pipes and irrigation ditches, and plant rhizospheres. Iron oxidizers found in acidic soil environments are acidophilic chemolithotrophs, such as *T. ferrooxidans*, significant for its role in generating acid mine drainage [49].

Facultative chemolithotrophic microaerophiles such as *Leptothrix ochracea*, *Sphaerotilus natans* and *Gallionella ferruginea* are common in mildly acidic to neutral environments. Fungi also oxidize metals in their environment. Desert varnish is an oxidized metal layer, a few millimeters thick, found on rocks and in soils of arid and semiarid regions, and is believed to be of fungal and bacterial origin.

Phosphatase mediated metal precipitation

In this process, metal or radionuclide accumulation by bacterial biomass is mediated by a phosphatase which liberates inorganic phosphate from a supplied organic phosphate donor molecule, e.g., glycerol 2-phosphate. Metal or radionuclide cations are then precipitated as phosphates on the biomass [9,80,82]. Most work has been carried out with a *Citrobacter* sp., and a range of bioreactors, including those using immobilized biofilms, have been described [118,119].

In 1999, zirconium was mineralized by a *Citrobacter* sp. to a mixture of $\text{Zr}(\text{HPO}_4)_2$ and hydrated zirconia (ZrO_2), biomineralization of uranium as HUO_2PO_4 was repressed by zirconium in the presence of excess inorganic phosphate. Cell bound HUO_2PO_4 facilitated Ni^{2+} removal by intercalative ion exchange into the polycrystalline lattice and also promoted Zr removal [120].

Oxalates and carbonates

Calcium oxalate is the most common form of oxalate encountered in the environment, mostly occurring as the dihydrate or the more stable monohydrate [15]. Calcium oxalate crystals are commonly associated with freeliving, pathogenic and plant symbiotic fungi and are formed by the precipitation of solubilized calcium as the oxalate [8,15]. This has an important influence on biogeochemical processes in soils acting as a reservoir for calcium, and also influencing phosphate availability. Fungi can also produce other

metal oxalates with a variety of different metals and metal bearing minerals, e.g., Cd, Co, Cu, Mn, Sr and Zn [15,22,46].

In many arid and semiarid regions, calcareous soils and near surface limestones are often secondarily cemented with calcite (CaCO₃). This phenomenon has been partly attributed to physicochemical processes; however, the abundance of calcified fungal filaments in weathered profiles of chalky limestone and Quaternary calcretes indicates fungal activity [15,121]. Mineralized carbonate precipitates are also found in association with bacterial biofilms [34].

CONCLUSION

Microbiological processes have significant role in determining environmental metal mobility and have actual or potential applications in bioremediation. Microorganisms play important roles in the environmental fate of toxic metals and metalloids with a multiplicity of physiochemical and biological mechanisms effecting transformations between soluble and insoluble phases. Although the biotechnological potential of most of these processes has only been explored at laboratory scale, however, some mechanisms like bioleaching, biosorption and precipitation, have been employed at a commercial scale. Of these, autotrophic leaching is an established major process in metal extraction but has also been applied to treatment of contaminated soil. There have been several attempts to commercialize biosorption using microbial biomass but success has been limited, primarily due to competition with commercially produced ion exchange media. As a process for immobilizing metals, precipitation of metals as sulfides has achieved large scale application. Continued exploitation of other biological processes will undoubtedly depend on a number of scientific, economic and political factors.

RECOMMENDATIONS

It is suggested to use microorganisms for the treatment of heavy metals. It is an innovative and inexpensive technique to get rid of metallic pollution. It should be emphasised that this area of research also provides understanding of the biogeochemistry of metalloid cycling in the environment and the central role of microorganisms in affecting metal mobility and transfer between different biotic and abiotic locations. Industrial waste should be pass through proper microbial treatments so that heavy metals could not harm our environment.

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