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Waste Biomaterials for Removal of Heavy Metals – An Overview

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ABSTRACT

Environment fortification must require the use of natural products instead of chemicals to minimize pollution. The detoxification of metal pollutants from wastewater by the development of biomaterials having higher affinity, capacity and selectivity had been found to be as an alternative over conventional technologies that were often inadequate to reduce concentrations in wastewater to acceptable regulatory standards. Plant-derived biomaterials and biomaterials of agricultural by-products for biosorption of heavy metals are an innovative and alternative low cost technology for treatment and/or reuse of waste products. Biotechnological exploitation of biosorption technology to remove heavy metals depends upon the efficiency of the regeneration of the biosorbent after metal desorption. The purpose of this paper is to approach one of the most relevant parts of biotechnology, namely bioremediation with its particular branch – biosorption – applied for heavy metal removal. In addition to that available information on the various cheaper biomaterials occurring as natural biosorbent, for clean up operation applications along with metal binding mechanism have been highlighted.

Keywords: biomaterials, bioremediation, biosorption, metals, wastewater

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INTRODUCTION

The advances in technology have sustained our industrialized society. During the twentieth century, the explosive development of chemical industries has produced a bewildering variety of chemical compounds that have led to the modernization of our life style. The large scale production of heavy metals has caused global deterioration of environmental quality. Waste products, range from raw sewage to nuclear waste, resulting from human life, has always been a serious problem. Environmental pollution caused by toxic heavy metals and wastewater treatment processes in removing dyes from textile effluents have become of increasing importance in recent years. The pollutants of serious concern includes arsenic, lead, chromium, copper, cadmium, mercury, nickel, gold, silver, selenium, uranium etc. due to carcinogenic and mutagenic nature (Modak and Natarajan 1995; Volesky and Schiewer 2000; Ahluwalia and Goyal 2007a; Nilanjana *et al.* 2008). These toxic materials may be derived from mining operation, refining ores, sludge disposal, fly ash from incinerators, the processing of radioactive materials, metal plating or manufacturing of electrical equipments, paints, alloys, batteries, pesticides or preservatives (Ahalya *et al.* 2005; Chojnacka 2010). In addition, mining, mineral processing and extractive-metallurgical operations generate large quantities of toxic liquid waste and their presence poses environmental-disposal problems owing to their non-degradable and persistence nature (Kratochvil and Volesky 1998; Gupta *et al.* 2000). Removal of heavy metal contaminants from wastewater discharge is a necessity for many industries, owing to environmental concerns and federal regulations. The use of a biological system for the removal and recycling of heavy metals could prove more economical than currently used physico-chemical processes.

Conventional methods for removing metals from aqueous solutions include chemical precipitation, chemical oxidation or reduction, ion-exchange, filtration, electrochemical treatment, reverse osmosis, membrane technologies and evaporation recovery (Yan and Viraraghavan 2001; Ahluwalia and Goyal 2007b). These processes may be ineffective or extremely expensive especially when the metals in solution are in the order of 1-100 mg/l as they are non-biodegradable at low concentration and their threat is multiplied by their accumulation in the environment through the food chain (Nourbaksh *et al.* 1994; Kapoor and Viraraghavan 1995; Chojnacka 2011). Another major disadvantage with conventional treatment technologies is the generation of toxic chemical sludge and its disposal/treatment becomes a costly affair, which is also not eco-friendly. Therefore, reducing toxic heavy metals to an environmentally acceptable limit in a cost effective and environmentally friendly manner assumes great importance. Further, an effluent treatment facility within the industry discharging heavy metals contaminated effluent will be more efficient than treating large volume of mixed wastewater in a general sewage treatment plant. Thus it is beneficial to devise separate treatment procedures for scavenging heavy metals from the industrial wastewater (Volesky and Schiewer 2000; Gardea-Torresdey *et al.* 2004a; Gavrilescu 2004).

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Invited Mini-Review

Bioremediation is not a panacea but rather a "natural process" alternative to such methods as incineration, catalytic destruction, the use of adsorbents and physical removal and subsequent destruction of pollutants. Biosorption of heavy metals from aqueous solution can be considered as an alternative and hence emerging technology that were shown to be effective in removing even very low levels of heavy metals from industrial wastewater (Vegliό and Beolchini 1997; Volesky 2007; Gadd 2009; Bhatnagar and Sillianpaa 2010). Moreover, biosorption is a promising method and major advantage particularly in the treatment of large volume of wastewater and low concentration of pollutants. Current research activity in this field is focused on evaluating, whether biosorption may eventually provide such an effective and economic alternative treatment process, while biological treatment is reasonably effective in removing organic pollutants, heavy metals however tend to accumulate in biological sludge, which is unfit as fertilizers and require incineration for its disposal (Ahluwalia and Goyal 2007a; Chojnacka 2010; Opeolu *et al*. 2010; Zhang *et al*. 2011).

MECHANISM OF HEAVY METAL BINDING

Researchers had sought to represent the equilibrium data in the form of adsorption isotherms. The most appropriate method of assessing the biosorbent capacity is the derivation of a whole sorption. Anything else represents potentially misleading shortcuts that may lead to outright erroneous conclusions. While experimental volume increases almost exponentially with the number of metallic species present in the solution, evaluation of multi-metal sorption system offers a special challenge (Park *et al*. 2004; Gavrilescu 2004; Volesky 2007; Wang and Chen 2009). Biosorption is a complex process, mainly comprising of ion exchange, chelation and adsorption by physical forces and entrapment in inter and intra-fibrillar capillaries and space of the structural polysaccharide network as a result of concentration gradient and diffusion. The perceptive of mechanism by which biosorbents accumulate/adsorbed metals is important to the development of processes for concentration, removal and recovery of heavy metals from aqueous solution. Mechanism like chemisorptions, complexation, adsorption-complexation, ion-exchange, micro-precipitation, heavy metals hydroxide and condensation as well as surface adsorption was involved in the biosorption process (Kapoor and Viraraghavan 1995; Volesky and Schiewer 2000; Gardea-Torresdey *et al.* 2004a; Ahluwalia and Goyal 2007b). Further the sorption of metals by biological materials might be attributed to their proteins, carbohydrates and phenolic compounds that have carboxyl, hydroxyl, sulfate, phosphate and amino groups that can bind metal ions at different sites. Metal sorption consists of several mechanisms that quantitatively and qualitatively differ according to the metal species in solution and the origin and processing of the sorbent (Villaesusa *et al*. 2004). Further, it is essential to identify the functional groups (carboxyl, hydroxyl, sulfate, phosphate, amino acids, amide, imine, and imidazol moeties) involved in the biosorption process because most of the functional groups involved in binding are found in the cell wall (Volesky and Holan 1995; Al-Asheh and Duvnjak 1997; Gadd 2009; Wang and Chen 2009). Moreover, the role of given functional group of the biomass plays depends upon the factors such as number of sites on the biosorbent materials, their accessibility and chemical state (i.e. availability) and the affinity between sites and metals (i.e. binding strength). In our studies with waste tea leaves, amine group played an important role in binding of lead and iron whereas C=O (acid) group was involved in binding of nickel and zinc (Ahluwalia and Goyal 2005).

REMOVAL OF HEAVY METALS BY DIFFERENT BIOMATERIALS

Removal of heavy metals from aqueous solution by using inactive and dead biomass is an innovative and alternative technology for removing these pollutants. Bioremediation has emerged as one of the most desirable approaches for cleaning up many environmental pollutants. Bioremediation is a pollution control technology that uses biological systems to catalyze the degradation of or transformation of various toxic chemicals to less harmful forms. Biomaterials are, therefore one of the most abundant renewable resource that are available for conversion into high value environmentally sustainable biomaterials, including low cost sorbents for treatment of water streams contaminated with persistent organic pollutants , toxic oily waste and reactive dyes (Gardea-Torresday *et al*. 2004a; Ahluwalia and Goyal 2007a; Bhatnagar and Sillianpaa 2010; Opeolu *et al*. 2010). Different low cost biosorbent/biomaterials had been tried by various researcher that includes seaweeds, moulds, yeasts, bacteria, crabs shells, agricultural products such as wools, rice straw, coconut husks, peat moss, exhausted coffee (Dakiky *et al*. 2002; Nagh and Hanafiah 2008), waste tea (Ahluwalia and Goyal 2005; Amir *et al*. 2005), Walnut skin, coconut fibre (Espinola *et al*. 1990), cork biomass (Chubar *et al*. 2003), seeds of *Ocimum Basilicum* (Melo and d'Souza 2004), defatted rice bran, rice hulls, soyabean hulls and cotton seed hulls (Marshall and Champagne 1995; Teixeira *et al*. 2004), wheat bran, hardwood (*Dalbergia sissoo*) saw dust, pea pod, cotton and mustard seed cakes (Iqbal *et al*. 2002), paper mill sludge (Ahluwalia and Goyal 2004) for the removal of metal ions from aqueous solutions, just to mention a few. However, the necessity of investigating more biomaterials is still important in order to obtain the best biomaterial for industrial application.

Many agricultural by products that are of little or no cost and also of no value to the environment have been utilized in the remediation of metallic contaminants. In view of these reasons, development of a more cost effective remediation process using biological system for removal of heavy metal ions from wastewater is necessary. The ability of the cork and yohimbe bark wastes for uptake of Cu(II) and Ni(II) from aqueous solution was studied (Villaescusa *et al*. 2000). Maximum sorption for both the metals was found to be at pH 6-7. Adsorption isotherms at the optimum pH were expressed by the non-competitive Langmuir adsorption model and adsorption equilibrium data fitted very well to the model in the concentration range studied. Between both the biosorbent, yohimbe bark waste was found to be the most efficient adsorbent for removal of both metals.

Biosorption capacity of plant biomass of Indian sarapарilla (*Hemidesmus indicus*) was studied with toxic heavy metals like As, Se, Zn, Fe, Ni, Co, Pb, Mn, Hg, Cr and Cu. Lead was preferentially removed followed by Cr and Zn at concentration less than 250 mg/l and with biomass quantity above 2g. Presence of co-ions such as As, Se and Hg did not affect Pb removal but Zn and Cr uptake decreased. Metal laden biomass was regenerated with HNO_3 and reused for three cycles without any loss in metal retention capacity (Chandrasekhar *et al*. 2003). Adsorption of Cd(II) and Ni(II) was found to be higher than Cr(VI) and Zn(II) when phosphate treated rice husk was used as an adsorbent (Ajmal *et al*. 2003). Sorption of Cd(II) was dependent on contact time, concentration, temperature, adsorbent doses and pH of the solution and follows Langmuir constant. Recovery of Cd(II) from aqueous solution by column operation was found to be higher than batch process. Adsorption of Cr(VI) with activated rice husk carbon and activated alumina (Bishnoi *et al*. 2004) and with formaldehyde treated saw dust and sulphuric acid treated saw dust carbon (Garg *et al*. 2004) was investigated. The amount of Cr(VI) adsorbed increased with increase in dose of these adsorbents and their contact time.

Reduction rate of Cr(VI) to Cr(III) by *Ecklonia* sp. biomass increased with decreasing pH, which appeared in the solution phase or was partly bound to the biomass (Park *et al*. 2004). The jack fruit peel (*Artocarpus heterophyllus*) was treated with sulphuric acid to produce a carbonaceous product, which was used as an adsorbent for the removal of

Cd(II) from aqueous solution (Inbaraj and Sulochana 2004). A complete recovery of the adsorbed metals ions from the spent adsorbent was achieved by using 0.01M HCl. The adsorption of activated carbon prepared from apricot stones, to remove Ni(II), Co(II), Cd(II), Cu(II), Pb(II), Cr(III) and Cr(VI) ions from the aqueous solution was studied (Kobya *et al.* 2005). Highest adsorption occurred at pH 1-2 for Cr(VI) and at pH 3-6 for the remaining metal ions. Further, adsorption capacities for these metals were found in the order of Cr(VI) > Cd(II) > Co(II) > Cr(III) > Ni(II) > Cu(II) > Pb(II) respectively. Potential of modified lignocellulosic fibre/ jute was assessed for adsorption of heavy metal ions like Cu(II), Ni(II) and Zn(II) from aqueous solution (Shukla and Pai 2005). The dye loaded jute fibre showed adsorption capacity of 8.4, 5.26 and 5.95 mg/g for Cu(II), Ni(II) and Zn(II) respectively, whereas oxidized jute fibre showed 7.73, 5.57 and 8.02 mg/g against 4.23, 3.37 and 3.55 mg/g for unmodified jute fibre, which followed Langmuir adsorption model. Desorption efficiency, regenerative and reuse capacity of these adsorbent were also assessed for three successive adsorption-desorption cycles. The sorption of lead by tree fern, an agricultural by product was carried out using agitated and baffled system (Ho 2005). The optimum pH for lead removal was 4.9. Removal of cadmium from aqueous solution by *Moringa oleifera* seed was studied in batch sorption experiments as a function of biomass dosage, contact time, metal concentration, particle size and pH (Sharma *et al.* 2006). Fourier transform infrared spectroscopy indicated the amino-Cd interaction responsible for this sorption. These findings open up new avenues in the removal of toxic metals by shelled *M. oleifera* seeds from water bodies as low cost, domestic and environment friendly safe technology. Grape bagasse generated in the wine production process showed the adsorption capacities in the range of 0.479 and 0.204 mmol/g for Cd(II) and Pb(II), at a pH 7.0 and 3.0 respectively within 5 min of contact (Farinella *et al.* 2007), whereas spent-grain showed the maximum adsorption capacity of Cu(II) ions in the range of 10.47 mg/g dry weight (pH 4.2) from aqueous solutions (Lu and Gibb 2008). Coconut coir pith, an agricultural solid waste after modification with a cationic surfactant, hexadecyltrimethylammonium bromide was used as biosorbent to remove Cr(VI) and the adsorption capacity was 76.3 mg/g (Namasivran and Sureshkumar 2008). Tobacco dust, a typical lignocellulosic agricultural residue, had exhibited a strong capacity for heavy metals, such as Pb(II), Cu(II), Cd(II), Zn(II) and Ni(II), with respective equilibrium loadings of 39.6, 36.0, 29.6, 25.1 and 24.5 mg of metal per g of sorbent (Qi and Aldrich 2008). Arshad *et al.* (2008) examined the adsorbent from mature leaves and stem bark of neem (*Azadirachta indica*) tree to remove zinc from aqueous solution. The maximum adsorption capacity was 147.08 mg Zn/g with neem leaves and 137.67 mg Zn/g with neem bark. Similarly, the biosorption of Pb(II) with seed husk of *Calophyllum inophyllum* was found to be 4.86 mg/g at pH 4 (Lawal *et al.* 2010). FTIR studies with seed husk revealed that carboxyl, amine, and hydroxyl groups on the biomass surface were involved in the adsorption of Pb(II) ions. Ahmed (2010) studied the removal of Cu^{+2} (90%), Cd^{+} (57%) and Zn^{+2} (37%) with Iraqi date palm tree of ≤ 1mm in size within (60 min) contact time at adsorbent loading ratio of 30 g/l.

Fruit of gular (*Ficus glomerata*) (Rao and Rehman 2010) was found to reduce Cr(VI) concentration in electroplating wastewater from 58 to 7 mg/l and exhibit promising adsorbent to remove Cr(VI) from industrial effluent. Uptake sorptions in single metal system were 24.4 mg Pb^{2+}, 22.50 mg Cu^{2+}, 18.93 mg Zn^{2+} and 17.62 mg Ni^{2+} per gram for *Mangifera* sp. (mango) biomass at a concentration of 150 mg/l (Ashraf *et al.* 2011). The adsorption toxic metal ions by African spinach stalk (*A. hybridus*) was in the 3.32 mg Mn(II)/100 cm^3 and 2.82 mg Pb(II)/100 cm^3 whereas with pawpaw seed (*C. papaya*) showed 4.1 mg Mn(II)/100 cm^3 and 3.63 mg Pb(II)/100 cm^3 from aqueous solution in 90 min of contact (Egila *et al.* 2011).

Biosorption studies have been carried out using easily available biomass in their native state or after simple processing. Among a variety of biomaterials, the majority has been focused on bio-waste generated as a by-product of large-scale industrial fermentation (Modak and Natarajan 1995; Puranik and Paknikar 1999), olive mill solid residues (Pagnanelli *et al.* 2002), activated sludge from sewage treatment plants (Hammaini *et al.* 2003), aquatic macrophytes (Keskinkan *et al.* 2003) and other plant derived materials (Gardea-Torresday *et al.* 2004a, 2004b). Norton *et al.* (2003) used dewatered activated sludge from a sewage treatment plant for removing zinc from aqueous solution and recorded adsorption capacity of 0.56 mM/g of sludge/ biosolids, which was favorable as compared to the bio-adsorption rate of 0.3 mM/g by the seaweed, *Durvillea potatorum* (Aderhold *et al.* 1996). Keskinkan *et al.* (2003) studied adsorption characteristics of copper, zinc and lead on submerged aquatic plant, *Myriophyllum spicatum* and found the adsorption capacities to be 46.60 mg/g for lead, 15.59 mg/g for zinc and 10.37 mg/g for copper. Pagnanelli *et al.* (2002) carried out a preliminary study on the use of olive mill residue as a heavy metal sorbent material. They found that copper was maximally adsorbed in the range of 5.0-13.5 mg/g under different operating conditions. The biosorption capacity of copper, cadmium and zinc on dried activated sludge was 0.32 mmol/g for metal systems such as Cu-Cd; 0.29 mmol/g for Cu-Zn and 0.32 mmol/g for Cd-Zn. Results showed that biomass had a preference for copper followed by cadmium and zinc (Hammaini *et al.* 2003). The maximum biosorption capacity of *Streptomyces rimosus* biomass was found to be 11.76 mg Al/g (Tassist *et al.* 2010), 38 mg Cu/l with *Penicillium* biomass (Zhang *et al.* 2011). The use of biosorbent for water treatment had been proven to have considerable advantage over traditional materials. Research is still in progress as different areas related to biosorption are being explored.

DEVELOPMENT OF BIOSORBENT MATERIAL AND BIOSORPTION COLUMNS

Bioremediation of industrial wastes containing heavy metals had been demonstrated by several biotechnology companies (Volesky 2007; Wang and Chen 2009; Chojnacka 2011). Moreover, environmental engineers/scientists are faced with the special challenge of becoming more innovative in the development of appropriate low cost technologies for treatment and or reuse of waste products. Further, removal of metal ions from solution by biosorption is essentially a conventional solid liquid contacting and separation process. Batch sorption process are usually limited to the treatment of small amount of effluent, more practical alternative to eliminate metal ions from aqueous solution on the scale up level is required. Biosorption column experiments are performed in order to evaluate the removal and recovery of metal ions under flow conditions (Modak and Natarajan 1995; Volesky and Holan 1995; Mahvi 2008) and these column techniques facilitate the treatment of effluents to remove heavy metals at the site of emission and before contaminants reach water bodies and soils. In our studies with a number of biosorbent, a flow through column sorption with paper mill sludge (239 mg Pb/g) and waste tea leaves (73 mg Pb/g) in up flow continuous column sorption system (Ahluwalia and Goyal 2004, 2005).

The biosorption column capacity, related to the initial dry weight of biomass (38 g) loaded in, shows no correlation with the decreasing breakthrough time (Volesky *et al.* 2003). The copper uptake obtained in the first sorption cycle (38.2 mg Cu/g) corresponds nearly exactly to the uptake obtained from the sorption isotherm (38.5 mg Cu/g) at the equilibrium concentration of 35 mg/l with no decreasing tendency in the following cycles. In the last cycle the initial column capacity had even exceeded (at 42.4mg Cu/g) probably due to the previous more thorough desorption ($CaCl_2$ wash, HCl wash and $CaCl_2$ regeneration).

Moreover, stirred and packed bed reactors falls in the solid liquid processing equipment and both have been applied in both laboratory and pilot scale investigations (Gavrilescu 2004; Volesky 2007). Stirred tank reactors may be operated in batch or continuous mode and applications to biotechnology range from classical activated sludge system to laboratory scale studies. The main requirement of a large scale sorption process is that the sorbent could be used in a suitable reactor configuration such as packed, fluidized bed or stirred tank reactor. Such large-scale biosorption in reactors requires suitably immobilized biosorbent where the biosorbent material is granulated into the pellets of appropriate dimension. The size, density and shape of particle are such that it should not cause clogging or much pressure drop across the biosorbent bed (in case of packed column) and at the same time should permit optimum flow properties (Zhou *et al*. 1999; Mahvi 2008; Tassist *et al*. 2010). Packed bed system obviates the need for additional solid/ liquid separation system and is well suited to continuous flow adsorption and regeneration cycles. Packed bed system is fixed bed or column reactor in which stationary biosorbent particles are contacted with metal bearing solution pumped through the column in an up flow or down flow arrangement. Fixed bed system such as fluidized bed and air lift reactors, the biosorbent particles mobilized by up flow or effluent through the column induced by pumping or rising air stream introduced at the column base. Disadvantage of greater space requirement, particle attrition and increased capital and operating cost are offset by reduced pressure drops and increase removal efficiencies and retention times (Bhatnagar and Sillanpaa 2010; Chojnacka 2010).

To provide an economically viable treatment, the appropriate choice of biomass and proper operational conditions have to be identified. To predict the difference between the uptake capacities of the biomass, the experimental results should be tested against an adsorption model. The development of a packed bed or fluidized-bed biosorption model would be helpful for evaluating industrial-scale biosorption column performance, based on laboratory scale experiments and to understand the basic mechanism involved in order to develop better and effective biosorbent.

BIOSORBENT REGENERATION AND METAL RECOVERY

Biotechnological exploitation of biosorption technology to remove heavy metals depends upon the biosorbent regeneration efficiency after metal desorption. Therefore, nondestructive recovery of mild cheap desorbing agent is desirable for regeneration of biomass for use in multiple cycles. The eluent used for desorption must have a higher binding affinity for metal than biomass metal binding. Dilute mineral acid has been in various studies to remove metals from metal laden biomass (Kapoor and Viraraghavan 1995; Volesky and Schiewer 2000; Ahluwalia and Goyal 2003; Chojnacka 2010). Increasing the acidity generally leads to an effective removal of metals from the biomass. The physicochemically sequestered metal to the cell surface can be easily destroyed by EDTA, carbonates and bicarbonates (Ahuja *et al*. 1999; Volesky *et al*. 2003). Once the metal laden biomass is saturated, biosorbed metals can be potentially be desorbed in order to regenerate the biosorbent material for reuse and reclaim valuable metals. The objective of desorption is to weaken the biomass-metal binding, the conditions that are least favorable for biosorption are ideally suited for desorption. In other words, the eluant used for desorption must have a higher binding affinity for the metal than the biomass metal binding. In general the number of times that altered biomass can be used is limited so that cycling biomass is uneconomic but this can be improved by immobilization (Volesky 2007; Chojnacka 2010). Further, as the capacity of microbial biomass for metal is strongly dependent on the biomass concentration during biosorption, increasing the biomass concentration may increase the total metal removal at the cost of reduced loading per unit of biomass and reduce the concentration of an eluted metal product, which further emphasizes that development of metal biosorption must be considered as part of an metal removal or metal reclamation process. Higher biomass concentration were required as reported earlier (Ahluwalia and Goyal 2010; Zhang *et al*. 2011), which may be due to that these waste were directly obtained from industries and contains several impurities due to processing and handling. Lower biomass concentration in the suspension at a given metal concentration enhances the metal/biosorbent ratio and thus increases metal uptake per gram of biosorbent, as longer as the latter is not saturated. After complete adsorption, metal laden biomass can be incinerated and metal content in ash could be disposed off either by land filling or can be coupled with possible metal recovery (Ahluwalia and Goyal 2004).

Critical analysis reveals that not all metal-polluted wastewater-generating industries had the interest or the capability to treat effluents and most of the industries opt only for basic treatment techniques simply to comply with regulations. To attract more usage of biosorption, strategies have to be formulated to centralize the facilities for accepting the used biosorbent where processing of the biosorbent can be done either to regenerate the biomass or convert the recovered metal into usable form. This will further require an interdisciplinary approach with integration of metallurgical skills along with sorption and wastewater treatment to apply biosorption technology for combating heavy metal pollution in aqueous system.

CONCLUSION AND FUTURE STRATEGIES

There is a need to orient the aspects of bioremediation research to modern biotechnologically integrated science and engineering efforts using field site demonstrations as vehicles for integration. Bioremediation is an interdisciplinary technology involving microbiology, engineering, ecology, geology and chemistry. However, current knowledge of biological contribution to the effect of bioremediation and its impact on the environment is limited. The potential application for biosorption appears to be enormous. Plant-derived biomass and biomass of agriculture by-products and in some case appropriate modification has shown to possess a high capacity for heavy metal adsorption. Scientists have begun to search for biomaterials with better biodegradation kinetics for a variety of contaminants within broad environmental habitats. The problems of bioremediation for heavy metal-contaminated sites are very different from those of bioremediation for organic pollution, but intensive interdisciplinary collaboration in basic and applied research in this economically important field is expected to be very beneficial in the near future. Moreover, it would be ideal if the bioremediation system maximized the extent and rate of degradation of waste materials, simultaneously minimizing the level of toxic substances during the operation.

The use of immobilized biomass rather than native biomass has been recommended for large-scale application but various immobilization techniques have yet to be thoroughly investigated for ease, efficacy and cost effectively. Biosorption processes are applicable to effluents containing low concentrations of heavy metals for an extended period. This aspect makes it even more attractive for treatment of dilute effluent that originates either from an industrial plant or from the primary wastewater treatment facility. Thus biomass-based technologies need not necessarily replace the conventional treatment routes but may complement them. While the high cost of the ion-exchange process limits its application (as demonstrated by the huge amount of untreated effluents still released), the cost advantage of biosorption technology would guarantee a strong penetration of the large market of heavy metal polluting industries.

Presently, information on different biosorbent materials is inadequate to define accurately the parameters for process scale up and design perfection including reliability and economic feasibility. It can be easily envisaged that cheaper biosorbent would open up new, particularly environmental, markets so far non-accessible to ion exchange resins because of their excessive cost which make them prohibitive for clean up operation applications. To attract more usage of biosorption, strategies have to be formulated to centralize the facilities for accepting the used biosorbent where processing of the biosorbent can be done either to regenerate the biomass or to convert the recovered metal into usable form. This will further require an interdisciplinary approach with integration of metallurgical skills along with sorption and wastewater treatment to apply biosorption technology for combating heavy metal pollution in aqueous system.

In the future, modification and adaptation of nanotechnology will extend the quality and length of life. The breath of anticipated opportunities, cross-disciplinary nature, potential for innovation, historical track records and the impact of the potential gains of nanotechnology research have led to the reorganization of this area with special emphasis.

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