

***CHAPTER I:
Biosorbents; A Literature Review***

Abstract

The present chapter deals with the literature review concerning the biosorbents used for removal of toxic heavy metals. The chapter contains the summarized report on heavy metals impact on fauna and flora, sources of heavy metals in the aquatic environment, various methods available to minimize heavy metals content in the aquatic environment along with their merits and demerits and a brief detail pertaining to various biosorbents obtained from different sources, their preparation, use and efficiency of metal removal reported in literature reviewed followed by concluding remarks.

Introduction

Rapid industrialization has led to release of a range of toxic substances in the environment which have adverse effects on the environment and on biological systems. Heavy metals are one of these toxic substances which need considerable attention in lieu of their wide ranging adverse impacts. Activities ranging from natural to anthropogenic have led to release of heavy metals in the environment. Effluents from industries and leaching of rocks along with other causes have led to their release in aquatic environment. Various methods including physical, chemical, physicochemical and biological have been developed to minimize their concentration in the aquatic environment. Use of biosorbents derived from bacteria, Fungi, Algae, higher plants, agricultural wastes and industrial wastes have a considerable attention due to easy availability of basic materials and ecofriendly nature of the method of metal removal. Research is going on in the direction to explore new sources biosorbents, design of equipment, method development for industrial use of the biosorbents and enhance their efficiency of metal removal.

Heavy metals and their impacts on fauna and flora

Metals with density greater than 5 mg/cm^2 constitute a group of metals known as heavy metals [1]. Enhanced anthropogenic industrial activities have led to their release in environment to a great extent. They are environmental pollutants and hazardous to humans [2]. Heavy metals are non biodegradable and are persistent in nature [3,4]. Various diseases and disorder are caused by heavy metal accumulation in living organism [5-7]. The heavy metals show toxicity by accumulation in the biological system and cause serious health problems [8]. Heavy metals are highly toxic even at low concentration [9] and their toxicity is determined by their solubility [10]. Maximum permissible limit of Ni (II) ion in drinking water is 0.02 mg/L (BIS, 1994). 2 gm/L is the recommended limit of copper in drinking water as intake of Cu in high concentration may lead to gastrointestinal disease [11]. Maximum permissible limit of Hg, Cd, As, Pb, Cr and Cu ion in drinking water is 2,5,10,15,100 and 1300 $\mu\text{g/L}$ respectively as prescribed by US environmental protection agency [12]. Heavy metals are carcinogenic and mutagenic in nature [13,14]. Heavy metal pollutants may led to severe damage to kidney, liver, and nervous system [15]. Heavy metals have capability to block functional groups of vital enzymes hence cause severe toxicity [16]. Hypertension, nephritis, renal dysfunctions, nervous system related mal function and gastrointestinal tract disease, birth defects are reported due to presence of Cd, Pb and Zn even at very low concentrations [17]. Ingestion, inhalation and skin contact of heavy metal may cause damage to human body [18-20]. Physical illnesses are also reported to be caused due to heavy metals [21]. Mass deaths are also reported due to heavy metal toxicity [22]. Dermatitis, allergies, renal disturbances, liver dysfunction, infertility, lung cancer, stomatitis, gingivitis, insomnia, nauseas, kidney and cardiovascular dysfunction are caused by Ni(II) toxicity [23-25]. Itai-itai

disease, hypertension, anemia, renal damage is caused by cadmium toxicity [26]. Minamata disease is caused by toxicity of mercury.

Heavy metal sources in aquatic environment

Heavy metals which contaminate the soil, water etc. exist in soluble form [27]. Important sources of metal contamination are agricultural, industrial and military operations [28]. Intensification in accumulation of heavy metal pollutants is due to rise in industrial activities [29]. Discharge of effluent from electroplating, leather tanning, wood preservation, pulp processing and steel manufacturing industries contains heavy metals of carcinogenic and mutagenic nature [13,14]. Smelters, power stations, metal containing pesticides, fertilizers and fossil fuel consumption are also the sources of metal contamination in environment [30-32]. Battery, textile, plastic, pigment industrial effluents discharge, agricultural runoff, sewage disposal results in heavy metal release in environment [33,34,35,36]. Dye stuff and petroleum industries may be a cause of metal contamination [37]. Natural processes like seepage from rock or volcanic activities are also a cause of metal contamination [38]. Human activities which are metal processing, metals plating and finishing [39], incineration of waste, land fill leaches, automobile exhaust, ore refining, electronic finishing, painting and paper industries [40] are responsible for metal contamination of environment. Mining, milling and surface finishing industries are responsible for release of metals particularly Cd, Cu, Ni, Co, Zn and Pb [8]. Pb and Cu contamination of the air due to use of lead bullets for hunting and use of pesticide for agriculture purpose has also been reported [41,42]. Waste water from brewery and pharmaceutical industries contains Cd, Pb, and Zn [43,44].

Removal /Recovery of heavy metals from aquatic environment

Owing to severe toxicity related effects of heavy metals, it is important to remove or minimize their content in the waste water. Various methods have been devised to treat the waste water, these include physical, chemical and biological methods.

1. Chemical preapitation:- The method is simple, inexpensive and most of the metals can be removed but it is ineffectual for the treatment of water where concentration of metal is less than 10 mg/L, it produces large amount of sludge and creates disposal problems [45,46].

2. Ion exchange method:- The method is conventional method, it has the advantage of high regeneration, is metal selective but it is expensive and less number of metal ions are removed, it is ineffective at low metal ion concentration (1-100 mg/L) [46-48].

3. Electro chemical method:- Electro chemical method is metal selective method, it do not consume chemicals and metals can be recovered in pure form but it is expensive and involves high capital cost and running cost, initial solution pH and other technical requirement are typical [45].

4. Oxidation-reduction method:- The process is expensive and is ineffective at lower metal concentration [46].

5. Chemical coagulation:- The method has advantage of sludge settling and dewatering but it has disadvantage of high cost and consumption of large amount of chemicals e.g. lime coagulation [49].

6. Reverse osmosis:- Method is expensive and involves technical constraints [15].

7. Solvent extraction:- It involves high cost [16].

8. Adsorption by activated carbon:- Method is of high efficiency and most of the metal can be removed but it involves high cost of activated carbon and regeneration is not possible [45].

9. Membrane process and ultra filtration:- The method produces less solid waste and consume less chemical, is of high efficiency but it is expensive high ruining cost, flow rate is lower, presence of other metals affect the removal percentage [45].

Due to production of toxic sludge, involvement of high cost, consumption of chemicals, non regeneration and recycling and limitation of the methods below metal ion concentration of 100 mg/L requires alternate waste water treatment. Use of biosorbents which is ecofriendly and cost effective is a field of emerging research and proving to be a future methodology.

Use of biosorbents for removal of heavy metals from aquatic environment

Industrial/agriculture solid wastes, specially propagated microbial biomass of possessing characteristic adsorbent properties are generally used biosorbents for the biosorption process to remediate heavy metals pollution from aquatic environment [39,50,51]. Metabolically independent process of metal ions binding by living or inactivated biomass is referred as biosorption [52,53]. Biosorption has the advantage of cost effectiveness, minimum sludge production, effective for very

dilute effluents/aqueous solutions [54,55]. Functional groups like carboxyl (-COOH), amide (-NH₂), thiol (-SH), phosphate (PO₄³⁻) and hydroxyl (-OH) are found to be present on the biological surfaces and are responsible for metal complexation by coordination [56]. Use of biosorbents derived from bacteria, fungi, algae and other plant materials is under wide consideration by scientific community.

Bacteria as source of Biosorbents

Vecchio et al. [57] have investigated the Pb, Cd, and Cu bivalent metal ions removal capability of *brevibacterium* cells from aqueous solution, tolerant to various metals. The metal binding capacity of the incubated cells in batch experiment at pH 6.3, temp 30⁰C in a thermostat, provided with a rotary shaker (100 revolutions per minute) for 2-5 h (believed to attain equilibrium state) for metals Cu, Pb, and Cd (used as copper(II)chloride, lead nitrate, cadmium chloride) was found to be 0.54, 0.36 and 0.14 mmol metal /g dry weight cells respectively. Bivalent ions removal capability of immobilized polyacrylamide cells of the micro organism in a flow through system when present in alone or in pairs from aqueous solution has also been evaluated to study competitive effects. It shows that lead has high affinity towards the cell binding sites and its presence in aqueous solution impairs the efficiency of Cu and Cd removal. The desorption studies of the metal ions were study using EDTA, a chelating agent which regenerates the biosorbent but with lesser efficiency

Ahn et al. [58] have studied the biosorption heavy metals (Cu, Cd, Zn and Mn) by immobilized *Zoogloea ramigera* and its extracellular polymer zooglan in batch and packed bed column experiments. The commercial ion-exchange resin, styrene type strong acidic-cation exchange resin (SKIB, samyang, Korea) have been used to compare the metal ion uptake

efficiency. The biomass has been immobilized to produce biomass-silica bed using NaCl solution containing sodium alginate sodium metasilicate CaCl_2 solution and polyethylene. Using batch experiment at pH 5.0, temp 25°C at sorption equilibrium which is after 2 h, using solutions of CuCl_2 , CdCl_2 , ZnCl_2 and MnCl_2 at 10 g/L initial metal concentration showed higher adsorption capacity for Cd and Cu ions when compared to Mn ions. Cd ion uptake capacity was high for immobilized zoogloea and zooglan than commercial resin. Presence of Ca and Mg ions in solution do not reduce the Cu ion uptake capacity of biomass while that of commercial resin was reduced in presence of Ca and Mg ion. Column experiment showed the heavy metal ion uptake efficiency as $\text{Cu} > \text{Cd} > \text{Zn} > \text{Cr}$. The biosorbent was regenerated using nitrotriactic acid (NIA) or sulfuric acid. Sulfuric acid was found to be more effective in biosorbents regeneration.

Pazirandeh [28] has reported use of recombinant *E. coli* expressing the *Neurospora crassa* metallothionein gene (NCP). Metallothionein is rapid and selective for the Cd uptake from aqueous solution. The bacteria NCP has been used for free cells as well as encapsulated in either alginate or acrylamide. Heavy metal uptake experiment using free cells by NCP for cadmium, mercury, chromium, lead, zinc, nickel and copper showed most efficient accumulation of mercury and lead followed by cadmium, zinc, nickel and copper by incubation for 1h at room temperatures. Regeneration of biosorbent by sodium acetate solution or dil. HCl was performed. HCl was found to be promising agent for regeneration of biosorbent without loss of metal binding sites. Presence of other toxic compounds in the medium viz; phenanthrene, naphthalene, fluoranthene, phenol, chloroform and toluene upto 1000 ppm do not inhibit Cd uptake capacity of bacteria. Alginate or acrylamide immobilized NCP shows efficient Cd removal.

Veglio et al. [39] have used membrane reactor device (Tangential flow membrane model [59]) to study copper and lead adsorption on to *Sphaerotilus natans* biomass at pH 5.0 and obtained equilibrium parameters of Langmuir competitive model ($q_{\max}=0.67$ mmol/g, $b_{\text{cu}}=12$ L/mmol, $b_{\text{pb}}=40$ L/mmol, which showed that lead uptake prevails over copper uptake when equimolar feed is used, wing to differential affinities for the metals due to dissimilar acidic nature of metal ions. The biosorption for binary metal system was simulated to study multimetal biosorption into a series of membrane reactor and showed that metal with minor affinity is released first.

Kaewchai and Prasertsan [60] have investigated the biosorption of nickel and cadmium by using polymer producing bacterial strains– *Bacillus subtilis* WD 90, *Bacillus subtilis* SM 29 (Gram Positive) and *Enterobactor agglomerans* (Gram Negative) or their biofloculants at different pH, metal concentrations and incubation time. The biofloculants which are biopolymer obtained from these bacterial strains showed highest metal removal property than the bacterial cell dry biomass or wet biomass. The highest removal of nickel 92.8% was showed by biofloculant of *E. agglomerans* SM 38 at pH 7.0 after 24h incubation at 30⁰C with metal concentration 10 ppm and the highest removal of cadmium 91.4 % was showed by biofloculant of *B. subtilis* SM 29 at pH 8.0 after 24h incubation at 30⁰C. The experiment further showed that the optimum pH range for the removal of metal ions from aqueous solution is 7.0 to 8.0 depending on the metal and biosorbent material. At lower pH the proton ion concentration is higher and they compete with metal ions for binding site hence lower pH inhibits the metal ion uptake by biosorbent material.

Pagnanelli et al. [61] have used *Anthrobacter species* cells for biosorption studies of copper and cadmium. Potentiometric titration of biomass with

0.1 N NaOH showed the presence of two monoprotic weakly acidic sites. Biosorption test in batch reactor performed using ‘subsequent addition method’ (SEM), a more sophisticated and less time consuming method for very fast kinetic showing biosorption. The metal uptake increased with increase in pH. Specifically uptake of copper was found to be more than that of cadmium at the same equilibrium pH. Cadmium and copper biosorption was simulated using chemical model other than competitive Langmuir equation. The proposed model is good fit for cadmium adsorption at the studied pH values i.e. pH 3, 4, 5 and 6 while for copper adsorption above pH 5, the model showed deviation indicating complex adsorption behavior. Mechanically stressing conditions were existing at higher biomass concentration and at high pH values as revealed by the simulation studies for the biosorption test in membrane reactor.

Veglio [62] has studied the biosorption of copper onto *Sphaerotilus natans* and calcium alginate to develop the mathematical model using the equilibrium biosorption data using Langmuir model as reference model. Equilibrium biosorption experimental results at different equilibrium pH values were described by making empirical changes to the Langmuir model. The model considers the mixed complex competitive and non competitive mechanisms on the adsorption sites of protons and metal ions.

Pagnanelli et al. [63] have studied the simulation of equilibrium models viz; Langmuir (equation 1), Freundlich (equation 2) and Redlich Peterson isotherm (equation 3) using copper biosorption onto *Shpaerotilus natans* cells by ultra filtration membrane reactor system.

$$q_{eq} = \frac{q_{max}bC_{eq}}{1+bC_{eq}} \quad \dots 1$$

$$q_{eq} = K_F C_{eq}^{1/n} \quad \dots 2$$

$$q_{eq} = \frac{K_R C_{eq}}{1 + a_R C_{eq}^\beta} \quad \dots 3$$

Where,

q_{qe} = (mg/g), is equilibrium metal concentration in solid phase

C_{eq} = (mg/l), is equilibrium metal concentration in liquid phase

q_{max} , b , K_F , n , K_R , a_R , and β are adjustable parameters

For the ultrafiltration membrane device coupled with CSTR (Continuous Stirred Tank Reactor) the dynamic behavior of metal is given by equation 4-

$$FC_0 - FC - rV = V \frac{dC}{dt} \quad \dots 4$$

Where it is assumed that there is material balance i.e. (A) diffusion in the liquid was not a kinetic limiting step and (B) equilibrium conditions were established with in the residence time

Where –

F=feed flow rate with co metal concentration

V=CSTR volume

C=metal concentration in permeate

R=removal kinetic

And $r=X \, dq/dt$

Different differential equations were obtained and data was simulated with that of the experimental data. For different phenomena occurring, various correction terms were added. The Langmuir model predicted low metal uptake for low equilibrium metal concentration as compared to Freundlich and Redlich Peterson. Empirical equation curves which include permeates flow and copper reaction coefficient changes versus time, single and tow stage membrane reactor systems have been theoretically simulated to found that series of bioreactor showed better biosorption.

Lu et al. [64] have studied the biosorption of lead, copper and cadmium by heavy metal-resistance *Enterobacter species* J1. The biosorption studies carried out using 100 mg/l heavy metal solution with 1.5-2.5 g/l cell concentration at 25⁰C at the pH values 5.0, 5.0 and 6.0 in case of lead, copper and cadmium respectively for 8 min time course of biosorption. The adsorption isotherm were studied in solution with heavy metal concentration varying from 0 to 500 mg/l with cell concentration in the range of 1.5-2.5 gm/l for 24 hr at 25⁰C with the pH as above. The maximum biosorption was obtained for lead which is nearly 50 mg Pb/g dry cell which is a higher biosorption value than biosorption values of copper and cadmium which is around 30 mg/g dry weight of cell. Langmuir and Freundlich models have been used to describe the adsorption equilibrium phenomenon. Both models were found to be in good agreement with the biosorption data of copper and cadmium. As showed by high correlation coefficient. Biosorption data of Pb better fits in Freundlich model showing that biosorption mechanism of lead follows intracellular uptake along with surface binding. Adsorption of Pb, Cu and Cd occurred rapidly with in the first 100 min. The pseudo second order adsorption and intra particle diffusion model (a new combinations model) was developed successfully to predict the metal biosorption kinetics. 0.1M HCl was added to regenerate the biosorbents. The recovery of Pb, Cu and Cd achieved over 90% by pH adjustment. The reusability of the biomass and recovery efficiency studies were performed. Over 90% recovery metal from metal loaded biomass and 75-90 % of original adsorption capacity was obtained. Cell surface morphology was observed by SCM (Scanning Electron Microscopy) and the identity of metal ions was confirmed by EDS (Energy Dispersive Spectrometry). The studies showed that surface of metal loaded cell was vague and distorted and

damaged and confirmed the presence of metal adsorbates on the cell mass.

Kim et al. [8] have investigated biosorption capacity of bacterial strain CPB4 (*Bacillus Sp.*) using Metals Pb, Cu, Cd, Zn, Co, Cr, and Mn solution in terms of metal binding capacity as well as the distribution of heavy metals in cells. The biosorption experiments were performed using single or mixed (with 100 mg/l of each metal) for different time intervals, at different pH values (3.0, 4.0, 6.0 and 7.0) and at different temperature values (10, 20, 30, and 40⁰C) with 100±0.3 mg of dry weight of washed cells in 100 ml of desired metal solution using batch equilibrium technique. Highest heavy metal binding was observed with Pb followed by the order Pb > Cd > Cu > Ni > Co > Mn > Cr > Zn. The highest Pb uptake activity was around 90% after 40h. The optimum temperature was 20⁰-40⁰C and optimum pH was 5-7. Transmission Electron Microscopy TEM and EDS were used to determine the localization of adsorbed heavy metal in biosorbents. It was found that most uptake of heavy metal takes place on the cell wall and the cell membrane and this fraction is more than 90%. Further results showed that proteins of the cell components are important for heavy metal uptake.

Pagnanelli et al. [65] have developed a dynamic model for continuous biosorption studies of binary metal solutions on the *Sphaerotilus natans* free cells using UF/MF membrane reactor and validated by experimental data. Biosorption batch tests were performed on the biomass (1gm/l) at various pH values (range 3 to 5) using Cu, Cd and Pb. Biosorption tests were also performed in membrane reactor at 25⁰C with tangential velocity 0.3 ms⁻¹, trans membrane pressure 200k pa, total area 36 cm⁻², 100000 Da molecular weight cut off using a vessel of biomass suspension (1 gm/l) fed with a metal solution at constant pH. The model was obtained by combining the metal mass balance in the system. The equilibrium

mathematical models were derived from the Langmuir isotherm using adjustable parameters for membrane reactor which were simultaneous results of the membrane reactor equations 5, 6 and 7.

$$q_i = \frac{q_{max,i} b_i C_i}{1 + b_i C_i + b_j C_j} \quad \dots 5$$

$$q_i = \frac{q_{max,i} (b_i/\eta_i) C_i}{1 + (b_i/\eta_i) C_i + (b_j/\eta_j) C_j} \quad \dots 6$$

$$q_i = \frac{Q_{max} B_i C_i}{1 + B_i C_i + B_j C_j} \quad \dots 7$$

Where, $Q_{max,i}$, b_i and b_j are adjustable parameters and η_i = correction parameter

Data showed the inadequacy of Langmuir predictive model with multi metal system. Due to complex physical and chemical mechanisms that operate in metal biosorption in representing the effect of competition among different ionic species in solution. Consideration of non-ideal competition among adsorbents for multi component system in derivation of equilibrium model produced good simulation results with experimental values.

Freeze dried *Ralstonia sp.* and *Bacillus sp.* as biosorbents have been used to investigate the sorption efficiency for Cd, Cu and Pb ions in the solution by Chio et al. [2]. Different parameters evaluated for different amounts of biosorbents (0.01, 0.05, 0.1, 0.2, 0.5, 1.0, 2.0 and 3.0 gm/l of each metal solution), at different pH conditions (pH 1.0, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0, 10.0 and 12.0) and for different reaction time durations (10, 30, 60, 120, 180, 300 and 480 min) with initial concentration of metal 5.0 ml/l. *Bacillus sp.* has better removal efficiency of metal. The maximum removal efficiencies are found in approximately pH 3-5 range. High pH resulted in the precipitation of the material from the solution. The reaction time required to obtain removal efficiency more than 60% is 10

min, suggesting surface phenomenon. TEM analysis image of *Ralstonia sp.* And *Bacillus sp.* before and after metal sorption were performed, which showed the biosorption activity took place on the cell wall and cells were found to be in distorted conditions. Langmuir (Equation 8) and Freundlich isotherm (Equation 9) models were used to study the sorption behavior of the biosorbent, which are given as

$$q = \frac{q_m \cdot b \cdot C_e}{1 + b \cdot C_e} \quad \dots 8$$

$$q = kC_e^{1/n} \quad \dots 9$$

Where,

q= amount of metal sorbent at equilibrium (mg/g)

C_e=residual metal concentration equilibrium (mg/l)

q_m= amount of maximum adsorption

b=Langmuir isotherm constant

k=sorption coefficient

1/n= constant

The biosorption isotherm of metals followed Freundlich model better than Langmuir model as showed by r² value which is maximum in case of Cu (0.995) with biosorbent *Ralstonia sp.*

Biosorption studies of Cr metal have been performed using gram positive and gram negative bacterial biomass obtained from attenuated cells of *Bacillus subtilis* and *Pseudomonas aeruginosa* at different pH values, biomass concentration, time and initial metal concentrations [66]. The studies evaluated indivial and mix bacterial culture. Optimum pH was 3.0, temperature range was 24⁰C to 32⁰C, biomass concentration was 1mg/l and contact time was approximate 30 min. Initially with incase in metal concentration, the absorption efficiency increased till saturation of biosorbent. At low pH the cell surface binding sites compete either for proton or for metal and at higher pH the solubility of the metal complex

decreases. At higher temperature there is physical damage to the biosorbent. At high biomass concentration there is complex interaction like interference between the binding sites. Biomass of mixed culture showed maximum biosorption of Cr (85%) at pH 3.0, 32⁰C temperature, within 30 min and with biomass concentration of 1 mg/l. Biosorption equilibrium isotherm were expressed using Langmuir and Freundlich model.

Ramachandran et al. [29] have reported biosorption of heavy metal ions (Cd, Cu, Cr and Ni) from aqueous solution using *Nostoc calcicola* immobilized in silica coated calcium alginate and silica gel. Characterization of silica coated calcium alginate with SEM were performed, it showed cell free CAG without silica. Silica-coating possessed large pores and channels on the bead surface. Biosorbent containing CAG bead without silica coating possesses large cell clusters covered the bead surface. Silica coating of CAG bead revealed that the biosorbent is glued by homogeneous and dense mineral layer. It provided mechanical strength to the biosorbent as well as chemically stability and negligible swelling properties. The biological activity of cells was intact. The biosorption experiment with respective metal concentration, 100 mg/l for 2h at optimum pH, (Cd 7.0; Cu 5.0; Cr 5.0 and Ni 7.0) at 25⁺°C temperature and biomass concentration of Ca.1 mg/ml showed maximum metal uptake (mg/g) by silica coated calcium alginate immobilized *N. calcicola* beads. Metal desorption studies using copper solution and dil. HCl were performed. Silica coated CAG immobilized *N. calcicola* showed maximum copper uptake without significant loss of sorption properties after multiple sorption cycle.

Heavy metal resistant bacteria isolated from an electroplating industrial effluent sample were used for comparative assessment of heavy metal removal using industrial waste water [67]. Heavy metal adsorption was

studied using dead bacterial cells as well as immobilized bacterial cells and compared. The bacterial isolates studied were *Bacillus sp.*, *Pseudomonas sp.*, *Micrococcus sp.* The metals studied for the biosorption were Cu, Cd and Pb. The bacterial isolate had maximum adsorption at pH 6 and 7 depending on the bacteria isolated and type of the metal studied. The immobilized bacterial cells revealed greater adsorption capacity than that of dead bacterial cells due to strong mechanical strength and high rigidity. The maximum biosorption was 90.4 % of Cd by immobilized cells of *Pseudomonas species* [27].

Abd-alla et al. [9] have used freeze dried biomass of heavy metal resistant isolate of *Rhizobium leguminosarum* bv. *viciae* for investigation of biosorption efficiency for Cd and Co metal. The bacteria was tested for its heavy metal resistance by Agar plate and broth methods to different heavy metals (Ni^{+2} , Al^{+2} , Ba^{+2} , Zn^{+2} , Co^{+2} , Cd^{+2} and Hg^{+2}) and was found to have broad resistance. The *Rhizobium* isolated was identified by phenotypic and genotypic characterization. Effect of pH and contact time was studied on biosorption efficiency and found the maximum adsorption at pH 6.0 and contact time around 30 min for Cd and Co. The equilibrium distribution of metal ions between aqueous and solid phase was described using Langmuir and Freundlich isotherm. Langmuir isotherm model best described the experimental data with correlation coefficients ($r^2 > 0.98$) showing monolayer formation of the metal ion on the surface biomass. Maximum adsorption capacity by *Rhizobium* isolate biosorbent for Cd and Co biosorption are 135.3 and 167.5 mg/g as calculated from Langmuir adsorption isotherm at pH 6.0 and contact time 30 min at room temp.

Fan et al. [68] have investigated the heavy metal resistance and biosorption capacity of the two environmental isolates *Ochrobactrum*

intermedium LBr and *Cupriavidus metallidurans* CH34 for copper and Cr metals biosorption by dead and live biomass. The bacterial resistance was investigated by determination of minimum inhibitory concentration of Cu and Cr which showed higher MIC to Cu and Cr than other well known micro organisms. The maximum resistance was shown by *O. intermedium* LBR for Cr (MIC=900 ppm). Microbial susceptibility on heavy metals in logarithmic and stationary phase were determined and found that cells in stationary phase were less susceptible to heavy metals (Cu and Cr) than the cells in the logarithmic phase. Time course biosorption under environmental conditions was determined using 30 ml Tris-medium (TSM) containing 100 ppm of Cu^{2+} , Cr^{2+} for 400 min, using live biomass in stationary and logarithmic phase and dead biomass. Dead cells presented higher adsorption capacities for Cu and Cr than in the growth phases, which were attributed to an increasing release and exposure of intercellular binding sites caused by the heat treatment. Optimum pH for maximum heavy metal removal capacity for *C. metallidurans* was 6.0 and for *O. intermedium* was 7.0 for Cr and Cu. Optimum temperature conditions were 37⁰C or 27⁰C depending on the bacterium and metal type. Adsorption capacities were modeled using Langmuir model and it was maximum for *C. metallidurans* CH34 (86.78 mg/g). The competitive biosorptions assessed for Cu and Cr under environment and optimum conditions and found that percentage of Cu removal is always higher than that of Cr. SEM and EDS analysis and FTIR performed to study biosorption mechanism. It was found that functional groups responsible for the biosorption are C-H, C=O, COOH, NH₂ and OH.

Cells of a heavy metal tolerant bacterium *Micrococcus luteus* DE2008, had been used for the study of biosorption of Pb and Cr by Puyen et al. [69]. The bacteria was exposed to different concentrations of Pb and Cu

solutions at 27⁰C for 12h at pH 6.5-7 to study the effect on bacteria which showed that Pb do not have any effect on the biomass while minimum metal concentration of Cu affecting the biomass is 0.1 mM. Bacterial cells produced extra cellular polymeric substances of the amount 8.596-74.78 ($\mu\text{ggEPS}^{-1}\text{gDW}^{-1}$) which contained protein (2.710-10.967), uronic acid (0.109-2.616) and carbohydrate (4.612-51.165) expressed as($\mu\text{ggEPSgDW}^{-1}$) with varying concentrations of heavy metals Pb and Cu (0-1.5mM). Biosorption (removal capacity) for Pb and Cu by bacterial cells at pH 6.5 to 7.0 at 27⁰C for 12 h with different metal concentrations (0, 0.5, 1.0 and 1.5 mM) was evaluated and it was found that specific removal capacity is 408 m/g for Cu and 1965 m/g Pb. Removal capacity of the organism to Pb is greater than that of copper.

Fungi as source of biosorbent

Fungal biosorbent (by products of fermentation industries) have been used for the study of heavy metal biosorption such as Ni, Zn, Cd, Pb by Fourest et al. [70]. Biomass obtained from fungi *R. arrhizus*, *P. chrysogenium*, *M. mieiheii* and *A. niger* was used for comparison of sorption capacity. Biosorption experiment using dead biomass of *R. arihizus* with no pH control for the 5h, using 300mg fungal powder per 100 ml solution containing 10-600 mg/l of metal produced sorption isotherm which followed the typical Langmuir adsorption Pattern given by equation 10.

$$C_{eq}/q = K_d/Q + C_{eq}/Q \quad \dots 10$$

Where,

C_{eq} =residual metal concentration

Q =maximum adsorption capacity

q =metal uptake

K_d =dissociation constant

Adsorption capacity (Q) is the amount of metal per gram of biomass corresponding to the saturation of adsorption sites

K_d (dissociation constant) is the metal concentration corresponding to half saturation of biosorbent in these experimental conditions, also indicates the affinity ($K_a=1/K_d$) of metal ion for corresponding biomass uptake capacity from the above experiment derived from Langmuir isotherm and can be given as table 1.

Table I.1

Uptake capacity	Nickel	Zinc	Cadmium	Lead
Q (mg/g)	18.7	13.5	26.8	55.6
Q (mmol/g)	0.32	0.21	0.24	0.27

Reduction in biomass concentration at a given metal concentration increased metal uptake per gram biosorbent till the saturation of the later. The biosorption at different pH showed that Optimal adsorption was at pH 7.0 for Ni and Zn, pH 5.0 for Pb. Comparison of biosorption capacities of various fungal biosorbents showed that maximum adsorption of Zn is on *R. arrhizus* dead biomass due to higher chitin and chitosan cell wall contents.

Szilva et al. [71] have prepared heavy metals biosorbent by immobilization of cell wall envelopes obtained from yeast cell *Saccharomyces cerevisiae* for study of sorption capacity for metals Cd, Cu and Ag. Cell envelopes were immobilized using cross linking agents organic or siliceous (prepolymers synthesized via transesterification and hydrolysis from tetraethoxysilane (TEOS) and methanol. Epichlorohydrin was used as organic cross linking agent. Biosorption capacity of

biosorbents with silica and cross-linked epichlorohydrin were compared. The intensity of biosorbent was 2-3 times higher for biosorbent prepared by esterification of TEOS than biosorbent cross linked with epichlorohydrin. Both biosorbents showed equal absorption capacities. Biosorption experiments were performed using batch experiment as well as by column experiment. Silica provided porous matrix to the biosorbent as revealed by microscopy, it also provided stability and mechanical strength.

Delgado et al. [72] have studied biosorption capacity of *Fusarium flocciferum* using Cu, Cd and Ni. Batch experiments were performed and metal concentration remaining in the solution was determined by total reflection X-ray fluorescence using equation 11.

$$Q = \frac{C_i - C}{m_b} V \quad \dots 11$$

Where,

Q=metal uptake (mg metal/100 mg biosorbent)

C_i=initial metal concentration (mg /l)

m_b=quantity of biosorbent (mg)

V=suspension volume (ml)

Optimum pH for maximum uptake of Cu was 5-9 ± 0.1 and for Cd and Ni was in the pH range of 7.5 to 8.0. At high pH, metal hydroxide precipitation was observed and at lower pH there is competition between protons and metal ions for the same sites. Langmuir model was better fit to study biosorption phenomena of Cd and Ni with r² 0.973 and 0.903 respectively. Maximum uptake of Ni and Cd at the optimum pH estimated was 5.2 ±1.8 and 19.2±7.8 (expressed as mg metal per 100 mg biosorbents). In case of Cu, split Langmuir model (considering multiple sites on biosorbent of different affinity for metal) was used to describe biosorption (r²=0.928) at pH 4.5. With change in pH mechanism involved

was found to be different. Optimum metal biomass ratio was observed to be 0.5 to 1 for Cu removal and contact time to achieve equilibrium was 1 to 2 min. Old culture fungus showed less biosorption capacity.

Sag et al. [73] have studied mono and multi component biosorption of Pb Ni and Cu using *Rhizopus arrhizus* in a Continuous Flow Stirred Tank Contactor (CFST). Langmuir equation given by equation 12 was used to study the biosorption and further mathematical models were developed for CFST of 1l volume using mass balance for liquid and solid phase to generate concentration curve to compare experimental results.

$$q_{eq} = \frac{Q_m C_{eq}}{C_{eq} + K_d} \quad \dots 12$$

For multi component adsorption of Pb(II), Ni(II) and Cu(II) biosorption on *R. arrhizus* in CFST single metal situation at pH 5.0 temperature 25⁰C biomass concentration 1gm/l showed adsorption equilibrium time 5 to 60 min for Pb and 30-120 min for Cu and Ni system, optimum flow rate determined was 3 ml min⁻¹. The relative capacity reported was in order Pb(II)>Ni(II)>Cu(II)> at milder concentration. The simulated concentration curves were plotted and predicted values were in good agreement with experimentally measured values. The simulation biosorption of Pb(II) and Cu (II) and Pb (II) and Ni(II) from the binary metal mixture by *R. arrhizus* using CFST showed that increasing concentration of other metal ion inhibits the equilibrium uptake of competing metal ion. Pb is selectively adsorbed from the binary solution. Ni and Pb showed synergistic effect towards each other. Simultaneous biosorption of Pb (II), Cu(II) and Ni(II) from the ternary metal mixture by *R. arrhizus* in CFST showed that interactive effects of metal ions are synergistic and lead to high total metal ion quantities adsorbed as compared to than that of mono and binary systems. The relative capacity were found Pb(II) >Ni (II)>Cu(II).

Biosorption parameters are optimized using *phanerochaete chrysosporium* derived biosorbent for the biosorption studies of Cu, Pb and Cd by Gopal et al. [74]. Experiment with different metal ion concentrations (25-300mg/l) at 32⁰C and for 30 min showed that Cu and Cd removal decrease with increase in concentration while that of Pb showed marginal increase. Freundlich and Langmuir isotherm described well the biosorption results. Order of removal indicated was as Pb> Cu> Cd>Pd. Pb adsorption capacity was highest (90 mg/g) followed by Cu (43 mg/g) and Cd (17 mg/g). Various parameters for the biosorption Viz; initial metal ion concentration, biosorbent dose and pH and their interaction on the biosorption process had been optimized by statistical analysis of Full Factorial Central Composite Design of the experiment and found that effect of metal ion concentration was highly significant (p=0.001, 0.0034 and 0.001 for Cd, Cu and Pb respectively), biomass concentration was highly significant in case of Cd and effect of pH was least significant and other variables were not significant. The desorption of metals with HCl was studied and found that Cd was easily desorbed (34.7 %) than other metals (Cu=17 % and Pb 15.5%), Table I.2.

Table I.2 Optimum values of variables obtained by solving regression equation

Parameters	Pb	Cu	Cd
Initial metal ion concentration (ppm)	85.24	41.27	7.43
Biosorbent dose (gm)	0.35	0.75	1.18
pH	6.34	4.69	5.32
Metal removal (%)	92.4	76.5	36.6

Trametes vaersicolor mycelia, immobilized in carboxymethyl cellulose (CMC beads), a natural polymeric matrix, live and heat inactive forms

were used for biosorption of Cu, Pb and Zn metals by Bayramoglu et al. [53]. Contact time to achieve biosorption equilibrium was 30 min for CMC beads. Optimum pH reported was in range of 4.0-6.0, biosorption was found to be temperature independent over the temperature range 15-45⁰C. The amount of metal adsorbed (per unit mass of biosorbent) increased with increasing initial metal concentration. Metal ions immobilized heat inactivated fungus showed higher biosorption capacity than the immobilized live fungus. Biosorption capacities in reference to metals were in order Cu>Zn>Pb. Desorption of metals was obtained by using HCl solution and more than 95% of adsorbed metal ions were desorbed, Table I.3.

Table I.3 Maximum biosorption capacities (competitive biosorption capacity) in terms of mmol/g of dry biosorbent

Biosorbent	Cu⁺²	Pb⁺²	Zn⁺²
Immobilized live fungus	1.51(0.67)	0.85(0.36)	1.33(0.48)
Immobilized heat inactivated fungus	1.84(0.75)	1.11(0.43)	1.67(0.59)

Different forms of *Phanerochaete chrysosporium* Viz; NaOH treated, heat-inactivated and active have been used for comparative studies of heavy metals [Cd(II), Hg(II)] biosorption capacity [75]. 60 min were required to reach plateau values of biosorption capacities. At pH 6.0 maximum adsorption of Cd and Hg was obtained. Approximate 450 mg/l of initial metal ion concentration was found to be optimum for maximum biosorption capacity Table 4. HCl solution was used to recover adsorbed metal (up to 98 %) to regenerate biosorbent.

Table I.4

Biosorbent	Cd(II)		Hg(II)	
	(Mg/g)	(mmol/gm)	(Mg/g)	(mmol/gm)
NaoH treated	148.37	1.32	224.67	1.12
Metal inactivated	78.68	0.70	122.37	0.61
Active	68.56	0.61	88.26	0.44

Polysaccharides extracted from culture of *Cunninghamella elegans* (IFM 46109), characterized as chitin and its deacetylated derivative, chitosan have been used to study they biosorpton of heavy metals Fe, Pb and Cu by Franco et al. [32]. Optimum pH for maximum metal uptake was 4.0, optimum initial metal ion concentration was 1-2 mmol, the polysaccharide concentration was 1 % (w/v), temperature was 25 °C and reaction time was 80h Table I.5. Metal recovery was calculated using equation 13.

$$q = \frac{C_i - C_f}{m} \quad \dots 13$$

Where,

q= metal uptake

C_i= initial metal concentration

C_f= final metal concentration

m = polysaccharide concentration

Table I.5 Maximum heavy metal recovery (%) by chitin and chitosan from *C. elegans* (IFM46109)

Biosorbent	Fe ⁺²	Pb ⁺²	Cu ⁺²
Chitin	56.0 %	45.0 %	50.0 %
Chitosan	54.8 %	52.0 %	75.0 %

Teskova et al. [76] have reported the role of different functional groups involved in biosorption of heavy metals Cu and Co using *Penicillium cyclopium* dried and powdered as biosorbents. Role of functional groups Viz; carboxylic, amines, phosphate, hydroxyl, lipid was investigated by the chemical treatment of biosorbent via esterification (for carboxylic groups, phosphate groups, hydroxyl groups), methylation (for amines) and extraction (for lipid fraction) and by comparing IR spectra of raw and chemically treated biosorbent and comparing change in biosorption of metals. It was found that biosorbent contains amine, hydroxyl and amide functional groups and most considerable is high content of hydroxyl group. Maximum inhibition in uptake of Cu was observed in hydroxyl modification (55 % inhibition). Modification of amino group lead to 40 % inhibition of Cu uptake. Strong inhibition occurred when hydroxyl group were acetylated and significant inhibition occurred in modification of amino group. Phosphate groups and lipids do not play any role in metal uptake. K, Mg and Ca ions are released non-stoichiometrically when Cu and Co were adsorbed showing ion exchange mechanism.

Dried biomass of yeast was investigated for the biosorption studies of Cr. [77]. Optimum removal efficiency was obtained at pH 4.0. Metal uptake increased with increasing biomass concentration upto 10 gm biomass per/l due to increase in metal binding sites. Optimum percentage of removal of metal was obtained at contact time 45 min. 10-15 mg/l of metal concentration required about 5 min to complete biosorption while it is 32 to 60 min for higher initial metal concentration. Experiment at different initial metal ion concentrations at pH 4.0, 185 rpm, 10 gm/l of biosorbent dose were used to study the adsorption isotherm and it was found that Freundlich isotherm model had better fit to the absorption data ($r^2=0.945$) than that of Langmuir model ($r^2=0.906$). q_{\max} determined from

the slope of the plot was 90.90 mg/g. Spontaneity of the biosorption process was shown by negative value of change in free energy and large positive value of the entropy change showed increased randomness. Column biosorption studies were also performed. The adsorbent was regenerated using 0.1 M tris-HCL buffer (pH 7.8).

Biomass of *Rhizopus sp.* immobilized on various textiles has been evaluated for biosorption of heavy metal Cu from aqueous medium [11].

Various fabrics used for immobilization were-

1. Polypropylene-based knitted single jersey
2. Polypropylene-based knitted single jersey
3. Polypropylene-based knitted single jersey
4. Polyamide-based weave Nm 14;12 threads /cm
5. Polyester-based satin weave ;12 thread/cm
6. Polyester-based plain weave; 12 thread/cm
7. Polyester-based honeycomb weave;12 thread/cm
8. Wool-based plain weave;12 thread /cm
9. Jute –based weft-dominated satin weave;12 thread/cm
10. Jute-based honeycomb weave;12 thread/cm

Biosorption experiment of various biosorbents (1 to 10) at 20⁰C, pH 5.0 with 20 mg/l of Cu concentration at different time intervals 0 to 150 min showed maximum metal uptake by biosorbent number 5 (14.8 mg/gm as revealed by pseudo second order rate expression at equilibrium). Attachment and adequate immobilization of biomass on the media were found to be deciding factors of the biosorption capacity. Higher initial metal ion concentration slightly increased in mass biosorbed. Immobilized biomass can lead to about 98% removal of the metal.

Saccharomyces cerevisiae characterized by morphological identification, physiological characterization and molecular characterization was dried

at 60⁰C for 24h to obtain the biosorbent and evaluated for its biosorption properties for Cr⁺², Cd⁺², Pb⁺², Cu⁺², Zn⁺² and Ni⁺² metal solutions[38]. Biosorption experiment at 25⁰C for 2h with varying metal concentrations (50, 100, 150 and 200 mg/l) and 1 gm/l of biomass dose using different metal solutions showed maximum biosorption 67 % (as calculated using equation 15) of Cd at 50 mg/l of metal concentration. The order of metal removal was found as- Cd(67%) > Pb(61%) > Ni(64%) > Cr(63%) > Cu(57%) > Zn(53%).

$$\% \text{ Removal} = \frac{\text{Heavy metal ions removed (mg)}}{\text{Heavy metal ions available (mg)}} \times 100 \quad \dots 15$$

Langmuir model was better fit ($r^2=0.9979$) than Freundlich model isotherm ($r^2=0.8170$). SEM analysis showed altered morphology and uniformly bound metal on biosorbent (*S. cerevisiae*). Optimum pH for biosorption was in the range 4.0 to 5.0, temperature (optimum) is 20⁰ C to 30⁰C and 60 to 90 min contact time period gave high metal biosorption. Percentage of biosorption decreased with increase in number of metals present in the solution.

Multi-input and single output sigmoid model has been developed by Ozen et al. [78] for the biosorption of Ni cations by *Schizosaccharomyces pombe* derived biosorbent. Biosorption experiments had been performed at various temperature (25, 30, 35, 50⁰C) and at different pH values (4.0, 5.0, 6.0) and equilibrium values metal uptake were reported in terms of mg/gm dry weight (q_e) (Equation 16).

$$q_e = \frac{(C_i - C_e)V}{m} \quad \dots 16$$

Freundlich Langmuir and combined Langmuir–Freundlich isotherm (SIPS) were used to study the biosorbent. Freundlich and sips showed better fits. Model developed was validated by studying chi-square test

and uncertainty and sensitivity analysis. The model successfully correlated ($r^2 > 0.94$).

Biosorbent of pretreated biomass of *Saccharomices cerevisae* have been utilized to study the role of amino acids involved in heavy metal biosorption [79]. Experiments were performed using 25 mg biomass (dry weight) in 50 ml of metal ion solution (1ml/l), for 120 min at pH value 3.5, 5.0 and 6.0. HPLC chromatography and FTIR spectroscopy were performed to identify the amino acids. Amino acid involved in biosorption were found to be Arg, met, Ala, Gly and Thero. Appropriate pH is 6.0. Amino acids are involved in complex formation by coordinating with heavy metals Cu, Zn and Pb.

Strontium metal biosorption by *Saccharomices cerevisae* under batch culture conditions with varying initial metal concentration (0.5, 100, 200, 400, 500, 800 and 1000 mg/l) for 2 to 40 hr showed maximum bio removal efficiency (equation 17) upto 96% in 40 hr [80].

$$R = \frac{C_0 - C_t}{C_0} \times 100 \quad \dots 17$$

Where,

C_0 (mg L⁻¹) is the initial concentration of strontium

C_t (mg L⁻¹) is concentration of the strontium in solution at the present culture time.

Initial adsorption on cell wall was found more than 90 % at high initial metal ion concentration and decreased with time due to bio accumulation by bacterial cell. Program gradient descent biosorption in three cycles showed removal upto \approx 100 % and the volume and weight of the biosorption and adsorbent reduced by ashing processing $>$ 1000 times and \approx 40 times respectively leading to $>$ 500 times of metal enriched ash. The experiment showed that cell wall adsorption was approximately 90

%, and cytoplasmic bio accumulation was about 10 %. The methodology has been proposed for radioactive waste disposal.

Biosorbent material of *Sargassum* has been used to study the biosorption behavior of two metal system (Cd and Fe) [81]. Sorption isotherm curve were obtained by biosorption experiment using 2.0 gm/L (biomass concentration) with varying initial metal concentration (0.1 to 10 mM/ 50 ml), at pH 4.5 at room temperature for 3h the same experiment was performed except in place of a single metal the solution containing Cd and Fe at varying concentration (0.1-10 mM) was used to obtain three dimensional sorption isotherm surface. For single metal system Langmuir type isotherm model was followed (q_{\max} =for Cd =1.041 mmol/g and for Fe =0.99mmol/g). Cd inhibited very strongly the uptake of Fe metal (1.5 mmol Cd lead to 55% reduction in Fe uptake while for 50 % reduction of Cd uptake required 4.5 mmol of Fe).

Role of carboxylic and sulfonate groups present in dry biomass of *Sargassum fluitans* has been investigated in the biosorption of Cd by Fourest and Volesky [82]. Strong and weak acidic groups present in biomass were 0.25 ± 0.05 mmol/g and 2.0 mmol/g respectively as determined by potentiometric and conductometric titration in modified biomass (by treatment with methanolic HCl propylene oxide). Chemical analysis showed 0.275 mmol of sulfonate group per gram of biomass. Maximum biosorption obtained 0.91 mmol/g and 1.06 mmol/g for Cd and Pb respectively at pH 4.5 at room temperature for overnight, with initial metal concentration 2.0 mmol. Uptake of Cd and Pb reduced about 15 % in methanol treated biomass while reduction was 80% (for Pb) and 95 % (for Pb). Uptake decreased with propylene oxide esterified biomass. FTIR spectroscopy of protonated and metal biosorbed biosorbent showed that C=O, C-O were involved in biosorption. Sulfonate groups were less involved in biosorption than carboxylic functionality

Biosorption studies of (Ca, Zn, Cd, Cu and Pb) by various Algae has been investigated by Fourest et al. [83] on Alginate (family of linear poly saccharides containing 1,4- linked β -D mannuronic (M) and α -L guluronic (G) acid residues). Content had been determined in raw biomass and protonated biomass of *Sargassum fluitans*, *Ascophyllum nodosum*, *Fucus vesiculosus*, *Laminaria japonica*. It was highest in protonated biomass (0.44, 0.40, 0.36 and 0.56 g/g ($\pm 10\%$)). Heavy metal binding was according to the content of carboxylic groups (Alginate content). Maximum biosorption obtained at pH 4.5 by *S. fluitans*. Also metal binding was directly related to the electronegativity and was in order- Pb > Cu > Zn \geq Ca.

Immobilized biomass of non living algae *Undaria pinnatifida* using Ca-alginate method (Ca-ALG) Ba –alginate method (Ba- ALG), polyethylene glycol method (PEG) and Carrageenan method (CARR) was evaluated for metal uptake of Cu at different initial Cu concentration (25, 50, 100, 200, 300 and 500 mg/l, using varying biomass amount (0.15,0.3 and 0.6 for Ca–ALG ,Ba-ALG, and PEG, 0.375, 0.75 and 1.5 g of biomass for (ARR) in 500 ml solution, at different pH values (2, 3, 4, 5 and 6) [84]. Maximum adsorption was obtained at 500 mg Cu /L, optimum contact time 2h, maximum removal efficiency 0.6 gm of biosorbent, optimum pH 4.0 to 6.0. Langmuir isotherm best described the biosorption. Maximum Cu uptake showed by Ca- alginate biomass. Acidic treatment regenerated the biosorbent.

Biosorption of Ni, Cu and Cd metals on pretreated biomass of *Durvillaea potatorum* has been described well at varying pH values (pH 3, 5 and 6 for Ni and pH 3,4 and 5 for Cu and Cd) by modified Langmuir equation (correlation coefficient of about 0.95 or higher). Maximum adsorption capacity (mmol/g) was 1.13 at pH 6.0 for Ni, 1.40 at pH 5.0 for Cu and

1.18 at pH 5.0 for Cd. [85]. Different functional groups were considered to be involved in biosorption of different metals.

With increase in pH from 2.5 to 4.5 increased the binding of Cu by protonated biomass of *Sargassum*. Increase in Cu concentration increased the binding of Cu on biomass. Carboxyl and sulfate groups are involved in metal. [86] Binding with increase in ionic strength decrease the metal binding ion exchange processes involve in metal binding multi component sorption isotherm is developed to predict the metal binding. Cations exchange such as Pb^{+2} vs Ca^{+2} vs Cu^{+2} and Pb^{+2} vs Cu^{+2} was observed in the study of biosorption by Ca loaded *Laminaria japonica* biomass in continuous process using chromatographic column. 1.22 mm/g of Cu and 1.08 mm/g of Pb was observed as metal uptake in single metal system within 60 h, initial metal concentration of solution was used 0.48 mM/L for each metal. Biomass showed strong affinity towards Pb. pH =4.5, Column length (packing)=27 cm, ID =2.5 cm and flow rate of solution =2 cm/min [37].

Calcium loaded *Sargassum fluitans* biomass showed 78.4%, 82.7%, 85.1%, 89.8% and 51.2 % reduction in uptake of Pb, Cu, Zn, Cd and Cr in presence of Al ion of 1mM in the system, at pH 4.5, final equilibrium concentration of metals were 1mM. Experiment was performed for 30h with 100 mg of biomass in 100 ml of metal bearing solution. Multicomponent Langmuir Isotherm described the biosorption phenomena of two metal system with correlation coefficient > 0.81 [87].

A mathematical model based on thermodynamic approach has been developed to describe the equilibrium behavior of biosorption of Cd, Cu, Pb and Zn by living and heat treated biomass of *Oocystis sp.* and *chlorococcum sp.* at fixed pH. The model takes into consideration the equilibrium concentration of metal, metal sorption per unit Algal

biomass, concentration of algal biomass, and initial metal concentration [88].

Biosorption of Cu, Pb and Zn in single metal and mixed metal system by non living dried biomass of *U. pinnatifida*, *H. fusiformis* and *S. fulvellum* was investigated by Lee et al. [34], Table I.6.

Table I.6 Metal removal efficiency (%)

Biomass	Cu	Zn	Pb	Cr
<i>U. pinnatifida</i>	46%	41%	70%	50%
<i>H. fusiformis</i>	44%	39%	64%	41%
<i>S. fulvellum</i>	22%	23%	56%	36%

Optimum pH range was 4.0 to 5.3 (Cu), 4.0 to 6.0 (Pb) and 3.0 to 6.0 (Zn) for maximum removal. Maximum metal uptake value was 2.6 meq /g in pH range 5.3 -4.4 for Pb by *U. pinnatifida*

In mixed metal system the sum of each metal ion uptake was higher than that in single metal system. The maximum biosorption (mmol) was 4.47 and 4.06 for Cr and Cu respectively by pretreated biomass of spirogyra at pH 4.0, initial metal concentration 4.5 Mm, 5 gm/50 ml of pretreated biomass concentration, at room temperature (27-28⁰C) for 36h [15]. Maximum percentage adsorption reported is 99.93 % (for Cr) and 90.22 % (for Cu). Cr ion presence showed antagonistic effect on the adsorption of Cu ions. Light metals Ka and Na presence has less significant effect on biosorption of Cu and Cr ions .

Sheng et al. [89] have used biomass of *Sargassum sp.* for study of Pb, Cu and Cd biosorption at different pH values (5.0, 4.0, 3.0) for 6h, at room temperature (22±1⁰C), biomass concentration was (0.1g) per 100 ml using various concentration values of metal (Equation 18)

$$q \left(\frac{\text{mmol}}{\text{g}} \right) = \frac{(C_i - C_f)}{w} \quad \dots 18$$

Where,

q=metal uptake

V=volume of solution

C_i=initial metal concentration

C_f=final metal concentration

W=amount of biomass

3h were required to obtain the equilibrium. Langmuir model fits best, $r^2=0.98$ at pH 5.0 for Pb $q_{\text{max}}=1.16$, $r^2=0.99$ $q_{\text{max}}=1.03$ at pH 3.0 for Cu and $r^2=0.98$ $q_{\text{max}}=0.80$ at pH 4.0 for Cd. Electronegativity and stability constant determined the biosorption. The uptake capacity was as Pb>Cu>Cd. Antagonistic effect was observed in multiple metal biosorption experiment. Pb exerted most inhibitory effect on biosorption.

Biosorption of Pb, Cd, Mn, Cu and Cr by brown seaweeds biosorbents (*Hizikia fusiformis*, *Laminaria japonica* and *Undaria pinnatifida*) showed biosorption of heavy metals in range 95.7 to 47.8 %. Maximum biosorption is reported by *H. fusiformis* for Pb i.e. 95.7 % pH 4 or 6 was optimum for maximum biosorption. Maximum biosorption was obtained within 30 min. Langmuir and Freundlich isotherm models described the biosorption with r^2 values 0.93 to 0.98 respectively [90].

Biosorption studies of Pb, Cd, Co by green Algal waste biomass (*U. lactuca*) showed maximum biosorption at pH 5.0, contact time 30 min and at low temperature. Langmuir model was followed to describe biosorption with r^2 values more than 0.99. Maximum biosorption capacity evaluated was 0.36 for Pb. Biosorption capacity order was Pb(II) > Cd(II) > Co(II) [91].

Heavy metals (Ni, Cd and Pb) biosorption by Ca treated *Entemorpha linza* was studied by Sibel Yalcin [92]. Functional groups involved in

biosorption was carboxyl group. Free amino acids were also found to be involved in biosorption. pH 5.0 to 5.5 gave maximum biosorption. 5 to 10 min were required to reach maximum biosorption. Optimum biosorption was obtained at 0.1 gm biomass Dose. Increase in biomass dose resulted in increased biosorption efficiency, while decrease in biosorption capacity. Best fit equilibrium model was Langmuir isotherm. Biosorption capacity was 41.44mg/g (Ni), 107.09 mg/g (Cd) and 197.78 mg/g (Pb). Biosorbent was regenerated using HNO₃.

Biosorption of Cu, Cd and Pb were studied by Tran et al [93] by Gelatinous colonies collected from rice fields. Optimum pH was 4.0 for Cu, 5.0 for Cd and Pb. 30 to 60 min were required to obtain biosorption equilibrium. Temperature range 30⁰ to 60⁰C did not affect biosorption. Biosorbent dose 0.2 gm/L resulted biosorption efficiency 42.31, 63.56 and 31.82 % while biosorption capacity was 11.17, 16.08, and 80.6 mg/g for Cu²⁺, Cd²⁺ and Pb²⁺ respectively while at the Dose 0.5 gm/L, efficiency increased to 64.85, 82.52 and 61.94 % while capacity decreased to 7.03, 8.45 and 63.63 mg/g for Cu, Cd, Pb respectively. Maximum adsorption was 27.78 (Cu), 28.57 (Cd), and 76.92 (Pb) in mg/g. Both Langmuir and Freundlich adsorption isotherm models described the biosorption well. Desorption was achieved using HNO₃.

Heavy metals (Pb, Cu, Fe and Zn) biosorption was studied onto dried biomass of (*Eucheuma denticulatum*) [94]. Biosorption capacity (mg/g) was calculated using equation 19.

$$q_e = \frac{(C_0 - C_e)V}{m} \quad \dots 19$$

and biosorption efficiency was calculated using equation 20.

$$R (\%) = \frac{(C_0 - C_e)100}{C_0} \quad \dots 20$$

Where

C_0 = initial metal concentration (mg/L)

C_e =equilibrium metal concentration (mg/L)

V =volume of metal solution (L)

m =mass of dry biosorbent (g)

pH 5.0 was optimum pH for maximum biosorption efficiency. Contact time 120 min was required to attain saturation. Increase in initial concentration of metal from 25-200 mg/L decreased biosorption efficiency of metal uptake while increased biosorption capacity. Increase in temperature from 298 to 323⁰ K increased in % removal of metal. Langmuir, Freundlich, Temkin, D-R isotherm models were used to study the biosorption. Langmuir model fit well with r^2 more than 0.99. competitive adsorption showed the order as Pb^{2+} >, Cu^{2+} >, Fe^{2+} >, Zn^{2+} (92.59, 92.33, 73.80, 68.08 % removal respectively). Pseudo second order kinetics model was followed well. Functional groups amine, aliphatic, carboxylate, carboxyl, sulfonate and ether are involved in biosorption.

Biomass of *Ludwigia stolonifera* (dried plant material has been used for the heavy metals (Cd and Ni) biosorption [95]. Biosorption capacity for the different plant material (Root, floating root and leaves for Cd was 43, 93, 128 mg/g) dry weight material. Metal ion exchange mechanism against Ca, Mg, K and Na, was found taking place. Pectin content was 5±0.97 % 10±1.5 % 8±1.5 % in roots, floating roots and leaves biomass respectively.

Olive pomace (Agricultural waste) biosorption has been used for removal of heavy metals Cu, Cd, Pb [96]. Potentiometric and IR studies showed that carboxylic and phenolic functional groups are associated with metal binding. Metal uptake increased with increase in pH from 3-5. q_{max} - maximum absorption (Langmuir) was 0.062 for Cd, 0.67 for Cu and 0.076 mmol/g for Pb respectively at pH 5.0.

Coconut fiber and sawdust biomass has been used to study the biosorption of Hg, As and Pb [97]. The maximum amount adsorbed by unmodified sawdust was 940.0 mg/g for As (pH 12), 933.0 mg/g for Pb (pH 2) and 739.0 for Hg (pH 12), by thiolated sawdust maximum amount adsorbed was 528.0 for As (pH 12), 487.0 for Pb (pH 12) and 612.0 for Hg (pH 12), by carboxy methylated sawdust maximum amount adsorbed was 407.9 for As (pH 2) 376.6 for Pb (pH 2) 394.2 for Hg (pH 2) and by unmodified coconut fiber maximum amount adsorbed was 986.0 for As (pH 2), 679.5 for Pb (pH 4) and 975.0 for Hg (pH 12.0) by thiolated coconut fiber maximum amount adsorbed was 975.0 for As (pH 12), 978.0 for Pb (pH 10) and 981.0 for Hg (pH 12) and by carboxy methylated coconut fiber maximum amount adsorbed was 953.7 for As (pH 12), 677.3 for Pb (pH 2) and 965.5 for Hg (pH 12) the values of metal adsorbed are in terms of mg/g.

Sour sop seeds biosorbent has been used for the removal of heavy metal ions (Cu, Ni, Zn and Pb) [43]. 120 min contact time gave highest removal %. Increase in rate of removal occurred in increase of biosorbent dose. pH 5 to 7 gave maximum percentage removal. The highest removal percentage was 77.6 for Cu, 68.5 for Ni, 56.4 for Zn, 40.6 for Pb.

Sorption potential of modified and unmodified short hemp fibers was investigated for heavy metals (Pb, Cd and Zn) removal [44]. pH 5.5 and contact time 10 to 30 min was found optimum for maximum metal removal. Initial concentration of metal ion change from 0.05-0.2 mmol/L increased the amount sorbed of Cd, Pb and Zn from 0.019 to 0.056, 0.020 to 0.078 and 0.019 to 0.060 mmol/g respectively. Maximum uptake capacity was 0.078 mmol/g for all the 3 metal ions (Pb, Cd, and Zn). In presence of ternary mixture the biosorption capacities reported are 0.074, 0.075 and 0.035 mmol/g for Pb, Cd and Zn respectively.

Cd and Co removal using *Nasturtium officinale* biosorbent from aqueous solution was investigated by Okumus et al [98]. Freundlich isotherm model best described the adsorption equilibrium data with r^2 values more than 0.99. Maximum biosorbent capacity, according to Freundlich isotherm were 2.23 mg/g for both metal ions (Cd and Co).

Cd ion removal capacity of *Cassia siamea* bark biosorbent was investigated by John et al. [99]. Increase in pH from 2 to 7 increased metal adsorption upto 6.55 mg/g. A linear increase in Cd biosorption capacity was reported from 2.48 to 9.81 mg/g with increase in initial metal concentration 52 to 200 mg/L. 120 min contact time was required to attain equilibrium. Freundlich isotherm model better described biosorption with r^2 values 0.995. Biosorption kinetics was described by pseudo second order kinetics model.

Rapeseed waste obtained from biodiesel production have been used as biosorbent for heavy metal ions (Cu and Cd) removal [100]. pH 4.5 to 5.0 was optimum for maximum removal. With increase in initial metal ion concentration from 21.38 (Cu) and 22.61 (Cd) mg/L to 231 (Cu) and 271 (Cd) increased removal capacity from 2.10 (Cu) and 1.89 (Cd) mg/g to 17 (Cu) and 19.36 (Cd) mg/g while decreased biosorption percentage from 93 (Cu) and 95.79 (Cd) % to 59.30 (Cu) and 62 (Cd) % removal respectively. Percentage removal of metals increased from 49 to 91 for Cu and from 61 to 97 for Cd with increase in biosorbent dose from 5 to 30 g/L while biosorption capacity decreased down to 1.60 mg/g for Cu. Langmuir isotherm model best described the biosorption with r^2 values more than 0.98. With increase in temperature increased the biosorption. Pseudo second order kinetics was followed.

Coconut shell powder was investigated as an adsorbent for removal of Cu ions from aqueous solution [101]. Up to 96 % metal removal was obtained at pH 9.0. pH 7.0 was found optimum. Decrease in particle size

of biosorbent increased biosorption. Ion exchange mechanism was found taking place.

Heavy metal ions (Cr) biosorption was studied using modified waste bark material as biosorbent by Kumar et al [16]. Increase in absorbent concentration from 0.2 gm to 1 gm per 100 ml increased percentage removal of Cr from 52 to more than 66%. pH 5.0 was optimum pH for maximum adsorption. With increase in temperature from 32 to 60 °C increased the biosorption. Percentage removal decreased from 68 % to 52 % with increase in initial metal concentration from 20 to 100 mg/L. 45 min contact time was required to attain the equilibrium.

The enzymatic hydrolysis lignin grafted glycine (EHL-GLY) and cystine (EHL-CYS) copolymers have been used for study of biosorbent of heavy metals Cu and Co [102]. FTIR showed presence of O-H, N-H, C-H, C-O, C-N, C=O, C-S and S-S binding functionalities. pH 6.0 showed maximum biosorption capacity. 50°C temperature was optimum for maximum biosorption (mg/g). Presence of CaCl₂ affected the biosorption while NaCl did not have any effect on biosorption. Pseudo second order kinetics model was well suited. Cu biosorption followed Langmuir while Co biosorption followed Freundlich model well.

Lignocellulosic material (chemically modified hemp fibers) were used to develop mathematical model for biosorption of heavy metal ions (Cd, Zn and Pb) [17]. Chemical composition of biosorbent was 8.03% of α cellulose, 8.89% of hemicellulose and 4.09 % of lignin. Maximum uptake capacity of biosorbent was at the pH 5.5. 5 min were required for approximate 80% metal uptake of total metal uptake capacity. Metal uptake was 0.037 for Pb, 0.038 for Zn and 0.039 for Cd in terms of mmol/g. Mathematical model was based on second Fick's Law. Metal ion biosorption depend on transport phenomena, electrostatic interaction between ions. Effectiveness of sorption was in order Pb > Cd > Zn.

Aquatic weed *Myriophyllum spicatum* compost have been investigated as biosorbent for biosorption study of Pb, Cu, Cd, Ni and Zn [103]. C=O, C-O, (phenolic), COOH, COO₃⁻, OH groups were showed to be present by FTIR analysis in biosorbent. pH 5.0 was optimum for maximum biosorption. Increase in biosorbent dose increased biosorption. More than 1.25 gm biosorbent dose did not increase metal ion removal. Pseudo second order kinetic model was best fit. sip isotherm model was best fit for the biosorption data. Ion exchange mechanism was followed in biosorption. Multi layer biosorption took place as shown by SEM analysis. Desorption was obtained by 0.1 M HNO₃. Biosorption capacity order was found as Pb > Cu > Cd > Zn > Ni.

Physically pretreated oil palm empty fruit bunches (OPEFB) have been used as biosorbent for removal of heavy metal ion Cu, Zn and Pb [104]. FTIR spectra of biosorbent showed presence of peaks at 3400cm⁻¹, 2906 cm⁻¹, 1432, 1375, 1326, 1644, 1895 and 1735 cm⁻¹ attributed to presence of OH, CH, CH₂, CH, C-O and C=O functional groups. Milled and powdered sorbent showed higher adsorption efficacy than raw fiber. 90 min time was required to achieve peak adsorption capacity. Adsorption capacity increased with increasing metal ion concentration from 100 to 1000 ppm. optimum pH for maximum biosorption was 9.0 for Cu 7.5 for Zn and Pb.

Inaerobic digested corn stover has been used as biosorbent for removal of heavy metal ions Cu and Cd [105]. First hour of contact time showed maximum removal of Cu and Cd. Increase in initial heavy metal dose from 5.0 to 100 gm/L, the removal efficacy decreased while adsorption density increased due to saturation of adsorption sites. Competitive adsorption in binary solution showed higher affinity for Cu, than Cd. 83.3 and 50.0 mg/g were adsorption capacities of biosorbent for Cd and Cu respectively as obtained from Langmuir isotherm model.

Iron oxide nano-crystal coated by sugarcane bagasse have been investigated for magnetic nanobiosorption of heavy metal uranium [106]. Optimum pH for maximum removal (%) was 3.0. 120 min of contact time was required to attain equilibrium. 98% removal (adsorption capacity of 10 mg/g) was attained with 5 gm/L of biosorbent dose. 5ppm uranium concentration gave maximum uranium adsorption. Langmuir isotherm was best suited for the biosorption data ($r^2= 0.979$). X- ray powder diffraction and SEM methods were used to characterization of biosorbent .

Lettuce leave (fresh dried and powder) have been investigated as biosorbent to remove heavy metal Pb, Cu and Zn from industrial waste water [107]. The best biosorption occurred at pH 4, 50⁰C and with contact time of 1h. Highest removal was of Pb (48.7±1) by leaf powder and lowest metal removal was by dry pieces of leaf of Zn (11.4±0.4 mg/L). Leaf powder was best biosorbent.

Sodium hypochlorite oxidized Chinese fir bark powder was investigated as biosorbent for the removal of heavy metal ions (Cu, Cd and Pb) from aqueous solution [108]. Biosorbent was characterized by BET for surface area. Functional groups OH, CH₂, C=O, and COO were revealed by FTIR spectra. Surface was investigated by SEM imaging. Maximum adsorption for Cd, Cu and Pb was 1.223, 0.983 and 0.966 mmol/g respectively by oxidized fir bark. Langmuir isotherm model gave good fit with r^2 more than 0.99. Optimum pH 5.0 and contact time was 30 min. Pseudo second order adsorption kinetics model was best suited.

Agricultural waste- peanut shell and banana peel were evaluated as biosorbent for the removal of heavy toxic metal ions Cd, Cu, Pb and Zn [22]. XRD confirmed the particular heavy metal ions adsorption. SEM revealed presence of heavy metal ions at the pore of the biosorbent. The powder biosorbent had particle size, 600 μm, 425μm and 300 μm. Order

of adsorption was $Cd > Cu > Pb > Zn$ for banana peel biosorbents while it was $Pb > Zn > Cu > Cd$ for pea nut shell biosorbent.

Heavy metals (Cu, Zn and Cr) biosorption by *jatropha curcas* leaf biomass in single and multi metal system has been investigated by Rawat et al. [109]. Adsorption efficiency increased with increasing biomass concentration from 0.1 to 0.75 gm after that no significant difference was observed in biosorption efficiency with increase in biomass concentration upto 2.0 gm due to cell crowding. With increase in initial metal concentration from 10 mg/L to 250 mg/L increased the adsorption capacity (mmol/g). Optimum adsorption was at pH 5.0 (Zn), 2.0 (Cr) and 6.0 (Cu). Contact time required to achieve equilibrium was 120 min for Zn and Cu while 60 min for Cr. Pseudo second order equation predicted the biosorption kinetics. Adsorption capacity decreased in binary and multi metal system due to inhibitory effect of metal ions. Maximum biosorption efficiency was 92.6 % for Cu while maximum biosorption capacity was 7.41 mg/g for Cu, while biosorption capacity was maximum for Cr in terms of mmol/g (0.135). 40 mg/g metal concentration saturated the binding site for the biosorbent present in 0.5 gm dose concentration.

Nanoscale zero-valent ion-impregnated cashew nut shell (NZVI-CNS), obtained by processing of agricultural waste has been used as biosorbent to investigate the removal of heavy metal ion (Ni) from aqueous solution [110]. Increasing initial Ni ion concentration from 25 to 150 mg/L decreased metal removal from 99.7 to 87.89% (solution pH =5.0 adsorbent Dose =2 gm/L contact time =30 min at temperature 30°C), due to decreased ratio of active sites to the metal ions. Percentage removal of metal increased with increase in the pH of the experimental solution from 2.0 to 5.0. Increase in temperature from 32 to 60°C decreased the percentage removal of metal ions. It showed the exothermic nature of the adsorption process. With increase in adsorbent dose from 0.5 to 3.0 gm/L,

increased the biosorption due to increased availability of binding site. 30 min are required to attain the equilibrium. Pseudo first order kinetic model was followed in the adsorption process. Freundlich isotherm model was followed well.

Mucilage isolated from *Dicerocaryum eriocarpum* plant was investigated as biosorption medium for removal of metal ions Cd, Zn, Ni, Cr and Fe [111]. Carboxyl, hydroxyl and carbonyl functional groups were involved in biosorption as revealed by FTIR. 8 to 10 min were required to achieve equilibrium for Zn, Cd and Fe while 20 to 30 min were required for Zn, and Cr biosorption. Optimum pH for removal of Zn, Cd, Ni and Fe is 4.0 while for Cr is 6.0. Pseudo second order kinetic model was fitted well. Freundlich isotherm model best described the biosorption data. Biosorption capacity of the biosorbent was 0.0101, 0.125, 0.688, 2.387 and 4.902 for Zn, Ni, Cd, Cr and Fe respectively in terms of mg/g.

Biomass of honey comb, a byproduct of honey industry have been investigated as biosorbent for removal of toxic heavy metal ions (Pb, Cd, Cu and Ni) from aqueous solution [112]. Hydroxyl, amino, carboxyl, carbonyl functionalities were revealed by FTIR spectroscopy studies in biosorbent. Micro structure and ball shaped protuberance were present as shown by SEM analysis. pH 4 to 6 was optimum for maximum biosorption (90 to 95%). Biosorbent Dose of 0.6 gm was found to be optimum. 40 min were required to attain equilibrium. Pseudo second order kinetic model was well suited. Langmuir isotherm model best described biosorption results. The following order was found based on biosorption capacity – Pb >Cd >Cu >Ni. $Q_{max}(mg/g)$ was 74.17, 61.16, 56.52 and 52.71 for Pb, Cd, Cu, and Ni. Desorption and reusability was investigated using 0.1 M HCl.

Biosorbent obtained from aquatic weed plant *Myriophyllum spicatum* has been used to study biosorption of Pb, Cu, Cd, Ni, and Zn. Cellulose,

hemicelluloses and lignin were chemical components of biosorbent [10]. FTIR analysis showed presence of carbonyl, carboxyl, hydroxyl and phenyl functionalities as binding sites. Ion exchange and complexing mechanism was involved in biosorption process. pH 5.0 was found to be optimum. Pb > Cu > Cd > Zn > Ni was the order of preference by the biosorbent material. Sorption quantities were 0.1126, 0.0976, 0.0229, 0.0477 and 0.0424 mmol/g for Pb, Cu, Cd, Ni and Zn respectively.

Infused tea leaves (*Camellia sinensis*) has been investigated as low cost adsorbent for removal of Pb, Fe, Cd from aqueous solution [113]. pH 6 was found optimum for maximum adsorption for Cd, while pH 5 was optimum for Pb and Fe adsorption. Increase in dose from 0.22 to 1.0 gm increased biosorption of Cd from 54.76 % to 37.62 % of Pb 80.64 % to 99.72 % of Pb and from 41.42 % to 62.39 % Fe. Increase in initial metal ion concentration from 20 mg/L to 100 mg/L decreased percentage removal down to 33.55 % from 64.65 % of Fe while increased amount of metal adsorbed upto 24.77 mg/g from 9.37 mg/g for Pb. 75 to 90 min time was required to reach equilibrium. Langmuir isotherm model was found best suited to the biosorption results. Maximum adsorption capacities were 29.32 mg/g for Pb, 14.29 mg/g for Cd and 12.38 mg/g for Fe. Pseudo second order kinetic model was followed in the adsorption. Hydroxyl, carboxyl, carbonyl groups were involved in biosorption process as investigated by FTIR.

Conclusion

The literature survey reveals that use of biosorbents for the removal of heavy metals from the aqueous medium has advantage of cost effectiveness and ecofriendly in nature. The metal removal efficiency and the affinity of the biosorbent to the metal depends on the type of biosorbent used, pH, temperature, contact time, design of the equipment

used and type of the metal under consideration. The field is in the research and development phase. This is emerging field of explorative research and has immense potential for industrial application.

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