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Biosorption of Lead (II) and Cadmium (II) from Aqueous Solutions by Protonated *Sargassum* Sp. Biomass

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Abstract: Biosorption of lead (II) and cadmium (II) from aqueous solutions in batch system by protonated brown algae *Sargassum* sp. biomass was studied. The data obtained from experiments of single-component biosorption isotherms were analyzed using the Freundlich, Langmuir, Freundlich-Langmuir and Redlich-Peterson isotherm models. The Redlich-Peterson equation was found in the best fitness with the experimental data. The other models too described the isotherms of Pb^{2+} and Cd^{2+} biosorption with relatively high correlation coefficient ($R^2 > 0.93$). According to the Langmuir model, the maximum uptake capacities (q_m) of *Sargassum* sp. for Pb^{2+} and Cd^{2+} were obtained 1.70 and 1.02 mmol g^{-1} , respectively. The optimum initial pH values for biosorption of Pb^{2+} and Cd^{2+} were determined as 4.5 and 5.0, respectively. The effect of Na^+ , K^+ , Mg^{2+} and Ca^{2+} (light metal ions) on equilibrium capacities of Pb^{2+} and Cd^{2+} biosorption was studied in the binary system at initial heavy metal ion concentration of 1 mmol L^{-1} and various initial concentrations of light metal ion. The effect of Na^+ and K^+ on the biosorption of Pb^{2+} was not significant, but Mg^{2+} and Ca^{2+} decreased the equilibrium capacity of Pb^{2+} biosorption. The presence of Na^+ , K^+ , Mg^{2+} and Ca^{2+} in solution affected the biosorption of Cd^{2+} considerably, so that equilibrium uptake of Cd^{2+} was reduced at initial concentration 6 mmol L^{-1} of Na^+ , K^+ , Mg^{2+} and Ca^{2+} by 10, 17, 35 and 56%, respectively.

Key words: Biosorption, *Sargassum*, lead (II), cadmium (II), isotherm, light metal ions

INTRODUCTION

Contamination of the aqueous environment by heavy metals is a worldwide environmental problem due to their toxic effects and accumulation through the food chain. Among heavy metals, lead and cadmium have high priority for removal from aqueous environments (Rama *et al.*, 2002; Kapoor *et al.*, 1999; Sternberg and Dorn, 2002; Volesky, 2001). The conventional technologies for the removal of heavy metals from wastewater include, mainly, chemical precipitation, ion exchange, adsorption, membrane processes and evaporation that require high capital investment and running costs (Aksu, 2002; Eckenfelder, 2000; Gupta *et al.*, 2001). Therefore, there is an urgent need for development of innovative but low cost processes, where metal ions can be removed economically. The search for new treatment technologies has focused on biosorption (Dönmez *et al.*, 1999; Figueira *et al.*, 2000; Hamdy, 2000; Loukidou *et al.*, 2003).

Biosorption is a term that describes the removal of heavy metals by the passive binding to nonliving

microorganisms (bacteria, fungi and algae) and other biomass (such as peat, rice hull, fruit peel, leave and bark of tree etc.) from an aqueous solution (Davis *et al.*, 2003; Ma and Tobin, 2003; Bailey *et al.*, 1999). Biosorption has many advantages including low capital and operational costs, the selective removal of metals, biosorbent regeneration and metal recovery potentiality, rapid kinetics of adsorption and desorption and no sludge generation. Biosorption technology has been shown to be a feasible alternative for removing heavy metals from wastewater. This technology can utilize naturally abundant biomass such as seaweeds, and of these *Sargassum* has been identified for its high sorption capacity (Davis *et al.*, 2003; Diniz and Volesky, 2005; Volesky, 2001).

Biosorption of lead (II) and cadmium (II) from aqueous solutions using various biomass has been studied. Matheickal and Yu (1999) observed that the maximum uptake capacities of *Durvillaea potatorum* and *Ecklonia radiata* for Pb^{2+} were 1.6 and 1.3 mmol g^{-1} , respectively. The maximum capacity of Cd^{2+} biosorption by *Streptomyces rimosus* was obtained 0.58 mmol g^{-1} and

the Langmuir model was found in the best fitness with the equilibrium data (Selatnia *et al.*, 2004a). Biosorption of Pb²⁺ and Cd²⁺ by the fungus *P. chrysosporium* was studied and the maximum uptake capacities of Pb²⁺ and Cd²⁺ were obtained 0.25 and 0.41 mmol g⁻¹, respectively (Say *et al.*, 2001).

In this study, removal of Pb²⁺ and Cd²⁺ from aqueous solutions by protonated *Sargassum* sp. biomass was investigated. In order to analyze the isotherm data, the Freundlich, Langmuir, Freundlich-Langmuir and Redlich-Peterson models were used. In addition, the effect of pH and light metal ions on Pb²⁺ and Cd²⁺ biosorption was determined.

MATERIALS AND METHODS

Biosorbent preparation: The biosorbent used in experiments was brown algae *Sargassum* sp. The biomass was harvested from Oman Sea on the coast of Chabahar, Iran. The biomass was washed with tap water and de-ionized water to remove sand and other impurities. The biomass sun-dried and then dried in an oven at 70°C. Dried biomass was ground in a laboratory blender. After this, the biomass was sieved to select particle between 0.2-0.3 mm for use. The biomass was subsequently loaded with H⁺ in a solution of 0.1 mol L⁻¹ HCl (biomass concentration of 50 g L⁻¹) for 30 min under slow stirring. Later the biomass was washed with de-ionized water to remove excess hydrogen ions. Finally the biosorbent again dried at 70°C for 24 h.

Chemicals: Synthetic solutions were prepared using de-ionized water and salts of Pb(NO₃)₂, Cd(NO₃)₂.4H₂O, NaCl, KCl, MgCl₂.6H₂O and CaCl₂.2H₂O (Merck supplied). Initial pH of solutions was adjusted with a pH meter (CAMLAB Ltd, Model CG842) to the desired values by using 0.1-1 mol L⁻¹ HCl and 0.1-1 mol L⁻¹ NaOH.

Equilibrium experiments: Kinetic experiments presented that maximum time required to reach equilibrium was 2 h (data not shown); therefore, the equilibrium time for equilibrium experiments was chosen 3 h. In all batch equilibrium experiments, solution volume was 1 L and the mixture of solution and biosorbent was agitated in 200 rpm. All experiments were conducted at room temperature (20±1°C). Initial pH of the solutions was adjusted to desired values. The reaction mixture pH was not regulated after the initiation of experiments and final pH was measured.

Biosorption isotherms: Biosorption isotherm experiments were conducted in the single-component system. The initial Pb²⁺ and Cd²⁺ concentrations were varied from 0.05

to 5 mmol L⁻¹. Initial pH of the solutions was adjusted to 5 and then 500 mg of *Sargassum* sp. biomass was added to experiment vessels.

Effect of pH on biosorption: The effect of pH on equilibrium capacities of Pb²⁺ and Cd²⁺ biosorption was studied in a single-component system. Initial heavy metal ions concentration was 1 mmol L⁻¹ and initial pH of solutions was varied from 2 to 5.5. After pH adjustment, 500 mg of *Sargassum* sp. biomass was added to experiment vessels.

Effect of light metal ions on biosorption: The effect of Na⁺, K⁺, Mg²⁺ and Ca²⁺ on equilibrium uptake of Pb²⁺ and Cd²⁺ was studied in the binary system (one heavy metal and one light metal). Initial heavy metal ion concentration was 1 mmol L⁻¹ and initial light metal ion concentration was varied from 0 to 6 mmol L⁻¹. Initial pH of the solutions was adjusted to 5 and then 500 mg of *Sargassum* sp. biomass was added to experiment vessels.

Metal analysis: The biomass was removed by filtration through 0.45 µm membrane filters (mixed cellulose ester) and filtrates were analyzed for residual heavy metal (Pb²⁺ or Cd²⁺) concentration by a flame atomic absorption spectrophotometer (FAAS, Chem. Tech Analytical, Model ALPHA4).

Modeling of biosorption isotherms: The isotherms of Pb²⁺ and Cd²⁺ biosorption were analyzed using the Freundlich, Langmuir, Freundlich-Langmuir and Redlich-Peterson models. The empirical Freundlich model based on sorption onto a heterogeneous surface is given below by Eq. 1.

$$q_e = K_F C_e^{1/n} \quad (1)$$

where, q_e is equilibrium capacity of biosorption (mmol g⁻¹); C_e is equilibrium concentration of metal ion (mmol L⁻¹); K_F and n are indicators of biosorption capacity and biosorption intensity, respectively (Loukidou *et al.*, 2004; Selatnia *et al.*, 2004b).

The Langmuir equation is based on the assumption that maximum adsorption corresponds to a saturated monolayer of solute on the adsorbent surface, that energy of adsorption is constant and that there is no transmigration of adsorbate in the plane of the surface. The Langmuir equation is given by Eq. 2.

$$q_e = \frac{b q_m C_e}{1 + b C_e} \quad (2)$$

where, q_m is the maximum capacity of biosorption (mmol g⁻¹) and b is a constant related to the affinity of the

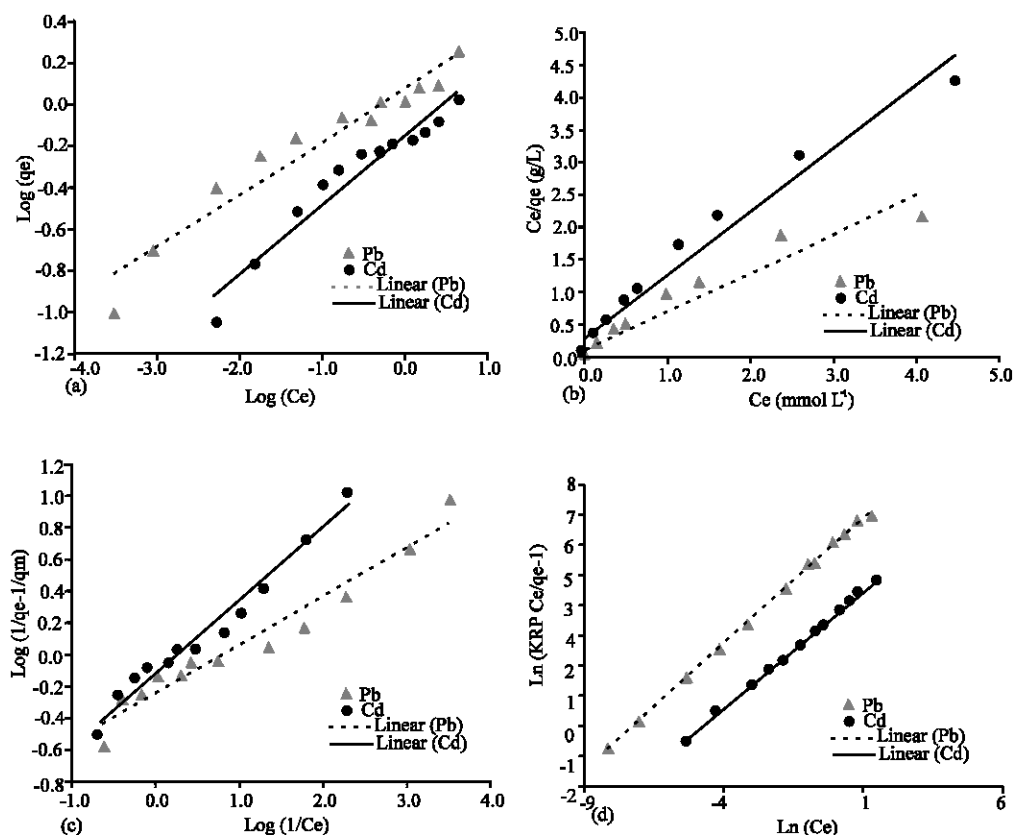


Fig. 1: Isotherms analysis of Pb²⁺ and Cd²⁺ biosorption by linear plots of (a) the Freundlich, (b) Langmuir, (c) Freundlich-Langmuir and (d) Redlich-Peterson models.

binding sites (Lmmol⁻¹) (Langmuir, 1918; Sheng *et al.*, 2004; Yalçınkaya *et al.*, 2002).

The three-parameter Freundlich-Langmuir model was developed to improve the fitness found by the Freundlich or Langmuir model. This model is given by Eq. 3.

$$q_e = \frac{bq_m C_e^{1/n}}{1 + bC_e^{1/n}} \quad (3)$$

where, b, q_m and n are the Freundlich-Langmuir parameters (Volesky, 2003).

The three-parameter Redlich-Peterson model is given below by Eq. 4.

$$q_e = \frac{K_{RP} C_e}{1 + a_{RP} C_e^\beta} \quad (4)$$

where, K_{RP} (L g⁻¹), a_{RP} (L mmol L⁻¹)^β and β (dimensionless) are the Redlich-Peterson constants. β lies between 0 and 1. For β = 1 the Redlich-Peterson model

converts to the Langmuir model (Aksu, 2002; Volesky, 2003).

RESULTS AND DISCUSSION

Biosorption isotherms: Isotherm data are basic requirements for the design of biosorption systems, moreover analysis of biosorption isotherms is important to develop an equation which accurately represents the results and which can be used for design purposes (Aksu, 2002; Volesky, 2001).

Figure 1a-d shows isotherms modeling of Pb²⁺ and Cd²⁺ biosorption by linear plots of the Freundlich, Langmuir, Freundlich-Langmuir and Redlich-Peterson models (Eq. 1-4). Isotherm parameters of these models for biosorption of Pb²⁺ and Cd²⁺ by *Sargassum* sp. biomass were shown in Table 1 and 2. The Redlich-Peterson equation described the isotherms of Pb²⁺ and Cd²⁺ biosorption with high correlation coefficient (R² > 0.99) and better than the other models. The other models too were found in relatively good fitness with the experimental data (R² > 0.93). According to Langmuir equation, the

Table 1: Isotherm parameters of the Freundlich and Langmuir models for the biosorption of Pb²⁺ and Cd²⁺ by *Sargassum* sp.

Metal ion	Freundlich model			Langmuir model		
	K _F	n	R ²	q _m	b	R ²
Pb ²⁺	1.21	3.88	0.937	1.7	4.47	0.931
Cd ²⁺	0.71	3	0.949	1.02	3.72	0.97

R = correlation coefficient

Table 2: Isotherm parameters of the Freundlich-Langmuir and Redlich-Peterson models for the biosorption of Pb²⁺ and Cd²⁺ by *Sargassum* sp.

Metal ion	Freundlich-Langmuir model				Redlich-Peterson model			
	q _m	b	n	R ²	a _{RP}	K _{RP}	β	R ²
Pb ²⁺	3.81	0.47	3.24	0.948	409.45	475.3	0.83	0.999
Cd ²⁺	1.54	0.88	2.13	0.977	40.25	29.01	0.78	0.998

R = correlation coefficient

Table 3: Comparison of maximum uptake capacities (q_m) of various biosorbents for Pb²⁺ and Cd²⁺

Metal ion	Biosorbent	q _m (mmol g ⁻¹)	Experimental conditions		Reference	
			pH	T (°C)		
Pb ²⁺	<i>Ecklonia radiata</i>	1.36	4.5-5.5	na	Matheickal and Yu (1996)	
	<i>Ulva</i> sp.	1.46	5	22±1	Sheng <i>et al.</i> (2004)	
	<i>Padina</i> sp.	1.25	5	22±1	Sheng <i>et al.</i> (2004)	
	<i>Gracillaria</i> sp.	0.45	5	22±1	Sheng <i>et al.</i> (2004)	
	<i>Cladophora glomerata</i>	0.35	4.5	30	Jalali <i>et al.</i> (2002)	
	<i>Phanerochaete chrysosporium</i>	0.41	6	25	Say <i>et al.</i> (2001)	
	<i>Mucor rouxii</i>	0.26	6	na	Yan and Viraraghavan (2003)	
	<i>Streptomyces rimosus</i>	0.66	na	na	Selatnia <i>et al.</i> (2004b)	
	<i>Pleurotus ostreatus</i>	0.58	6.5	25	Xiangliang <i>et al.</i> (2005)	
	<i>Sargassum</i> sp.	1.7	5	20±1	This study	
	Cd ²⁺	<i>Ulva onoi</i>	0.81	7.8	20	Suzuki <i>et al.</i> (2005)
		<i>Ulva</i> sp.	0.58	5.5	22±1	Sheng <i>et al.</i> (2004)
		<i>Padina</i> sp.	0.75	5.5	22±1	Sheng <i>et al.</i> (2004)
<i>Gracillaria</i> sp.		0.3	5.5	22±1	Sheng <i>et al.</i> (2004)	
<i>Mucor rouxii</i>		0.18	6	na	Yan and Viraraghavan 2003	
<i>Phanerochaete chrysosporium</i>		0.25	6	25	Say <i>et al.</i> (2001)	
<i>Trametes versicolor</i>		1.2	6	20	Yalçinkaya <i>et al.</i> (2002)	
<i>Streptomyces rimosus</i>		0.58	8	20	Selatnia <i>et al.</i> (2004a)	
chitin		0.14	5.8-6.4	25	Benguella and Benaissa (2002)	
<i>Sargassum</i> sp.		1.02	5	20±1	This study	

na = not available

maximum capacities of Pb²⁺ and Cd²⁺ biosorption (q_m) were obtained 1.70 and 1.02 mmol g⁻¹, respectively.

The Langmuir parameter q_m (maximum uptake capacity) is a suitable measure for comparing different sorbents for the same sorbate. The maximum biosorption capacities (q_m) obtained from this research with those of other biosorbents reported in the literature is given in Table 3. Although due to the various experimental conditions employed in different studies, comparison of their results is difficult, but maximum uptake capacity of *Sargassum* sp. biomass for Pb²⁺ and Cd²⁺ far exceed those of most of the biosorbents; consequently, the *Sargassum* sp. used in this study can be classified as a good biosorbent.

Effect of pH on biosorption: Other studies on heavy metal biosorption have presented that pH was an important parameter affecting the biosorption process (Yan and Viraraghavan, 2003; Selatnia *et al.*, 2004a). The effect of pH on biosorption was studied in the initial pH range of

2 to 5.5. At higher pH values, the experiments were not conducted to avoid formation of solid Pb²⁺ and Cd²⁺ hydroxides. The optimum initial pH values for Pb²⁺ and Cd²⁺ biosorption were determined as 4.5 and 5, respectively (Fig. 2). The sharpest increase in Pb²⁺ uptake was obtained between pH 2 and 3. The sharpest increase in Cd²⁺ uptake was determined between pH values of 2 and 4. The dependence of Pb²⁺ and Cd²⁺ biosorption on pH could be largely related to ionic state of binding sites on the algal cell wall (Matheickal and Yu, 1996; Sheng *et al.*, 2004).

Measurement of final pH represented the simultaneous release of H⁺ with the uptake of heavy metal ions, because final pH of solutions were less than initial pH of solutions, therefore ion exchange confirmed to be one of the biosorption mechanisms. Other studies with seaweed and fungal biomass have indicated ion exchange as the dominant mechanism of biosorption (Ahuja *et al.*, 1999; Fourest and Roux, 1992; Schiewer and Volesky, 1996; Volesky, 2001).

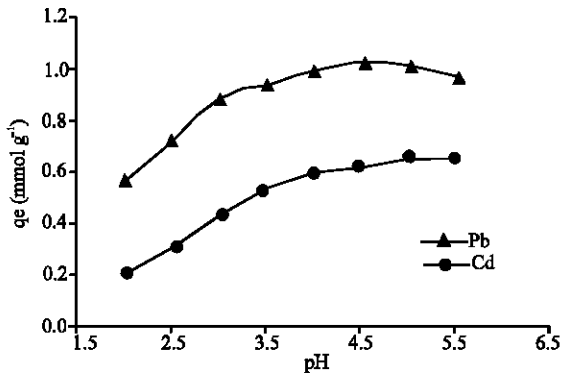


Fig. 2: Effect of pH on equilibrium capacities of Pb²⁺ and Cd²⁺ biosorption by *Sargassum* sp. biomass.

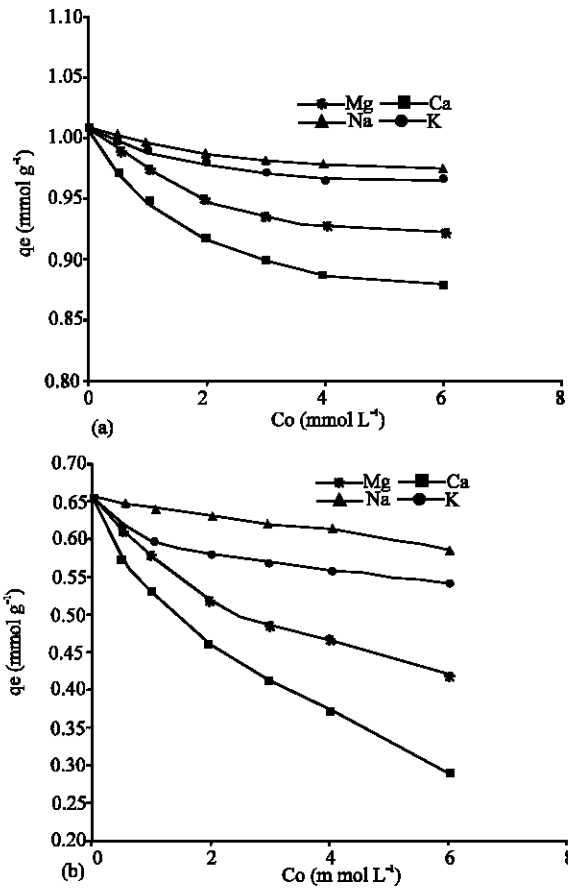


Fig. 3: Effect of Na⁺, K⁺, Mg²⁺ and Ca²⁺ on equilibrium capacities of (a) Pb²⁺ and (b) Cd²⁺ biosorption by *Sargassum* sp. biomass (C₀ = initial concentration of light metal ions).

Effect of light metal ions on biosorption: Industrial effluents contaminated with heavy metals contain various kinds of impurities such as light metal ions (Na⁺, K⁺, Mg²⁺ and Ca²⁺) that affect the heavy metal removal process

(Matheickal and Yu, 1999). The effect of light metal ions on heavy metal biosorption was investigated in other researches. Matheickal and Yu (1999) investigated the effect of Na⁺, K⁺, Mg²⁺ and Ca²⁺ on biosorption of Pb²⁺ by *Durvillaea potatorum* and *Ecklonia radiata*. The results showed that the biosorbents had much higher relative affinities for Pb²⁺ than for the light metal ions. The presence of Na⁺, K⁺, Mg²⁺ and Ca²⁺ in solution did not affect the biosorption capacity of Cu²⁺ by *Padina* sp. significantly (Kaewsarn, 2002).

The effect of Na⁺, K⁺, Mg²⁺ and Ca²⁺ on equilibrium capacities of Pb²⁺ and Cd²⁺ biosorption by *Sargassum* sp. biomass was shown in Fig. 3. The effect of Na⁺ and K⁺ on Pb²⁺ uptake was insignificant even at 6 mmolL⁻¹ concentration of these ions, but Mg²⁺ and Ca²⁺ had influence on Pb²⁺ biosorption. The equilibrium capacity of Pb²⁺ biosorption was reduced at initial Mg²⁺ and Ca²⁺ concentration of 6 mmol L⁻¹ by 9 and 13%, respectively. The presence of Na⁺, K⁺, Mg²⁺ and Ca²⁺ in solution affected the biosorption of Cd²⁺ considerably, so that equilibrium uptake of Cd²⁺ was reduced at initial concentration 0.5-6 mmol L⁻¹ of Na⁺, K⁺, Mg²⁺ and Ca²⁺ by 1-11, 6-17, 7-35 and 12-56%, respectively(Fig. 3).

REFERENCES

Ahuja, P., R. Gupta and R.K. Saxena, 1999. Zn²⁺ biosorption by *Oscillatoria angustissima*. Process Biochem., 34: 77-85.

Aksu, Z., 2002. Determination of the equilibrium, kinetic and thermodynamic parameters of the batch biosorption of nickel (II) ions onto *Chlorella vulgaris*. Process Biochem., 38: 89-99.

Bailey, S.E., T.J. Olin, R.M. Bricka and D.D. Adrian, 1999. A review of potentially low-cost sorbents for heavy metals. Water Res., 33: 2469-2479.

Benguella, B., H. Benaissa, 2002. Cadmium removal from aqueous solutions by chitin: Kinetic and equilibrium studies, Water Res., 36: 2463-2474.

Dönmez, G.Ç., Z. Aksu, A. Öztürk and T. Kutsal, 1999. A comparative study on heavy metal biosorption characteristic of some algae. Process Biochem., 34: 885-892.

Davis, T.A., B. Volesky and A. Mucci, 2003. A review of the biochemistry of heavy metal biosorption by brown algae. Water Res., 37 : 4311-4330.

Diniz, V. and B. Volesky, 2005. Biosorption of La, Eu and Yb using *Sargassum* biomass. Water Res., 39: 239-247.

Eckenfelder, W.W. Jr., 2000, Industrial Water Pollution Control, 3rd Edn., McGraw-Hill, Boston, MA., pp: 138-142.

- Fourest, E. and J.C. Roux, 1992. Heavy metal biosorption by fungal mycelial by-products: Mechanism and influence of pH. *Appl. Microbiol. Biotechnol.*, 37: 399-403.
- Figueira, M.W., B. Volesky, V.S.T. Ciminelli and F.A., Roddick, 2000. Biosorption of metals in brown seaweed biomass. *Water Res.*, 34 : 196-204.
- Gupta, V.K., A.K. Shrivastava and N. Jain, 2001. Biosorption of chromium (VI) from aqueous solutions by green algae *Spirogyra* species. *Water Res.*, 35 : 4079-4085.
- Hamddy, A.A., 2000. Biosorption of heavy metals by marine algae. *Current Microbiol.*, 41: 232-238.
- Jalali, R., H. Ghafourian, Y. Asef, S.J. Davarpanah and S. Sepehr, 2002. Removal and recovery of lead using nonliving biomass of marine algae. *J. Hazard. Mater.*, B 92: 253-262.
- Kapoor, A., T. Viraraghavan and D.R. Cullimore, 1999. Removal of heavy metals using the fungus *Aspergillus niger*. *Biores. Technol.*, 70: 95-104.
- Kaewsarn, P., 2002. Biosorption of copper (II) from aqueous solutions by pre-treated biomass of marine algae *Padina* sp. *Chemosphere*, 47: 1081-1085.
- Langmuir, I., 1918. The adsorption of gases on plane surfaces of glass, mica and platinum. *J. Am. Chem. Soc.*, 40: 1361-1401.
- Loukidou, M.X., K.A. Matis, A.I. Zouboulis and M.L. Kyriakidou, 2003. Removal of As(V) from wastewaters by chemically modified fungal biomass. *Water Res.*, 37: 4544-4552.
- Loukidou, M.X., A.I. Zouboulis, T.D. Karapantsios and K.A. Matis, 2004. Equilibrium and kinetic modeling of chromium (VI) biosorption by *Aeromonas caviae*. *Colloids and Surfaces A: Physicochem. Eng. Aspects*, 242: 93-104.
- Matheickal, J.T. and Q. Yu, 1996. Biosorption of lead from aqueous solutions by marine algae *Ecklonia radiata*. *Water Sci. Technol.*, 34: 1-7.
- Matheickal, J.T. and Q. Yu, 1999. Biosorption of lead (II) and copper (II) from aqueous solutions by pre-treated biomass of Australian marine algae. *Biores. Technol.*, 69: 223-229.
- Ma, W. and J.M. Tobin, 2003. development of multimetal binding model and application to binary metal biosorption onto peat biomass. *Water Res.*, 37: 3967-3977.
- Rama, M.P., J.A. Alonso, C.H. E.T. López and Vaamonde, 2002. Cadmium removal by living cells of the marine microalga *Tetraselmis suecica*. *Biores. Technol.*, 84: 265-270.
- Schiewer, S. and B. Volesky, 1996. Modeling of multi-metal ion exchange in biosorption. *Environ. Sci. Technol.*, 30: 2921-2927.
- Say, R., A. Denizli, M.Y. Arıca, 2001. Biosorption of cadmium (II), lead (II) and copper (II) with the filamentous fungus *Phanerochaete chrysosporium*. *Biores. Technol.*, 76: 67-70.
- Sternberg, S.P.K. and R.W. Dorn, 2002. Cadmium removal using *Cladophora* in batch, semi-batch and flow reactors. *Biores. Technol.*, 81: 249-255.
- Selatnia, A., M.Z. Bakhti, A. Madani, L. Kertous and Y., Mansouri, 2004a. Biosorption of Cd²⁺ from aqueous solution by a NaOH-treated bacterial dead *Streptomyces rimosus* biomass. *Hydrometallurgy*, 75: 11-24.
- Selatnia, A., A. Boukazoula, N. Kechid, M.Z. Bakhti, A. Chergui and Y. Kerchich, 2004b. Biosorption of lead (II) from aqueous solution by a bacterial dead *Streptomyces rimosus* biomass. *Biochem. Eng., J.* 19: 127-135.
- Sheng, P.X., Y.P. Ting, J.P. Chen and L. Hong, 2004. Sorption of lead, copper, cadmium, zinc and nickel by marine algal biomass: Characterization of biosorptive capacity and investigation of mechanisms. *J. Colloid Interface Sci.*, 275: 131-141.
- Suzuki, Y., T. Kametani, and T. Maruyama, 2005. Removal of heavy metals from aqueous solution by nonliving *Ulva* seaweed as biosorbent. *Water Res.*, 39: 1803-1808.
- Volesky, B., 2001. Detoxification of metal-bearing effluents: biosorption for the next century. *Hydrometallurgy*, 59: 203-216.
- Volesky, B., 2003. Biosorption process simulation tools. *Hydrometallurgy*, 71: 179-190.
- Xiangliang, P., W. Jianlong and Z. Daoyong, 2005. Biosorption of Pb (II) by *Pleurotus ostreatus* immobilized in calcium alginate gel. *Process Biochem.*, 40: 2799-2803.
- Yalçınkaya, Y., L. Soysal, A. Denizli, M.Y. Arıca, S. Bektaş and Ö. Genç, 2002. Biosorption of cadmium from aquatic systems by carboxymethylcellulose and immobilized *T. versicolor*. *Hydrometallurgy*, 63: 31-40.
- Yan, G. and T. Viraraghavan, 2003. Heavy metal removal from aqueous solution by fungus *Mucor rouxii*. *Water Res.*, 37: 4486-4496.