

Biosorption of lanthanide (praseodymium) using *Ulva lactuca*: Mechanistic study and application of two, three, four and five parameter isotherm models

K. Vijayaraghavan

Department of Chemical Engineering, Indian Institute of Technology Madras, Chennai 600036, India

ORIGINAL RESEARCH ARTICLE

ABSTRACT

Biosorption of praseodymium(III) ions from aqueous solutions using green seaweed (*Ulva lactuca*) was investigated. Biosorption pH edge experiments revealed that increasing the equilibrium pH favoured biosorption of Pr(III) ions onto *U. lactuca*. Isotherm curves obtained during Pr(III) biosorption at different pH conditions were concave and favourable. According to the Langmuir model, the maximum Pr(III) uptake of 0.495 mmol/g was observed at pH 5 and temperature of 32±1 °C. Apart from the Langmuir model, Pr(III) biosorption isotherms were described using the Freundlich, Jovanovic, Redlich-Peterson, Sips, Toth, Khan, Radke-Prausnitz, Fritz-Schlunder three parameter, Hill, Koble-Corrigan, Baudu, Weber-van Vliet and Fritz-Schlunder five parameter models were employed. The models were evaluated on the basis of correlation coefficient, % error, root mean square error and chi-square values.

KEYWORDS

bioremediation; biosorption; isotherm; lanthanides; seaweed; wastewater treatment

1. INTRODUCTION

Rare earth elements (REEs) have found wide applications in variety of high-end fields such as chemical engineering, information storage, energy conservation and nuclear energy (Zhu et al., 2015). The wastewater produced from these industries is often associated with high concentration of REEs. Even though, REEs are less toxic, their high prices and enhanced commercial usage (Vijayaraghavan et al., 2011) call for separation and purification of REEs from industrial wastewaters. Several approaches have been used to separate and isolate REEs such as ion-exchange (Xie et al., 2014), solvent extraction (Kakoi et al., 1997) and co-precipitation (Petrov et al., 2001). However, these conventional methods have some drawbacks, such as high utilization of chemicals and energy, low selectivity, high operational expenses and production of secondary metabolites (Zhu et al., 2015). Hence, search for alternative methods to isolate REE

from wastewaters is still on the horizon.

In recent years, bioremediation processes such as biosorption (Das and Das, 2013), bioaccumulation (Tomioka et al. 1998) and phytoremediation (Zhang et al., 2014) were shown to effectively isolate REEs from solutions. Of which, biosorption proved effective, cheap and practical. Biosorption can be defined as the passive uptake of pollutants by inactive/dead biomass through various physico-chemical mechanisms (Vijayaraghavan and Yun, 2008). Some REEs extensively studied for applicability of biosorption includes lanthanum (Texier et al., 1997; Vijayaraghavan et al., 2009), cerium (Sert et al., 2008; Vijayaraghavan et al., 2010), europium (Texier et al., 1997; Vijayaraghavan and Balasubramanian, 2010) and ytterbium (Diniz and Volesky, 2005; Vijayaraghavan et al., 2010). However, not much effort was made to elucidate the compatibility of biosorption for praseodymium. Praseodymium (Pr) is a strategic material with more resistant to corrosion in air than

Corresponding author: K. Vijayaraghavan

Tel: +91-44-22575156

Fax: +91-44-22570509

E. mail: cevijay@iitm.ac.in; erkvijay@yahoo.com

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lanthanum, europium, cerium or neodymium (Kumar et al., 2010) and used for magnetic materials, hydrogen storage materials, battery materials and glass materials (Zhang et al., 2014).

Of the different biomaterials employed for the removal of REEs, marine algae (seaweed) have been demonstrated to possess high biosorption capacity. Diniz and Volesky (2005) identified that brown alga (*Sargassum polycystum*) showed good biosorption capacity in the order of 0.8-0.9, 0.8-0.9 and 0.7-0.9 mmol/g for La, Eu and Yb, respectively. Similarly, Vijayaraghavan et al. (2010) explored biosorption potential of *Turbinaria conoides* towards different REEs, with the brown alga exhibited uptakes of 154.7, 154.8, 138.2 and 121.2 mg/g for La, Ce, Eu and Yb, respectively. Surprisingly, to-date, no systematic study has been conducted to explore the biosorption potential of green seaweed towards REE. Thus, the current investigation explores the potential of green seaweed (*Ulva lactuca*) to remove praseodymium from aqueous solutions. In addition, Pr(III) biosorption isotherms will be described using several one-, two-, three-, four- and five-parameter models.

2. MATERIALS AND METHODS

2.1. Seaweed and metal solution preparation

Samples of *U. lactuca* were collected from the beaches of Mandapam region (Tamilnadu, India). The biomass was washed extensively with deionized (DI) water and then dried in oven at 50 °C for 24 h. The dried biomass was then grounded using blender and sieved subsequently to obtain particles in the range of 0.75-1 mm.

Stock solution (5 mmol/L) of praseodymium was prepared by dissolving praseodymium nitrate (Sigma Aldrich, India) in DI water.

2.2. Experimental procedure

Biosorption experiments were performed by contacting 0.1 g of *U. lactuca* biomass with 100 mL known concentration of Pr(III) solution, at the desired pH, in 250 mL Erlenmeyer flasks. The reaction mixture was then placed on an incubated rotary shaker at 160 rpm and 32±1 °C. The pH of the solution was initially adjusted using either 0.1 M HCl or NaOH, which were subsequently used to control the pH during the experimental period. After 6 h of contact with the Pr(III) solution, the green algal biomass was separated by

filtration through 0.45 µm PTFE membrane filter and the supernatant was analysed for Pr(III) concentration using inductively coupled plasma- optical emission spectrometry (ICP-OES, Perkin Elmer Optima 5300 DV).

The amount of Pr(III) biosorbed by *U. lactuca* was determined using the following equation,

$$Q = V(C_0 - C_e) / M \quad (1)$$

where Q is the Pr(III) uptake (mmol/g), C_0 and C_e are the initial and equilibrium Pr(III) concentrations in the solution (mmol/L), respectively, V is the solution volume (L) and M is the mass of *U. lactuca* (g).

2.3. Error Analysis

Biosorption isotherm model parameters were estimated through nonlinear regression using SigmaPlot (version 4.0, SPSS, Chicago, IL). To measure goodness of fit, several error functions were used, which include correlation coefficient (R^2), % error (ϵ), residual root mean square error (RMSE) and the Chi-square test (χ^2). The average percentage error between the experimental and predicted values is calculated using:

$$\epsilon (\%) = \frac{\sum_{i=1}^N (Q_{\text{exp},i} - Q_{\text{pred},i} / Q_{\text{exp},i})}{N} \times 100 \quad (2)$$

where Q_{exp} and Q_{pred} represents experimental and predicted Pr(III) uptake values, respectively, and N is the number of data points.

RMSE can be defined as

$$RMSE = \sqrt{\frac{1}{N-2} \sum_{i=1}^m (Q_{\text{exp},i} - Q_{\text{pred},i})^2} \quad (3)$$

The Chi-square test can be defined as:

$$\chi^2 = \sum_{i=1}^m \frac{(Q_{\text{exp},i} - Q_{\text{pred},i})^2}{Q_{\text{pred},i}} \quad (4)$$

3. RESULTS AND DISCUSSION

3.1. pH edge studies

The biosorptive removal of Pr(III) as a function of pH (Figure 1) clearly showed that the solution pH played an important role in the biosorption of Pr(III) by *U. lactuca* biomass. The equilibrium pH was varied from pH 2 to 5. At the examined initial Pr(III) concentration

of 1 ± 0.01 mmol/L at 32 ± 1 °C, increase in equilibrium pH resulted in enhancement of Pr(III) uptake by *U. lactuca* biomass (Figure 1). At pH 5, maximum Pr(III) uptake of 0.348 mmol/g was obtained.

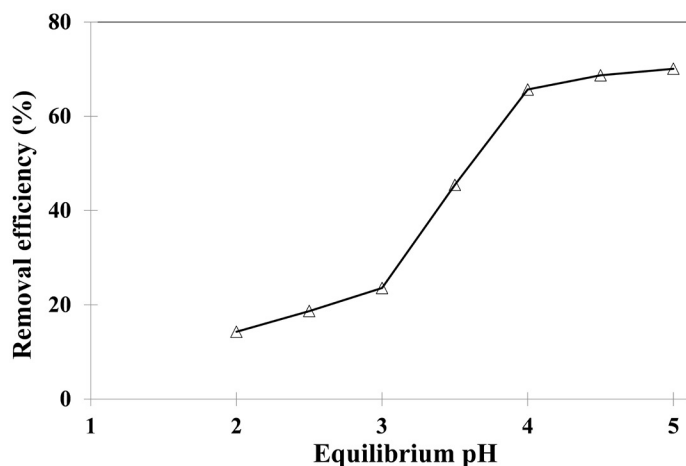


Figure 1. Influence of equilibrium pH on biosorption of Pr(III) ions onto *U. lactuca* (initial Pr(III) concentration = 1 ± 0.01 mmol/L; temperature = 32 ± 1 °C).

At the examined pH range (2-5), lanthanides exist as Ln^{3+} (Vijayaraghavan et al., 2011). On the other hand, negative functional groups on the surface of *U. lactuca* activated at the above pH range. The green algae, *U. lactuca* comprises on the dry weight basis 38 – 54% of cell wall polysaccharides with a majority of water-soluble ulvan (Robic et al., 2009). Ulvan is an anionic polyelectrolyte as it contains carboxylic and sulphate groups inside its structure; hence possess strong affinity towards metal cations. Biosorption can occur through ion-exchange mechanism in which negatively charged groups of the green marine alga binds the positively charged lanthanides. At low pH conditions, the presence of excess H^+ ions protonate the negatively charged binding sites; hence the metal uptake was minimal. As the pH increased, H^+ ion concentration decrease in the solution, which lead to increased interaction between metal cations and negatively charged binding sites of *Ulva* biomass. It is worth noting that the pKa value of carboxyl groups in seaweed lies between 3.6 – 4.5 (Romero-Gonzalez et al., 2001; Vijayaraghavan et al., 2006) and hence maximum uptake of lanthanides were expected in this pH range.

3.2. Biosorption isotherms

Biosorption isotherms are important to elucidate the maximum saturation potential of any sorbent and also

the affinity of sorbent towards the solute. Biosorption isotherm is a plot of equilibrium metal concentration versus equilibrium uptake at a fixed operating condition. For the present study, isotherms were obtained at pH 2, 3 and 5 at fixed temperature of 32 ± 1 °C (Figure 2). Conventional L-shaped isotherms (concave-shaped curves with strict plateau) were generally obtained at different all examined pH conditions. To be precise, all Pr(III) isotherms exhibited steep slopes, which indicates the high affinity of Pr(III) towards *U. lactuca*. However, among different pH conditions examined, it was clear that Pr(III) biosorption was optimal at pH 5. At this pH value, *U. lactuca* exhibited highest Pr(III) uptake of 0.456 mmol/g. This is equivalent to 5.3 times increase in Pr(III) uptake in comparison with Pr(III) uptake at pH 2.

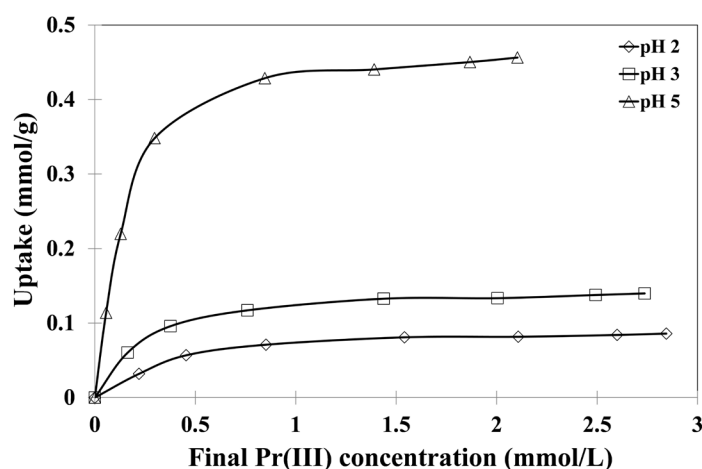


Figure 2. Experimental isotherms during biosorption of Pr(III) ions onto *U. lactuca* (temperature = 32 ± 1 °C).

Experimental Pr(III) isotherms were described using two-, three-, four- and five-parameter models. Isotherm models are very crucial in translating laboratory results for real applications as they aid in understanding process mechanisms, analyse experimental data, predict answers to operational conditions and optimize processes (Vijayaraghavan and Yun, 2008). Several models were proposed by investigators to describe isotherms and they are proven successful for sorption mechanism (Liu and Liu, 2008). Even though these are empirical models with simple mathematical relationships, characterized by number of adjustable parameters, they usually give a good description of the experimental behaviour over a large range of operating conditions (Esposito et al., 2002; Vijayaraghavan and Yun, 2008).

3.2.1. Langmuir model

The Langmuir isotherm (Langmuir, 1916) is one of the most widely used model to describe relationship between equilibrium concentration and uptake. It can be expressed as,

$$Q = \frac{Q_{\max} b_L C_e}{1 + b_L C_e} \quad (5)$$

where Q_{\max} is the maximum Pr(III) uptake (mmol/g) and b_L is the Langmuir equilibrium constant (L/mmol). The constant Q_{\max} is very useful to predict maximum solute uptake which is otherwise could not be obtained through the experiments. The other constant, b_L , corresponds to initial slope of isotherm and also quantitatively explain the affinity between the sorbent and metal ion. For the present data, maximum Q_{\max} and b_L values were obtained at pH 5 (Table 1). The Langmuir model describe the Pr(III) isotherm data satisfactorily with high R^2 and low % error, RMSE and χ^2 values.

Table 1. Isotherm constants of two-parameter models obtained during biosorption of Pr(III) onto *U. lactuca*.

Models		pH 2	pH 3	pH 5
Langmuir	Q_{\max} (mmol/g)	0.0976	0.1514	0.4948
	b_L (L/mmol)	2.74	4.34	6.51
	R^2	0.993	0.997	0.995
	ε (%)	1.16	0.302	2.24
	RMSE	0.0030	0.0021	0.014
	χ^2	0.0010	0.0002	0.0046
Freundlich	K_F (mg/g) (L/mg) ^{1/n_F}	0.066	0.114	0.398
	n_F	3.47	4.20	3.70
	R^2	0.962	0.974	0.943
	ε (%)	1.99	0.707	6.81
	RMSE	0.0071	0.0094	0.050
	χ^2	0.0047	0.0047	0.048
Jovanovic	Q_{\max} (mmol/g)	0.084	0.135	0.446
	K_J (L/mmol)	2.30	3.26	5.19
	R^2	0.997	0.994	0.999
	ε (%)	1.01	0.052	0.346
	RMSE	0.0018	0.0044	0.0078
	χ^2	0.0003	0.0010	0.0007

3.2.2. Freundlich model

The Freundlich equation (Freundlich, 1906) is another classical model frequently applied to describe adsorption systems. The model is interpreted as sorption to heterogeneous surfaces or surfaces supporting binding sites of varied affinities. It is assumed that the stronger

functional sites are occupied first and that the binding strength decreases with the increasing degree of site occupation. It may be represented as follows,

$$Q = K_F C_e^{1/n_F} \quad (6)$$

where K_F is the Freundlich constant (mmol/g) (L/mmol)^{1/n_F} and n_F is the Freundlich exponent. The constant K_F corresponds to binding capacity and n_F corresponds to affinity between the biosorbent and Pr(III) ions. At pH 5, both constants reached maximum values (Table 1). However, description of Pr(III) isotherm by the Freundlich model was not satisfactory as relatively low R^2 and high % error, RMSE and χ^2 values were obtained at different pH conditions.

3.2.3. Jovanovic model

In addition to the assumptions of the Langmuir model, the Jovanovic model (Jovanovic, 1969) considers the possibility of some mechanical contacts between the sorbate and de-sorbate molecules. The equation can be expressed as,

$$Q = Q_{\max} (1 - \exp(-b_J C_e)) \quad (7)$$

where b_J is the Jovanovic isotherm constant (L/mmol). Application of Pr(III) isotherm data to the Jovanovic model resulted in good prediction with high R^2 and low % error, RMSE and χ^2 values. However, the model under-predicted Pr(III) maximum uptake values at all pH conditions examined (Table 1).

3.2.4. Redlich-Peterson model

Redlich and Peterson (1959) combined the features of both the Langmuir and Freundlich model into a single equation and suggested the mechanism of adsorption is a hybrid and does not follow ideal monolayer adsorption. The equation can be expressed as,

$$Q = \frac{K_P C_e}{1 + a_P C_e^{\beta_P}} \quad (8)$$

where K_P is the Redlich-Peterson model isotherm constant (L/g), a_P is the Redlich-Peterson model constant (L/mmol)^{1/β_P} and β_P is the Redlich-Peterson model exponent. The exponent, β_P , lies between 0 and 1. There are two limiting behaviours: Langmuir form for $\beta_P = 1$ and Henry's law form for $\beta_P = 0$. Both K_P and a_P increases with increase in equilibrium pH and reached maximum at pH 5 (Table 2). On the other hand, β_P values were close to unity which confirms that

Pr(III) isotherms were more of the Langmuir form.

3.2.5. Sips model

Sips (1948) also combined the features of the Langmuir and Freundlich equations to predict the heterogeneous sorption systems and also avoiding the constraint of the rising sorbate concentration associated with Freundlich isotherm model. The equation can be expressed as,

$$Q = \frac{K_s C_e^{\beta_s}}{1 + a_s C_e^{\beta_s}} \quad (9)$$

where K_s is the Sips model isotherm constant (L/g) $^{\beta_s}$, a_s is the Sips model constant (L/mmol) $^{\beta_s}$ and β_s is the Sips model exponent. The Sips model described Pr(III) isotherm data onto *U. lactuca* very accurately with high R^2 and low % error, RMSE and χ^2 values. Similar to experimental data, Sips model constants were observed maximum at pH 5 (Table 2).

Table 2. Isotherm constants of three-parameter models obtained during biosorption of Pr(III) onto *U. lactuca*.

Models		pH 2	pH 3	pH 5
Redlich-Peterson	K_p (L/g)	0.198	0.581	2.58
	a_p (L/mmol) $^{1/\beta_p}$	1.66	3.65	4.85
	β_p	1.18	1.05	1.11
	R^2	0.997	0.999	0.998
	ϵ (%)	1.06	0.328	1.32
	RMSE	0.002	0.002	0.007
Sips	K_s (L/g) $^{\beta_s}$	0.508	0.849	6.59
	a_s (L/mmol) $^{\beta_s}$	5.80	5.81	14.17
	β_s	1.51	1.16	1.32
	R^2	0.999	0.999	0.999
	ϵ (%)	0.389	0.190	0.177
	RMSE	0.0011	0.0014	0.0041
Toth	Q_{max} (mmol/g)	0.086	0.145	0.458
	b_T (L/mmol)	1.92	3.60	4.73
	n_T	0.542	0.812	0.620
	R^2	0.999	0.999	0.999
	ϵ (%)	0.628	0.228	0.219
	RMSE	0.0013	0.0015	0.0035
χ^2	0.0001	0.0001	0.0001	

Khan	Q_{max} (mmol/g)	0.166	0.177	0.699
	b_K (L/mmol)	1.31	3.40	3.94
	a_K	1.28	1.06	1.15
	R^2	0.996	0.999	0.998
	ϵ (%)	1.21	0.328	1.63
	RMSE	0.002	0.002	0.009
	χ^2	0.0004	0.0001	0.0014
Radke-Prausnitz	a_R	0.276	0.667	2.26
	r_R	0.097	0.151	0.496
	b_R	0.0001	0.00002	0.00004
	R^2	0.993	0.998	0.968
	ϵ (%)	1.57	0.444	11.4
	RMSE	0.003	0.002	0.037
	χ^2	0.001	0.0003	0.027
Fritz-Schlunder three parameter	Q_{max} (mmol/g)	1.66	3.65	4.85
	K_R (L/mmol)	0.119	0.159	0.531
	m_R	1.18	1.05	1.11
	R^2	0.997	0.999	0.999
	ϵ (%)	1.11	0.344	1.31
	RMSE	0.0018	0.0016	0.0074
	χ^2	0.0003	0.0001	0.001
Hill	Q_{SH} (L/g)	0.09	0.146	0.465
	K_D (mmol/L)	0.172	0.172	0.071
	n_H	1.51	1.16	1.32
	R^2	0.999	0.999	0.999
	ϵ (%)	0.374	0.199	0.189
	RMSE	0.0011	0.0014	0.0041
	χ^2	0.0001	0.0001	0.0003
Koble-Corrigan	a_c (L n mmol $^{(1-n)}$ /g)	0.508	0.849	6.59
	b_c (L/mmol) nc	5.80	5.81	14.2
	n_c	1.51	1.16	1.32
	R^2	0.999	0.999	0.999
	ϵ (%)	0.387	0.189	0.177
	RMSE	0.0011	0.0014	0.004
	χ^2	0.0001	0.0001	0.0003

3.2.6. Toth model

Toth (1971) has modified the Langmuir isotherm equation to improve data predication and simultaneously applicable to heterogeneous sorption systems. The model equation can be expressed as

$$Q = \frac{Q_{max} b_T C_e}{[1 + (b_T C_e)^{1/n_T}]^{n_T}} \quad (10)$$

where b_T is the Toth model constant and n_T is the Toth model exponent. The maximum Pr(III) uptake values were well-predicted by the Toth model with high R^2 and low % error, RMSE and χ^2 values. The other model

constant (b_T) was observed maximum at pH 5 (Table 2).

3.2.7. Khan model

The Khan isotherm equation (Khan et al., 1996) is a generalized model suggested for the pure solutions and the model correlation has a unique characteristic by covering both extremes of the Langmuir and Freundlich equations. The equation can be expressed as,

$$Q = \frac{Q_{\max} b_K C_e}{(1 + b_K C_e)^{a_K}} \quad (11)$$

where b_K is the Khan model constant and a_K is the Khan model exponent. As illustrated in Table 2, the Khan model isotherm constants increased with enhancement in pH and reached maximum at pH 5.

3.2.8. Radke-Prausnitz isotherm

Radke-Prausnitz isotherm (Radke and Prausnitz, 1972) can be represented as:

$$Q = \frac{a_R r_R C_f^{b_R}}{a_R + r_R C_f^{b_R-1}} \quad (12)$$

where a_R and r_R are Radke-Prausnitz model constants and b_R is the Radke-Prausnitz model exponent. The model has produced good agreement with experimental data with model constants (a_R and r_R) increased with increase in pH (Table 2). In contrast, the reverse trend was observed with b_R which was highest at pH 2.

3.2.9. Fritz-Schlunder three parameter model

The three parameter Fritz-Schlunder model (Fritz and Schlunder, 1974) can be expressed as,

$$Q = \frac{Q_{\max} K_R C_e}{1 + Q_{\max} C_e^{m_R}} \quad (13)$$

where K_R is the Fritz-Schlunder equilibrium constant (L/mmol), and m_R is the Fritz-Schlunder model exponent. High R^2 and low % error, RMSE and χ^2 values were obtained for the model (Table 2).

3.2.10. Hill isotherm

The Hill isotherm equation (Hill, 1910; Ringot et al., 2007) describes the binding of different sorbates onto homogeneous substrates. According to the model, the sorption is a cooperative phenomenon, with the ligand binding ability at one site on the macromolecule, may influence different functional sites on the same

macromolecule (Foo and Hameed, 2010). The Hill model can be expressed as

$$Q = \frac{Q_{SH} C_e^{n_H}}{K_D + C_e^{n_H}} \quad (14)$$

where Q_{SH} is the Hill isotherm maximum uptake saturation (mmol/L), K_D is the Hill constant (mmol/L) and n_H is the Hill cooperativity coefficient of the binding interaction. At high R^2 and low % error, RMSE and χ^2 values, the model well the determined maximum Pr(III) uptake values at all pH conditions (Table 2).

Table 3. Isotherm constants of four- and five-parameter models obtained during biosorption of Pr(III) onto *U. lactuca*.

Models		pH 2	pH 3	pH 5
Baudu	Q_{\max} (mmol/g)	0.0803	0.139	0.465
	b_B (L/mmol)	12.0	8.43	14.2
	x	0.797	0.262	0.324
	y	0.069	0.033	0.027
	R^2	0.999	0.999	0.999
	ϵ (%)	0.097	0.108	0.171
	RMSE	0.0001	0.0014	0.0041
	χ^2	0.00004	0.0001	0.0003
Weber-van Vliet	a_1	0.066	0.114	0.398
	a_2	0.210	0.011	0.00001
	a_3	0.0001	0.0012	0.147
	a_4	0.078	0.228	0.270
	R^2	0.962	0.954	0.943
	ϵ (%)	3.04	4.12	4.34
	RMSE	0.009	0.009	0.010
	χ^2	0.005	0.008	0.009
Fritz-Schlunder five parameter	Q_{\max} (mmol/g)	0.264	1.082	2.44
	K_1 (L/mmol)	0.264	1.083	2.44
	K_2 (L/mmol)	0.055	8.43	12.68
	m_1	0.288	1.29	1.29
	m_2	0.000002	1.26	1.30
	R^2	0.962	0.999	0.999
	ϵ (%)	2.01	0.101	1.31
	RMSE	0.007	0.001	0.007
χ^2	0.005	0.00006	0.001	

3.2.11. Koble –Corrigan model

The Koble-Corrigan model (Koble and Corrigan, 1952) incorporates the features of both the Langmuir and Freundlich model into the following form,

$$Q = \frac{a_c C_e^{n_c}}{1 + b_c C_e^{n_c}} \quad (15)$$

where a_c is the Koble-Corrigan isotherm constant, n_c is the Koble-Corrigan model exponent and b_c is the Koble-Corrigan isotherm constant (L/mmol) n_c . According to Table 2, the model well-predicted Pr(III) isotherm data.

3.2.12. Weber-van Vilet model

The four parameter Weber-van Vilet model (van Vliet et al., 1980) can be expressed as,

$$C_e = a_1 Q_e^{(a_2 Q_e^{a_3} + a_4)} \quad (16)$$

where a_1 , a_2 , a_3 and a_4 are the model coefficients determined by a multiple non-linear curve fitting technique predicted on the minimization of the sum of square of residuals. Relatively low R^2 and high % error, RMSE and χ^2 values were obtained for the model. The model constants, a_1 , a_3 and a_4 increased with increase in pH, whereas a_2 decreased with pH increment (Table 3).

3.2.13. Baudu model

The transformed Langmuir model according to Baudu (1990) can be expressed as,

$$Q = \frac{Q_{\max} b_B C_e^{(1+x+y)}}{1 + b_B C_e^{(1+x)}} \quad (17)$$

where b_B is the Baudu model equilibrium constant; x and y are the Baudu model parameters. The calculation results revealed that the Baudu model agreed well with experimental isotherm data with R^2 values greater than 0.999 (Table 3).

3.2.14. Fritz-Schlunder five parameter model

Fritz-Schlunder five parameter model (Fritz and Schlunder, 1974) can be expressed as,

$$Q = \frac{Q_{\max} K_1 C_e^{m_1}}{1 + K_2 C_e^{m_2}} \quad (18)$$

where K_1 , K_2 , m_1 and m_2 are the Fritz-Schlunder model parameters. All model parameters increased with increase in pH and reached maximum at pH 5 (Table 3).

4. CONCLUSIONS

The following conclusions can be drawn from the present investigation,

- *U. lactuca* was identified as an excellent biosorbent for Pr(III) from aqueous solutions.
- Solution pH severely affected biosorption potential of *U. lactuca* with maximum biosorption occurred at pH 5.
- Isotherm experiments revealed that *U. lactuca* can bind Pr(III) as much as 0.456 mmol/g at pH 5.
- Isotherm data were modelled using several two-, three-, four- and five-isotherm models. Of the different models examined, the Langmuir, Jovanovic, Redlich-Peterson, Sips, Toth, Khan, Radke-Prausnitz, Fritz-Schlunder three parameter, Hill, Koble-Corrigan, Baudu and Fritz-Schlunder five parameter provided better description of Pr(III) isotherm data with very high R^2 and low % error, RMSE and χ^2 values.
- Taking the above results into consideration, it can be concluded that *U. lactuca* is an efficient and practical biosorbent for the removal of Pr(III) from wastewater.

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