

Potential of *Sargassum wightii* biomass for copper(II) removal from aqueous solutions: Application of different mathematical models to batch and continuous biosorption data

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Abstract

This paper reports biosorption of copper(II) ions onto *Sargassum wightii* biomass in batch and continuous mode of operation. Batch experiments were fundamentally aimed to determine the favorable pH for copper(II) biosorption. Langmuir model was used to describe the copper(II) biosorption isotherm and maximum uptake of 115 mg/g was obtained at pH 4.5. Continuous experiments in a packed column (2 cm i.d. and 35 cm height) were performed to study the influence of bed height, flow rate and inlet solute concentration on copper(II) biosorption. The highest bed height (25 cm), lowest flow rate (5 ml/min) and highest inlet Cu(II) concentration (100 mg/l) resulted in highest copper(II) uptake of 52.6 mg/g, compared to other conditions examined. Column data obtained at different conditions were described using the Thomas, Yoon–Nelson and modified dose–response models. All three models were able to predict breakthrough curves; in particular, the breakthrough curve prediction by the Thomas and Yoon–Nelson models were found to be very satisfactory. Also, the well-established design model, the Bed depth–service time (BDST) model was used to analyze the experimental data. The BDST model plot at 5 ml/min (flow rate) and 100 mg/l (inlet solute concentration) was used to predict bed depth–service time data at different conditions. The BDST model predicted values always coincide with experimental values with high correlation coefficients. © 2006 Elsevier B.V. All rights reserved.

Keywords: Biosorption; *Sargassum wightii*; Mathematical modeling; Packed column; Copper

1. Introduction

Biosorption, the passive uptake of metal ions by inactive/dead biological materials, is an emerging technology for the removal of metal ions from contaminated solutions. It gained importance due to its inherent advantages such as low operating costs, high efficiency and possible biomass regeneration. Both microorganisms (e.g., bacteria and fungi) and macroorganisms (e.g., seaweeds) are proved efficient in metal biosorption [1,2]. However microorganisms, when applied to biosorption, often associate with problems such as solid/liquid separation and mechanical stability [3,4]. On the other hand, seaweeds performed well in metal biosorption and its performance is always superior

both in the case of batch and continuous mode of operation [5–7].

Seaweeds, a renewable natural biomass proliferate ubiquitously and abundantly in the littoral zones of world oceans, have been used as manure, cattle feed, food for human consumption and as a source of phycocolloids such as agar, alginic acid and carrageenan [8]. Apart from these, in recent years, seaweeds are extensively used for metal biosorption [1,5,9,10]. The metal biosorption potentials of various seaweeds were evaluated by many investigators and the biosorption potential usually depends on the algal division. Seaweeds usually found in three basic colors (divisions): brown (Phaeophyta), red (Rhodophyta) and green (Chlorophyta). Among these, brown seaweeds are proved efficient in metal biosorption [5] because of their polysaccharide content.

Cell walls of brown seaweed have a fibrillar compartment formed mainly of cellulose microfibrils, which is embedded in an amorphous matrix of acid polysaccharides linked each other by proteins [11,12]. The acid polysaccharides are mainly composed

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Nomenclature

a_{mdr}	modified dose–response model constant
b	Langmuir equilibrium constant (l/mg)
b_{mdr}	modified dose–response model constant
C	outlet copper(II) concentration (mg/l)
C_0	inlet or initial copper(II) concentrations (mg/l)
C_b	breakthrough copper(II) concentration (mg/l)
C_f	equilibrium or final copper(II) concentration (mg/l)
dc/dt	slope of breakthrough curve from t_b to t_e (mg/(l h))
F	volumetric flow rate (ml/min)
k_{TH}	Thomas model rate constant (l/(mg h))
k_{YN}	Yoon–Nelson model rate constant (min^{-1})
K_a	BDST model rate constant (l/(mg h))
m	slope of the BDST line
m_{ad}	metal mass sorbed (mg)
m_{total}	total amount of metal mass sent to the column (mg)
M	biosorbent mass (g)
n	intercept of the BDST line
N_0	sorption capacity of bed (mg/l)
Q	metal uptake (mg/g)
Q_0	maximum solid-phase concentration of the solute from Thomas model (mg/g)
Q_{max}	maximum metal uptake (mg/g)
R^2	correlation coefficient
t	time (h)
t_b	breakthrough time (h)
t_e	exhaustion time (h)
V	solution volume (l)
V_{eff}	volume of metal solution passed into the column (l)
Z	bed height (cm)
τ	time required for 50% sorbate breakthrough (min)
v	linear velocity (cm/h)

of alginic acids and sulfated fucans. The alginic acids are linear carboxylated copolymers constituted by different proportions of 1,4-linked β -D-mannuronic acid (M-block) and α -L-guluronic acid (G-block) [13]. The M- and G-block sequences display significantly different structures and their proportions in the alginate determine the physical properties and reactivity of the polysaccharide [14]. Acidic polysaccharides found in the cell wall of brown algae have been associated with the metal biosorption capacity of these organisms.

Copper, one of the important heavy metals widely used in electroplating industries, is the model solute used in the present study. The presence of copper causes serious health problems; it is known to deposit in the brain, liver, skin and pancreas [9]. Therefore, this study was aimed to investigate the removal of copper(II) from aqueous solution using seaweed. *Sargassum wightii*, which has shown potential in the removal of cobalt [15] and nickel [16], is a brown marine alga and was employed in

the present study for copper(II) biosorption in batch and continuous mode of operation. Batch experiments were aimed to determine favorable pH for copper(II) biosorption. An up-flow *S. wightii* biomass packed column was employed to study the copper removal as a function of bed height, flow rate and inlet copper(II) concentrations. The breakthrough profiles were analyzed using Thomas, Yoon–Nelson, modified dose–response and Bed depth–service time models.

2. Materials and methods

2.1. Biomass preparation and chemicals

S. wightii biomass, collected in Mandapam (Tamilnadu, India), was washed with distilled water and sun-dried. The samples were then grounded to an average particle size of 0.767 mm and subsequently used for biosorption experiments. All chemicals obtained from Ranbaxy Fine Chemicals Ltd. (India), including $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ were of analytical grade.

2.2. Batch experiments

Batch equilibrium experiments were conducted by adding 0.2 g of *S. wightii* biomass to Erlenmeyer flasks containing 100 ml of different Cu^{2+} concentrations at 30 °C and desired pH conditions (using 0.1 M HCl or 0.1 M NaOH). The flasks were agitated at 150 rpm in a rotary shaker. The solution pH was controlled throughout the experiment. After 6 h of contact time, the algal biomass was separated from copper(II) solution by centrifugation at 3000 rpm for 10 min. The Cu(II) content in the supernatant was determined using Flame Atomic Absorption Spectrophotometer (AAS 6VARI0; Analytik Jena, Germany) at 324.7 nm. The instrument was calibrated before each use with standard copper(II) solutions. The samples were diluted, whenever necessary, with distilled water to improve accurate estimation. The amount of metal adsorbed by alga was calculated from the differences between the metal quantity added to the biomass and the metal content of the supernatant using the following equation:

$$Q = \frac{V(C_0 - C_f)}{M} \quad (1)$$

where Q is the metal uptake (mg/g), C_0 and C_f the initial and equilibrium metal concentrations in the solution (mg/l), respectively, V the solution volume (l) and M is the mass of biosorbent (g).

2.3. Continuous experiments

Continuous biosorption experiments were conducted in a glass column (2 cm i.d. and 35 cm height), packed with known quantity of seaweed biomass [4]. Copper(II) solution of known concentration was pumped upwards through the column at desired flow rate using a peristaltic pump. Effluent samples were collected at the exit at different time intervals and analyzed for Cu(II) concentration. All the column studies were performed at a constant temperature of 30 °C.

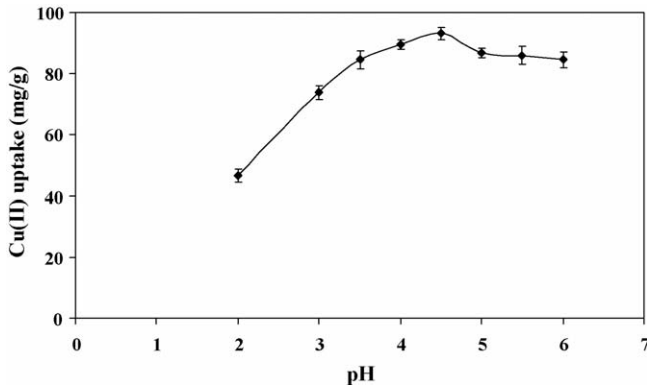


Fig. 1. Effect of pH on copper(II) uptake onto *S. wightii* ($M=2$ g/l; $C_0=1000$ mg/l; agitation rate = 150 rpm).

The total quantity of metal mass biosorbed in the column (m_{ad}) is calculated from the area above the breakthrough curve (outlet metal concentration versus time) multiplied by the flow rate. Dividing the metal mass (m_{ad}) by the biosorbent mass (M) leads to the uptake capacity (Q) of the biomass. The total amount of metal ions sent to the column can be calculated from the following equation:

$$m_{total} = \frac{C_0 \cdot F \cdot t_e}{1000} \quad (2)$$

where C_0 is the inlet metal ion concentration (mg/l), F the volumetric flow rate (ml/h) and t_e is the exhaustion time (h).

Total metal removal (%) with respect to flow volume can be calculated from the ratio of metal mass adsorbed (m_{ad}) to the total amount of metal ions sent to the column (m_{total}) as follows:

$$\text{Total metal removal (\%)} = \frac{m_{ad}}{m_{total}} \times 100 \quad (3)$$

All batch and continuous experiments were done in duplicates. The data were the mean values of two replicate experiments. Error bars were indicated wherever necessary.

3. Results and discussion

3.1. Batch studies

3.1.1. Effect of pH

The solution pH has been reported to be the most important variable governing the biosorption of metal ions by biosorbents [17]. Therefore, initially experiments were conducted to study the effect of pH on copper(II) biosorption onto *S. wightii* (Fig. 1). It was observed that the copper(II) biosorption was relatively less at low pH values (pH 2–3). The less metal uptake at these pH conditions may be explained on the basis of binding sites being protonated, resulting in a competition between H^+ and Cu^{2+} ions for occupancy of the binding sites [18]. As the pH increases, the competition by protons decreases and surface functional groups gets activated, which resulted in increased metal biosorption and the sharpest increase in copper(II) uptake was observed in the pH range of 4–5. Further increase in pH resulted in slight decline in metal uptake.

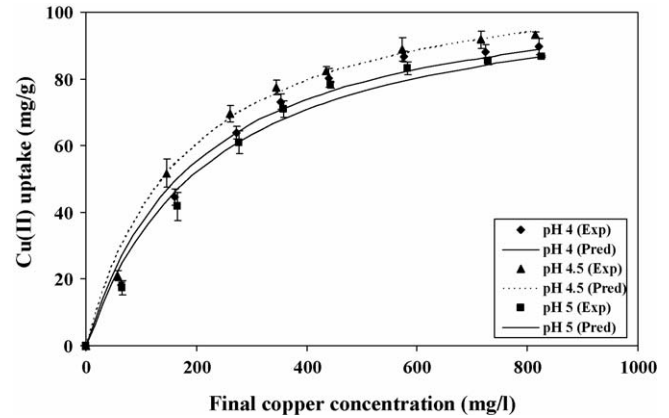


Fig. 2. Application of Langmuir model to experimental copper(II) biosorption isotherm at different pH conditions ($M=2$ g/l; agitation rate = 150 rpm).

3.1.2. Biosorption isotherms

Biosorption isotherm, the plot of metal uptake (Q) versus the residual concentration of the metal in the solution at equilibrium (C_f), was obtained in the pH range of 4–5 by varying initial $Cu(II)$ concentration from 100 to 1000 mg/l (Fig. 2). At all the pH conditions examined, as the metal concentration increases the uptake also increased and reached a plateau at higher concentrations. Among the pH values examined, pH 4.5 was observed as the optimum condition for copper(II) biosorption onto *S. wightii*.

In order to investigate the biosorption isotherms, the Langmuir isotherm model was used in the present study. It has the following form:

$$Q = \frac{Q_{max} b C_f}{1 + b C_f} \quad (4)$$

where Q_{max} is the maximum metal uptake (mg/g) and b is the Langmuir affinity constant (l/mg). The Langmuir model served to estimate the maximum metal uptake values where they could not be reached in the experiments. The constant b represents affinity between the sorbent and sorbate. The maximum copper(II) uptake (Q_{max}) was observed as 110.1, 115.0 and 109.9 mg/g at pH 4, 4.5 and 5, respectively. The constant b was recorded as 0.005, 0.006 and 0.004 l/mg at pH 4, 4.5 and 5, respectively. The correlation coefficients were always greater than 0.988. For good biosorbents, in general, high Q_{max} and a steep initial isotherm slope (i.e. high b) are desirable. Considering this, pH 4.5 was observed as favorable pH for copper(II) biosorption onto *S. wightii*, according to the Langmuir model.

3.2. Continuous studies

The sorption capacity of biosorbent, obtained from batch equilibrium experiments, is useful in providing fundamental information about the effectiveness of metal–biosorbent system. However, this data may not be applicable to most treatment system (such as column operations) where contact time is not sufficient for the attainment of equilibrium [19]. Hence, there is a need to perform biosorption studies using column. For this reason a packed column arrangement was employed in this study,

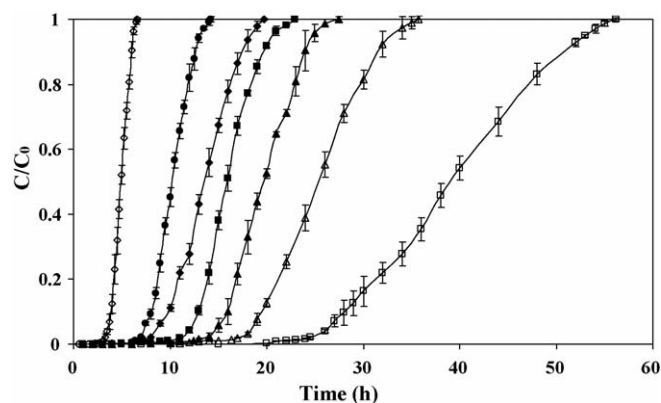


Fig. 3. Breakthrough curves for copper(II) biosorption onto *S. wightii* at different bed heights, flow rates and inlet copper(II) concentrations (influent pH 4.5). Bed height, flow rate and inlet Cu(II) concentration: (◆) 15 cm, 5 ml/min and 100 mg/l; (■) 20 cm, 5 ml/min and 100 mg/l; (▲) 25 cm, 5 ml/min and 100 mg/l; (●) 25 cm, 10 ml/min and 100 mg/l; (◇) 25 cm, 20 ml/min and 100 mg/l; (□) 25 cm, 5 ml/min and 50 mg/l; (△) 25 cm, 5 ml/min and 75 mg/l.

as it efficiently utilize the sorbent capacity and results in a better quality of the effluent [20].

3.2.1. Effect of bed height

Initially, the effect of bed height on the copper(II) biosorption characteristics of *S. wightii* in the continuous flow packed column was examined at pH 4.5 by varying bed height from 15 to 25 cm while the flow rate and the inlet copper(II) concentration were held constant at 5 ml/min and 100 mg/l, respectively. Fig. 3 shows the plot of C/C_0 versus time (breakthrough curve) at different bed heights. In order to yield different bed heights, 7.05, 9.38 and 11.73 g of *S. wightii* were added to produce bed heights of 15, 20 and 25 cm, respectively. The copper(II) uptake capacity of the biomass remained almost identical for different bed heights investigated (Table 1), probably because uptake capacity strongly depends on the amount of sorbent available for the sorption [21]. The breakthrough time (t_b , the time at which outlet Cu(II) concentration reached 1 mg/l) and exhaustion time (t_e , the time at which outlet Cu(II) concentration reached the value of inlet Cu(II) concentration) increased with the increase in bed height. The slope of the S-curve from t_b to t_e (dc/dt) decreased as the bed height increased from 15 to 25 cm, indicating the breakthrough curve becomes steeper as the bed height decreased. As expected, an increased bed height resulted in high volume of metal solution treated and high percentage of copper(II) removal.

Table 1

Column data and parameters obtained at different bed heights, flow rates and inlet copper(II) concentrations

Bed height (cm)	Flow rate (ml/min)	Inlet Cu(II) concentration (mg/l)	$Q \pm$ S.D. (mg/g)	t_b (h)	t_e (h)	dc/dt (mg/(lh))	Cu(II) removal (%)
15	5	100	51.7 ± 1.9	7.4	19.7	9.13	61.7
20	5	100	51.9 ± 1.3	9.8	22.9	8.89	70.9
25	5	100	52.6 ± 2.2	12.4	27.5	7.91	74.7
25	10	100	51.8 ± 1.8	6.4	14.2	14.81	71.3
25	20	100	48.9 ± 2.1	3.1	6.6	32.23	72.4
25	5	75	49.3 ± 1.2	16.4	35.7	4.30	72.1
25	5	50	48.4 ± 2.2	24.5	56.2	1.67	67.3

3.2.2. Effect of flow rate

Fig. 3 shows the breakthrough curves obtained at different flow rates (5–20 ml/min) while bed height and inlet Cu(II) concentration were held constant at 25 cm and 100 mg/l, respectively. The results in Table 1 shows that copper(II) biosorption onto *S. wightii* depends on flow rate. At the lowest flow rate (5 ml/min), typical S-shaped breakthrough curve was observed. A delayed breakthrough and exhaustion time resulted in efficient utilization of *Sargassum* bed, which in turn resulted in better metal uptake and percent metal removal at the lowest flow rate (Table 1). As the flow rate increased, breakthrough curves became steeper. Relatively early breakthrough and exhaustion time resulted in comparatively less copper(II) uptake and percent copper(II) removal at higher flow rates. This behavior may be due to insufficient residence time of the metal ions in the column [19,22].

3.2.3. Effect of inlet metal concentration

Experiments were also conducted at different inlet Cu(II) concentrations to examine the continuous biosorption performance of *S. wightii*. The breakthrough curves obtained by changing inlet Cu(II) concentration from 50 to 100 mg/l at 25 cm bed height and 5 ml/min flow rate are shown in Fig. 3. The lowest inlet Cu(II) concentration (50 mg/l) resulted in delayed breakthrough curve since the lower concentration gradient caused a slower transport [23]. As the inlet Cu(II) concentration increases, much sharper breakthrough curves were observed. Taking the column biosorption performance into account, highest inlet Cu(II) concentration resulted in better copper(II) uptake and percent copper(II) removal (Table 1). The driving force for biosorption is the concentration difference between the solute on the sorbent and the solute in the solution. A high concentration difference provides a high driving force, which favors biosorption. Much sharper breakthrough curve observed at the highest inlet Cu(II) concentration (Table 1), indicator of shortened mass transfer zone, is also preferable.

3.2.4. Column data modeling

To describe the column breakthrough curves obtained at different bed heights, flow rates and inlet metal concentrations, three models were used. These include,

Thomas model:

$$\frac{C_0}{C} = 1 + \exp\left(\frac{k_{TH}}{F}(Q_0M - C_0V_{eff})\right) \quad (5)$$

Yoon–Nelson model:

$$\frac{C}{C_0} = \frac{\exp(k_{YN}t - \tau k_{YN})}{1 + \exp(k_{YN}t - \tau k_{YN})} \quad (6)$$

Modified dose–response model:

$$\frac{C}{C_0} = 1 - \frac{1}{1 + (V_{\text{eff}}/b_{\text{mdr}})^{a_{\text{mdr}}}} \quad (7)$$

where k_{TH} is the Thomas model rate constant ($l/(mg\ h)$), Q_0 the maximum solid-phase concentration of the solute (mg/g), V_{eff} the volume of metal solution passed into the column (l), k_{YN} the Yoon–Nelson model rate constant (min^{-1}), τ the time required for 50% adsorbate breakthrough (min) and a_{mdr} and b_{mdr} are the modified dose–response model constants. All the model parameters were evaluated by non-linear regression using MATLAB[®] software.

The Thomas model is one of the most widely used methods to describe column biosorption data. The Thomas model, which assumes Langmuir kinetics of sorption–desorption and no axial dispersion is derived with the sorption that the rate driving force obeys second-order reversible reaction kinetics [23]. In the present study, the Thomas model predicted the breakthrough curves well at all conditions examined with very high correlation coefficients. The breakthrough curve predicted by the Thomas model for the column biosorption data obtained at optimum bed height (25 cm), flow rate (5 ml/min) and inlet Cu(II) concentration (100 mg/l) is shown in Fig. 4. Also, the predicted copper(II) uptake values always coincide with the experimental uptake values (Table 2). Contrary to the copper(II) uptake values, the Thomas model rate constant (k_{TH}) decreased with increase in bed height and inlet Cu(II) concentration, while increased with increase in flow rate values.

The Yoon–Nelson model is based on the assumption that the rate of decrease in the probability of adsorption for each sorbate molecule is proportional to the probability of sorbate sorption and the probability of sorbate breakthrough on the sorbent [23]. Table 2 shows the values of k_{YN} and τ at different conditions. The Yoon–Nelson model rate constant (k_{YN}) follows the same trend as that of the Thomas model rate constant (k_{TH}). The time required for 50% sorbate breakthrough (τ) obtained from the Yoon and Nelson model agreed well with the experimental data at all conditions examined. The experimental breakthrough curves were very close to those of pre-

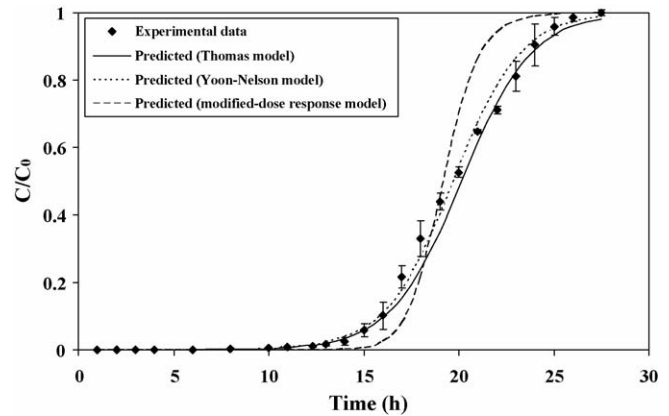


Fig. 4. Application of Thomas, Yoon–Nelson and modified dose–response models to experimental column data at bed height = 25 cm; flow rate = 5 ml/min; inlet Cu(II) concentration = 100 mg/l.

dicted by Yoon–Nelson model and one typical example is shown in Fig. 4.

The modified dose–response model [24] is also used to describe column biosorption data. Yan et al. [24] observed that use of this model minimizes the error resulting from the use of the Thomas model, especially at lower or higher time periods of the breakthrough curve. The model constants (a_{mdr} and b_{mdr}) are given in Table 2. The breakthrough curve predicted by modified dose–response model (for 25 cm bed height, 5 ml/min flow rate and 100 mg/l inlet Cu(II) concentration) is shown in Fig. 4. At all conditions examined, the predicted breakthrough curves showed reasonably good agreement with the experimental curves.

3.2.5. Bed depth–service time model

The Bed depth–service time (BDST) model, proposed by Bohart and Adams [25] and subsequently modified by Hutchins [26], is based on physically measuring the capacity of the bed at different breakthrough values. This simplified design model ignores the intraparticle mass transfer resistance and the external film resistance such that the sorbate is sorbed onto the sorbent surface directly [27]. The BDST model states that bed height (Z) and service time (t) of a column bears a linear relationship. The equation can be expressed as:

$$t = \frac{N_0 Z}{C_0 v} - \frac{1}{K_a C_0} \ln \left(\frac{C_0}{C_b} - 1 \right) \quad (8)$$

Table 2

Thomas, Yoon–Nelson and modified dose–response model parameters at different bed heights, flow rates and inlet Cu(II) concentrations

Z (cm)	F (ml/min)	C_0 (mg/l)	Thomas model			Yoon and Nelson model			Modified dose–response model		
			Q_0	k_{TH}	R^2	k_{YN}	τ	R^2	a_{mdr}	b_{mdr}	R^2
15	5	100	50.1	0.0067	0.995	0.67	13.7	0.995	15.4	3.93	0.970
20	5	100	51.6	0.0063	0.998	0.63	16.1	0.998	16.8	4.66	0.988
25	5	100	52.6	0.0054	0.994	0.56	19.7	0.995	20.3	5.76	0.967
25	10	100	52.2	0.0111	0.995	1.11	10.3	0.995	21.9	3.02	0.962
25	20	100	50.2	0.0240	0.993	2.40	4.9	0.994	22.4	1.43	0.954
25	5	75	48.7	0.0053	0.998	0.40	25.3	0.998	18.9	7.29	0.973
25	5	50	48.6	0.0049	0.994	0.24	39.4	0.992	19.8	11.27	0.957

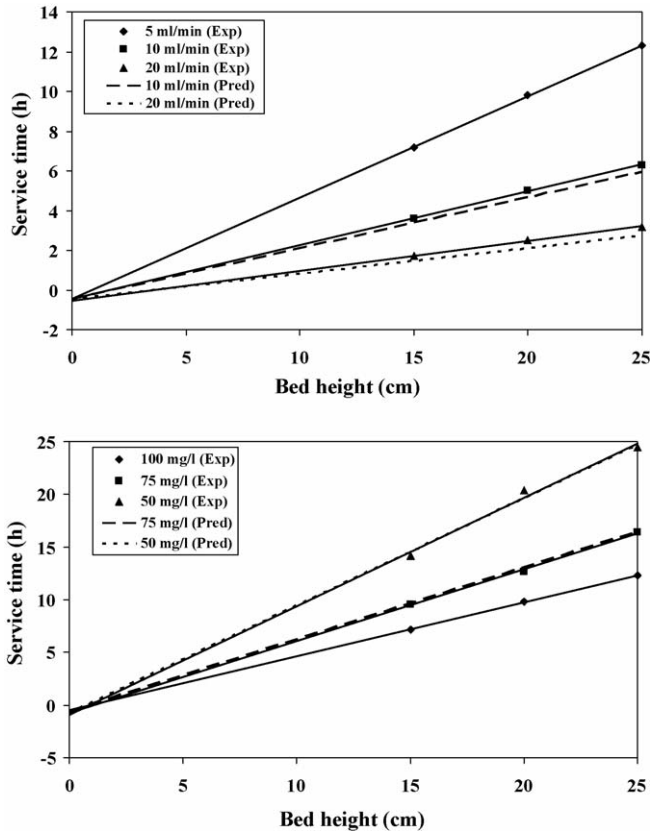


Fig. 5. BDST model plots for copper(II) biosorption at different flow rates and inlet Cu(II) concentrations.

where C_b is the breakthrough metal ion concentration (mg/l), N_0 the sorption capacity of bed (mg/l), v the linear velocity (cm/h) and K_a is the rate constant (l/(mg h)). Eq. (8) implies that the service time is a linear function of the bed height and hence it can be written as:

$$t = mZ - n \tag{9}$$

where m is the slope of the BDST line and n is the intercept of the BDST line.

The plot of service time against bed height at a flow rate of 5 ml/min and inlet Cu(II) concentration of 100 mg/l (Fig. 5) was linear ($R^2 = 0.999$) indicating the validity of BDST model for the present system. The sorption capacity of the bed per unit bed volume, N_0 , was calculated from the slope of BDST plot, assuming inlet concentration, C_0 , and linear velocity, v , as constant during the continuous operation. The rate constant, K_a , calculated from the intercept of BDST plot, characterizes the rate of solute transfer from the fluid phase to the solid phase [28]. The computed N_0 and K_a were 4872 mg/l and 0.106 l/(mg h), respectively, at 5 ml/min and 100 mg/l. If K_a is large, even a short bed will avoid breakthrough, but as K_a decreases a progressively longer bed is required to avoid breakthrough [28].

The BDST equation determined at a given flow rate (v) and inlet solute concentration (C_0) can be modified to predict the BDST equations at different v and C_0 . Cooney [28] suggested that the BDST model rate constant (K_a) is not significantly affected by the change in flow rate, and thus the intercept n of

Table 3

Experimental and predicted Bed depth–service time equation constants for biosorption of copper(II) ions onto *S. wightii*

Flow rate (ml/min)	Initial Cu(II) concentration (mg/l)	Analysis	Slope	Intercept	R^2
5	100	Experimental	0.51	−0.433	0.999
10	100	Experimental	0.27	−0.433	0.999
10	100	Predicted	0.26	−0.433	1.000
20	100	Experimental	0.15	−0.533	0.998
20	100	Predicted	0.13	−0.433	1.000
5	75	Experimental	0.68	−0.711	0.997
5	75	Predicted	0.68	−0.541	1.000
5	50	Experimental	1.03	−0.895	0.986
5	50	Predicted	1.02	−0.734	1.000

Eq. (9) remains essentially unchanged when flow rate is changed. However, the slope m of Eq. (9) does change with change in flow rate and hence given by:

$$\text{New slope} = \text{old slope} \left(\frac{v_{\text{old}}}{v_{\text{new}}} \right) \tag{10}$$

In contrary, the change in inlet solute concentration (C_0) usually results in change in slope and intercept of BDST equation. The new slope and intercept values can be determined from [28]:

$$\text{New slope} = \text{old slope} \left(\frac{C_{0,\text{old}}}{C_{0,\text{new}}} \right) \tag{11}$$

$$\begin{aligned} \text{New intercept} = \text{old intercept} & \left(\frac{C_{0,\text{old}}}{C_{0,\text{new}}} \right) \\ & \times \left(\frac{\ln[(C_{0,\text{new}}/C_b) - 1]}{\ln[(C_{0,\text{old}}/C_b) - 1]} \right) \end{aligned} \tag{12}$$

Table 3 shows the slope and intercept of BDST equations at different flow rates and inlet solute concentrations predicted using BDST model parameters obtained at 5 ml/min flow rate and 100 mg/l inlet solute concentration. BDST model parameters obtained experimentally at different v and C_0 is also shown in Table 4. Also, Fig. 5 compares the experimental and BDST model predictions for copper(II) biosorption onto *S. wightii*. It can be seen from Table 3 and Fig. 5 that the experimental and predicted values of slope and intercept showed excellent agreement. The advantage of the BDST model is that any experimental

Table 4

Bed depth–service time model parameters for biosorption of copper(II) ions onto *S. wightii*

Flow rate (ml/min)	Initial Cu(II) concentration (mg/l)	N_0 (mg/l)	K_a (l/(mg h))
5	100	4872	0.106
10	100	5159	0.106
20	100	5732	0.086
5	75	4901	0.083
5	50	4920	0.089

test can be reliably scaled up to other flow rates and inlet solute concentrations without further experimental test.

4. Conclusions

This study demonstrated that the raw biomass of brown marine alga, *S. wightii*, could be used as an effective biosorbent for the treatment of wastewater containing copper(II) ions. Through batch experiments, pH 4.5 was observed as the favorable condition for copper(II) biosorption. A maximum copper(II) uptake of 115 mg/g was obtained at pH 4.5, according to the Langmuir model. Continuous experiments revealed the importance of bed height, flow rate and inlet solute concentration on copper(II) biosorption. Increasing bed height and inlet solute concentration resulted in better column performance, while the lowest flow rate favored biosorption. It has also been demonstrated that column data could be adequately described by the Thomas, Yoon–Nelson and modified dose–response models. The BDST model provides a description of the experimental results for the bed height and service time at different flow rate and inlet Cu(II) concentrations.

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