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Biosorption of selenium from aqueous solution by green algae (*Cladophora hutchinsiae*) biomass: Equilibrium, thermodynamic and kinetic studies

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ABSTRACT

The equilibrium, thermodynamics and kinetics of selenium(IV) biosorption from aqueous solution by dead green algae (*Cladophora hutchinsiae*) biomass was investigated. Optimum biosorption conditions were determined with respect to pH, biomass concentration, contact time, and temperature. The equilibrium data were analyzed using the Langmuir, Freundlich and Dubinin–Radushkevich (D–R) isotherm models. The maximum biosorption capacity of *C. hutchinsiae* biomass for Se(IV) was found to be 74.9 mg/g at pH 5, biomass concentration 8 g/L, contact time 60 min, and temperature 20 °C. The biosorption percentage decreased from 96% to 60% as temperature was increased from 20 to 50 °C during the equilibrium time.

From D–R model, the calculated mean biosorption energy (10.9 kJ/mol) indicated that the biosorption of Se(IV) onto *C. hutchinsiae* biomass was taken place by chemical ion-exchange.

The highest recovery (95%) was achieved using 0.5 M HCl. The high stability of *C. hutchinsiae* permitted a slightly decrease about 20% in recovery of Se(IV) ions after ten times of adsorption-elution process. The calculated thermodynamic parameters, ΔG° (between −18.39 and −16.08 kJ/mol at 20–50 °C) and ΔH° (−45.96 kJ/mol) showed that the biosorption of Se(IV) onto *C. hutchinsiae* biomass was feasible, spontaneous and exothermic, respectively. The experimental data was also fitted to the Lagergren's first-order and pseudo second-order kinetic models. The results revealed that the pseudo second-order reaction model provided the best description these data with coefficients of determination in range of 0.992–0.999. The biosorption rate constant was calculated as 24.9×10^{-2} g/(mg min).

1. Introduction

Selenium is a relevant element due to its important role in life processes, being recognized as an essential nutrient [1,2]. On the other hand, selenium is toxic at concentrations above the range of that considered a health level in human diet, 1 mg of selenium per kg of body weight [3]. Selenium is also a byproduct of certain industrial processes, such as electrolytic copper refining and combustion of fossil fuels, and is used in insecticides, glass manufacturing, rectifiers, semiconductors, xerography, and photocells [4,5].

Selenate ($SeO_4{}^{2-}$), selenite ($SeO_3{}^{2-}$), elemental selenium, and selenide are four species of selenium that exist in soil, whereas Se(IV) and Se(VI) dominate in aqueous systems. In general, selenium species in the +4 oxidation state are more toxic than the species containing selenium in their +6 state [6,7]. Recently there has been a remarkable increase of interest in the study of selenium because of the strong correlation between cancer and the selenium concentration in diet [8–10]. Selenium is an essential element to life for concentrations below 40 mg g^{-1}, but it is toxic above 4000 mg g^{-1} [11].

The most widely used methods for removing heavy metals from wastewaters include ion-exchange, chemical precipitation, reverse osmosis, evaporation, membrane filtration, adsorption, and biosorption [12–14]. Biosorption is a relatively new technology to remove heavy metals from industrial wastewater. The major advantages of the biosorption technology are its effectiveness in reducing the concentration of heavy metal ions to very low levels and the use of inexpensive biosorbent materials [15–19].

Among the biological materials marine algae otherwise known as seaweeds have been reported to have high metal binding capacities due to the presence of polysaccharides, proteins or lipid on the cell wall surface containing functional groups such as amino, hydroxyl, carboxyl and sulphate, which can act as binding sites for metals [20–22]. Different sorbent species have been used for selenium removal from aqueous solution [23–28]. However, according to authors' survey, there is no extensive study on the biosorption of selenium using *Cladophora hutchinsiae* (green algae) biomass in literature. In addition, this material was chosen as novel biosorbent

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in this study due to being of its naturally abundant, renewable and thus cost-effective biomass.

The objective of the present work is to investigate the sorption capacity green algae (*C. hutchinsiae*) biomass for Se(IV) ions from aqueous solution. Optimum biosorption conditions were established at different pH 2–8, biomass concentration 1–20 g/L, contact time 5–120 min, and temperature 20–50 °C. The Langmuir and Freundlich models were used to describe equilibrium isotherms. The equilibrium data were also subjected to the D–R isotherm model to determine the nature of biosorption processes as physical or chemical. The desorption of Se(IV) from *C. hutchinsiae* was also studied by using 0.5 M HCl and 0.5 M HNO_3. In order to clarify the biosorption kinetics of Se(IV) by *C. hutchinsiae* biomass, Lagergren's pseudo first-order and pseudo second-order model were applied to the experimental data. In addition, thermodynamic parameters including the change in free energy (ΔG°), enthalpy (ΔH°) and entropy (ΔS°) were calculated to evaluate the thermodynamic behavior of the biosorption process.

2. Experimental procedures

2.1. Biomass preparation

The green alga (*C. hutchinsiae*) samples were collected from the Aegean coast of Turkey. Samples were collected in summer (June–August) in 2008. The collected samples were washed repeatedly with deionized water to remove extraneous materials and salts. The biomass was then dried in an oven at 333 K for 48 h until no variation in the sample weight observed. The dried algae biomass was chopped, sieved and the particles with an average of 0.5 mm was used for biosorption experiments.

2.2. Batch biosorption procedure

Se(IV) standard solution (1000 mg L^{-1}) was prepared from Na_2SeO_3 (E. Merck, Darmstadt, Germany). Sodium phosphate buffer (0.1 mol L^{-1}) was prepared by adding an appropriate amount of phosphoric acid to sodium dihydrogen phosphate solution to result in a solution of pH 2–4. Ammonium acetate buffers (0.1 mol L^{-1}) were prepared by adding an appropriate amount of acetic acid to ammonium acetate solutions to result in solutions of pH 4–6. Ammonium chloride buffer solutions (0.1 mol L^{-1}) were prepared by adding an appropriate amount of ammonia to ammonium chloride solutions to result in solutions of pH 6–8. The biomass was then added and content in the flask was shaken for desired contact time on an electrically thermostatic reciprocating shaker (Selecta multimatic-55, Spain) at 120 rpm. The time required for reaching the equilibrium condition was estimated by drawing samples at regular intervals of time until equilibrium was reached. The contents of the flask were filtered through filter paper and the filtrate was analyzed for selenium concentration by using HGAAS. The batch biosorption procedure mentioned above were repeated at different experimental parameters: the contact time 5–120 min, pH 2–8, initial metal concentration 10–400 mg/L, the biomass concentration 1–20 g/L and the temperature 20–50 °C. To ensure the accuracy, reliability and reproducibility of the collected data, all batch experiments were carried out in duplicated and the mean values of two data sets are presented. The error bars and were also shown in the presentation of the results. The percent biosorption of Se(IV) was calculated as follows:

$$\text{Biosorption}(\%) = \frac{C_i - C_f}{C_i} \times 100 \qquad (1)$$

where C_i (ng/L) and C_f (mg/L) are the initial and final Se(IV) concentrations, respectively.

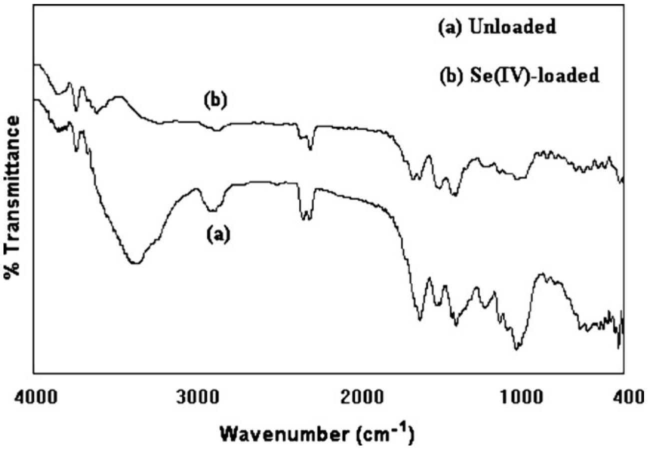

Fig. 1. FT-IR spectrum of unloaded and Se(IV)-loaded biomass.

2.3. Desorption procedure

The Se(IV) ions sorbed onto *C. hutchinsiae* biomass were desorbed using 10 mL of 0.5 M HCl and 10 mL of 0.5 M HNO_3, separately. Selenium content of the solution was determined by HGAAS. In order to use the biomass for the next experiment, the biomass was washed with excess of 0.5 M HCI solution and distilled water, sequentially.

3. Results and discussion

3.1. FT-IR analysis

Fourier Transform Infrared (FT-IR) spectra of dried unloaded biomass and Se(IV)-loaded biomass were recorded at 400–4000 cm^{-1} wavenumber range by using a FT-IR spectrometer (JASCO-430 model, Japan). This spectroscopic analysis was used to obtain information on the nature of possible cell–metal ions interactions and the results are presented in Fig. 1. The broad and strong bands at 3380–3740 cm^{-1} were due to bounded hydroxyl (–OH) groups of the algal biomass. The peaks at 2320 and 2355 cm^{-1} represent the stretching vibrations of $-NH_2^+$, $-NH^+$ and –NH groups of the biomass. The bands peaks at 1648, 1689 and 1543 cm^{-1} may be attributed to asymmetric and symmetric stretching vibration of carboxyl (–C=O) groups. The band observed at 1112 cm^{-1} was assigned to C–O stretching of alcohols and carboxylic acids. Some bands in the fingerprint region could be attributed to the phosphate groups.

After Se(IV) biosorption, the stretching vibration bands of hydroxyl were shifted to 3237–3752 cm^{-1} for Se(IV)-loaded biomass. The stretching vibration bands of amide groups were shifted to 2314 and 2371 cm^{-1}. The asymmetric and symmetric stretching vibration bands of carboxyl groups were shifted to 1639–1674 cm^{-1} and 1528 cm^{-1}. The bands assigned to C–O stretching were also shifted to 1124 cm^{-1}. The results indicated that the chemical interactions as ion-exchange between the metal ions and the hydrogen atoms of carboxyl, hydroxyl, and amide groups of the biomass were mainly involved in the biosorption. The similar FT-IR results were reported for the biosorption of different heavy metals on various algae species [29–32].

3.2. Effect of pH

One of the important factors affecting adsorption of metal ions is acidity of solution [33]. Solution pH affects the metal binding sites

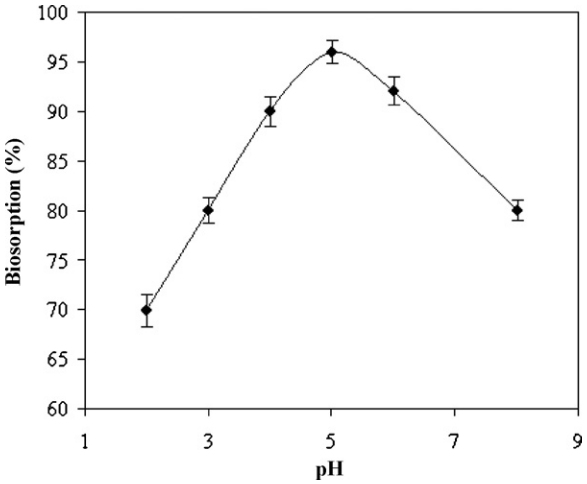

Fig. 2. Effect of pH on the biosorption of Se(IV) by *C. hutchinsiae* biomass (selenium concentration: 10 mg/L; temperature: 20 °C).

of the sorbent and the metal ion chemistry in aqueous solution [34,35]. Various authors have shown that solution pH greatly influences metal biosorption by algae biomass [36–39]. Algal biomasses contain high content of carboxyl groups from mannuronic and guluronic acids on the cell wall polysaccharides, which suggest that the biosorption process could be affected by changes in the solution pH [40].

The effect of pH on the biosorption of Se(IV) onto *C. hutchinsiae* biomass was studied at pH 2–8, metal concentration 10 mg/L, biomass concentration 8 g/L, and temperature 20 °C. The results were presented in Fig. 2. Se(IV) species in aqueous solution include seleniuos acid (H_2SeO_3), biselenite ($HSeO_3{}^-$) and selenite ($SeO_3{}^{2-}$) [41,42]. Between pH 3.5 and 9.0 biselenite ion is the predominant ion in water. Above pH 9.0 selenite species dominate and as pH decreases below pH 3.5, selenious acid dominates [43]. In the present work, the highest Se(IV) sorption was determined to be 96% at pH 5 as the lowest biosorption was found to be 70% at pH 2. Therefore, pH 5 was selected as optimum pH for further experiments. At low pH values, the low biosorption of selenium is due to the fact that the neutral species (H_2SeO_3) cannot undergo electrostatic interaction with the biosorbent. However, such species can interact with the unprotonated amino groups. Moreover, the high extent of sorption at pH 5 is related to protons sufficiency that allows more reduction of Se(IV) to elemental selenium to take place on the sorbent surface.

3.3. *Effect of biomass concentration*

The biosorption efficiency as a function of biomass concentration was investigated was investigated at other experimental conditions, metal concentration 10 mg/L, biomass concentration 8 g/L, pH 5 and temperature 20 °C. The results are represented in Fig. 3. The metal biosorption steeply increases with the biomass concentration up to 8 g/L. Increase in the biosorption percent with increase in biomass concentration was attributed to the availability of more sorption sites. At very low biomass concentration, the biosorbent surface becomes saturated with the metal ions and the residual metal ion concentration in the solution is large. However, there was no observed significantly increase in the biosorption percent. The biosorption yield was 96% for the biomass concentration 8 g/L as it was found to be 98% for the biomass concentration 20 g/L. Therefore, the biomass concentration 8 g/L was selected as optimum for further experiments.

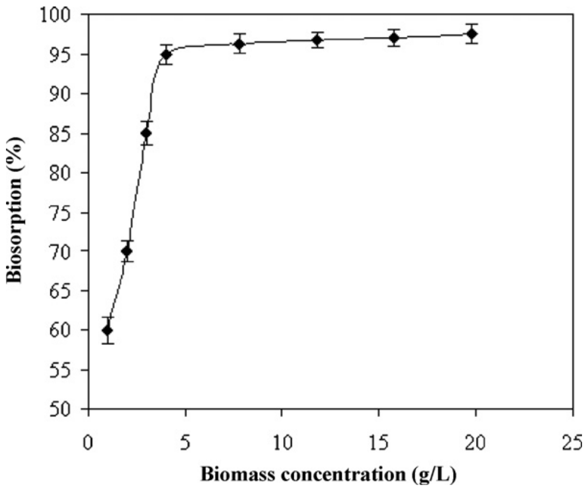

Fig. 3. Effect of biomass dosage on the biosorption of Se(IV) by *C. hutchinsiae* biomass (selenium concentration: 10 mg/L; pH: 5; temperature: 20 °C).

3.4. *Effects of contact time and temperature*

The rate of sorption is one of the most important parameters when designing a batch sorption experiment. The experimental runs measuring the effect of contact time on the biosorption of selenium at the conditions, metal concentration 10 mg/L, biomass concentration 8 g/L and pH 5. As shown in Fig. 4 the biosorption of selenium is fast and the equilibrium was achieved by 60 min of contact time.

Temperature of the medium affects on the removal efficiency of the pollutant from aqueous solution. To study the effect of temperature, biosorption experiments are carried out at 20–50 °C at optimum pH (5.0) and biomass concentration level, 8 g/L. The equilibrium contact time for biosorption was maintained at 60 min. As seen from Fig. 4, the biosorption percentage decreased from 96% to 60% as temperature was increased from 20 to 50 °C. These results indicated the exothermic nature of selenium biosorption onto *C. hutchinsiae* biomass. The decreasing in biosorption efficiency may be attributed to many parameters: the relative increase in the escaping tendency of the selenium ions from the solid phase to the bulk phase; deactivating the biosorbent surface or destructing some active sites on the biosorbent surface due to bond ruptures [44,45] or due to the weakness of biosorptive forces between the

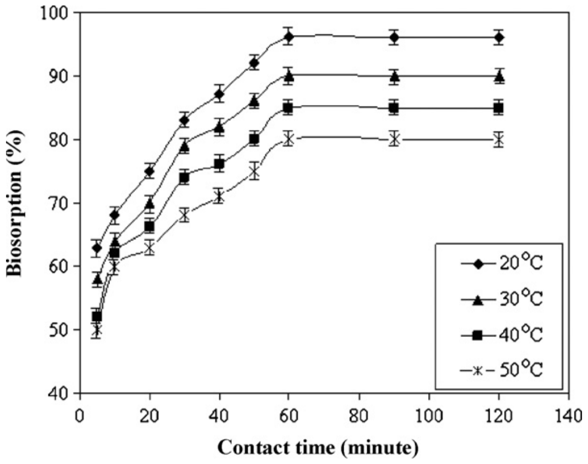

Fig. 4. Effect of contact time and temperature on the biosorption of Se(IV) by *C. hutchinsiae* biomass (selenium concentration: 10 mg/L; biomass concentration: 8 g/L; pH: 5).

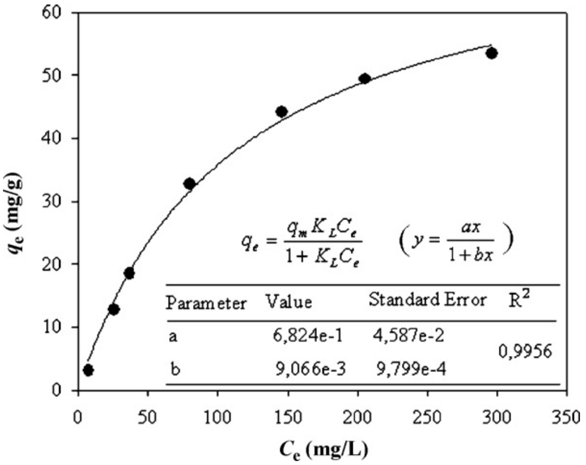

Fig. 5. Langmuir isotherm plots for the biosorption of Se(IV) by *C. hutchinsiae* biomass (biomass concentration: 8 g/L; contact time: 60 min; pH: 5; temperature: 20 °C).

active sites of the sorbents and the sorbate species and also between the adjacent molecules of sorbed phase [46]. The results are in agreement with the point of view of thermodynamics.

3.5. Biosorption isotherm models

A biosorption isotherm is characterized by certain constant values, which express the surface properties and affinity of the biosorbent and can also be used to compare the biosorptive capacities of the biosorbent for different pollutants. In this study, the biosorption isotherms were investigated using three equilibrium models, which are namely the Langmuir, Freundlich and Dubinin–Radushkevich (D–R) isotherm models were analyzed.

A basic assumption of the Langmuir theory is that sorption takes place at specific homogeneous sites within the sorbent. This model can be written in non-linear form [47].

$$q_e = \frac{q_m K_L C_e}{1 + K_L C_e} \tag{2}$$

where q_e is the equilibrium metal ion concentration on sorbent (mg/g), C_e is the equilibrium metal ion concentration in the solution (mg/L), q_m is the monolayer biosorption capacity of the sorbent (mg/g), and K_L is the Langmuir biosorption constant (L/mg) related with the free energy of biosorption. Non-linear regression analysis was carried out in SigmaPlot software (SigmaPlot 2001, SPSS Inc., USA) in order to determine K_L and q_m values.

Fig. 5 indicates the non-linear Langmuir isotherm plot and the standard error in the determination of the parameters. As seen from the figure, the coefficient of determination (R^2) was found to be 0.9956. This result indicates that the biosorption of the selenium ions onto *C. hutchinsiae* biomass fitted well the Langmuir model. In other words, the sorption of selenium using *C. hutchinsiae* was taken place at the functional groups/binding sites on the surface of the biomass which is regarded as monolayer biosorption. The maximum biosorption capacity (q_m) of *C. hutchinsiae* biomass was found to be 74.9 mg/g. The K_L value was found as 9.10^{-3} L/mg. In addition, Table 1 presents the comparison of biosorption capacity of *C. hutchinsiae* for selenium with that of various sorbents reported in literature [4,23–26,42]. The biosorption capacity of *C. hutchinsiae* biomass for selenium is higher than that of the majority of other biosorbents mentioned. Therefore, it can be worthy noted that the *C. hutchinsiae* biomass has important potential for the removal of selenium from aqueous solution.

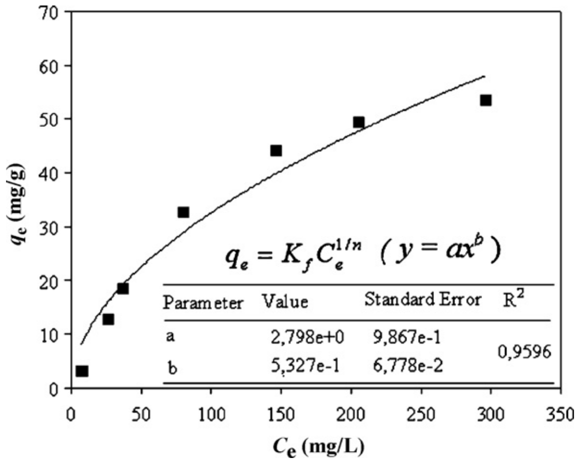

Fig. 6. Freundlich isotherm plots for the biosorption of Se(IV) by *C. hutchinsiae* biomass (biomass dosage: 8 g/L; contact time: 60 min; pH: 5; temperature: 20 °C).

The Freundlich model assumes a heterogeneous adsorption surface and active sites with different energy. The Freundlich model [48] is

$$q_e = K_f C_e^{1/n} \tag{3}$$

where K_f is a constant relating the biosorption capacity and $1/n$ is an empirical parameter relating the biosorption intensity, which varies with the heterogeneity of the material.

Fig. 6 indicates the non-linear Freundlich isotherm plot and the standard error in the determination of the parameters. The K_f and $1/n$ values were found using non-linear regression analysis (SigmaPlot software, SigmaPlot 2001, SPSS Inc., USA).

From the plot, K_f and $1/n$ values were found to be 2.8 and 0.53, respectively. The $1/n$ value were between 0 and 1 indicating that the biosorption of Se(IV) using *C. hutchinsiae* biomass was favorable at studied conditions. The R^2 value was found to be 0.9596. This results indicated that the Freundlich model was not able to adequately to describe the relationship between the amount of sorbed Se(IV) onto the biomass and its equilibrium concentration in the solution.

The equilibrium data were also subjected to the D–R isotherm model to determine the nature of biosorption processes as physical or chemical. The linear presentation of the D–R isotherm equation [49] is expressed by

$$\ln q_e = \ln q_m - \beta \varepsilon^2 \tag{4}$$

where q_e is the amount of metal ions sorbed on per unit weight of biomass (mol/L), q_m is the maximum biosorption capacity (mol/g), β is the activity coefficient related to biosorption mean free energy ($\mathrm{mol^2/J^2}$) and ε is the Polanyi potential ($\varepsilon = RT\ln(1 + 1/C_e)$).

The D–R isotherm model well fitted the equilibrium data since the R^2 value was found to be 0.992 (Fig. 7). The q_m value was found using the intercept of the plot to be 8.3×10^{-4} mol/g. The biosorption mean free energy (E; kJ/mol) is as follow:

$$E = \frac{1}{\sqrt{-2\beta}} \tag{5}$$

The E (kJ/mol) value gives information about sorption mechanism, physical or chemical. If it lies between 8 and 16 kJ/mol, the sorption process takes place chemically and while $E < 8$ kJ/mol, the sorption process proceeds physically [50]. The mean biosorption energy was calculated to be 10.9 kJ/mol. This result suggests that the biosorption processes of Se(IV) by *C. hutchinsiae* biomass could be taken place by chemical ion-exchange mechanism because the sorption energy lies within 8–16 kJ/mol.

Table 1
Comparison of sorption capacity of *C. hutchinsiae* biomass Se(IV) with that of different sorbents.

Biosorbent	Sorption capacity (mg/g)	pH	Reference
Sulphuric acid treated rice husk (wet sorbent)	40.9	1.5	[4]
Sulphuric acid treated rice husk (dry sorbent)	34.1	1.5	[4]
Sulphuric acid-treated peanut shell	32.3	1.5	[23]
Sulphuric acid-treated peanut shell	23.8	1.5	[23]
Zn–Al-layered double hydroxides	125.0	5–10	[24]
Mg–Al-layered double hydroxides	152.0	5–10	[24]
Aluminum oxide coated sand	1.08	4.8	[25]
Iron oxide coated sand	1.34	4.5–6	[26]
Polyamine-type weakly basic ion-exchange resin	134.2	3–12	[42]
Cladophora hutchinsiae	74.9	5	Present study

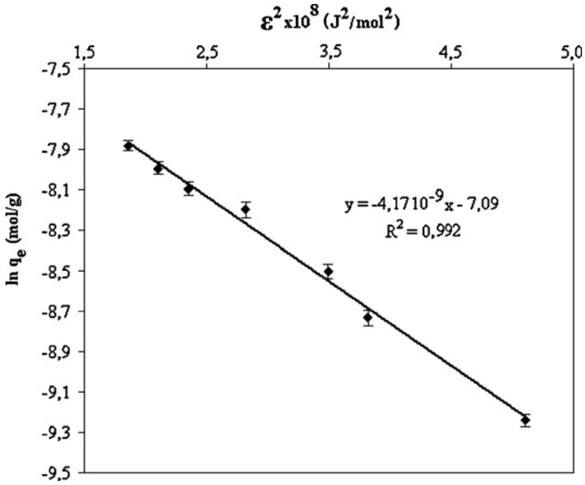

Fig. 7. D–R isotherm plots for the biosorption of Se(IV) by *C. hutchinsiae* biomass (biomass concentration: 8 g/L; contact time: 60 min; pH: 5; temperature: 20 °C).

3.6. Desorption efficiency

Desorption of Se(IV) from the *C. hutchinsiae* biomass was also studied by using 0.5 M HCl and 0.5 M HNO_3. For the desorption studies, 10 mL of each eluent was used. The highest recovery was found to be 95% and 83% using HCI and HNO_3, respectively. In addition, as it can be seen from Fig. 8, the high stability of *C. hutchinsiae* biomass permitted ten times of biosorption–desorption process along the studies with a decrease about 20% in recovery of Se(IV). Based on the results, it can be concluded that the *C. hutchinsiae* was considered as good biosorbent in terms of biosorption performance after a large number of sorption–desorption cycling.

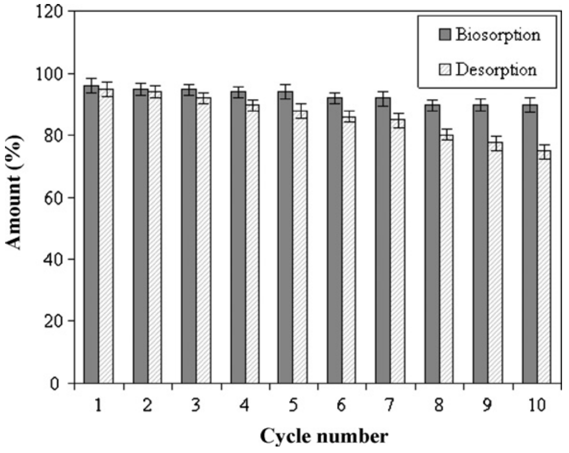

Fig. 8. Biosorption–desorption efficiency with cycle number (biomass concentration: 8 g/L; contact time: 60 min; temperature: 20 °C).

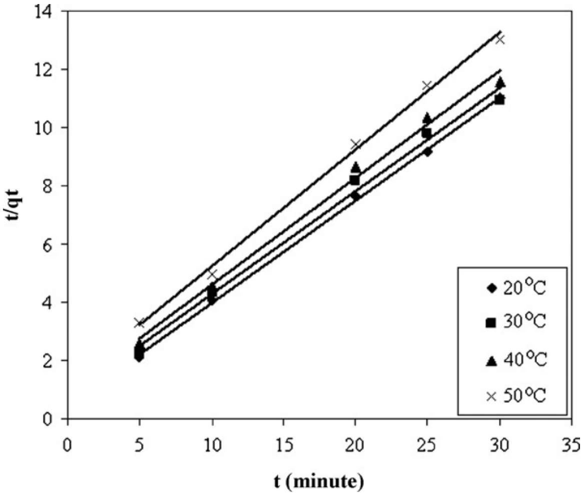

Fig. 9. Pseudo second-order kinetic plots at different temperatures (metal concentration: 10 mg/L; pH: 5; biomass concentration: 8 g/L).

3.7. Biosorption kinetics

The prediction of biosorption rate gives important information for designing batch biosorption systems. Information on the kinetics of pollutant uptake is required for selecting optimum operating conditions for full-scale batch process. In order to clarify the biosorption kinetics of Se(IV) by *C. hutchinsiae* biomass, two kinetic models which are Lagergren's pseudo first-order [51] and pseudo second-order model [52] were applied to the experimental data. As seen from the R^2 and $q_{e,exp}$ values in Table 2, the pseudo first-order model is not suitable for modeling the biosorption of Se(IV) onto *C. hutchinsiae* biomass.

Experimental data were also tested by the pseudo second-order kinetic model which is given in the following form [52]:

$$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + (\frac{1}{q_e})t \tag{7}$$

where k_2 (g/mg min) is the rate constant of the second-order equation, q_t (mg/g) is the amount of biosorption time t (min) and q_e is the amount of biosorption equilibrium (mg/g).

This model is more likely to predict kinetic behavior of biosorption with chemical sorption being the rate-controlling step [53]. The linear plots of t/qt vs t for the pseudo second-order model for the biosorption of Se(IV) by *C. hutchinsiae* at 20–50 °C were shown in Fig. 9. The rate constants (k_2), the R^2 and q_e values are given in Table 2. The R^2 values are in range of 0.992–0.999 and the theoretical $q_{e2,cal}$ values were closer to the experimental $q_{e,exp}$ values. Based on these results, it can be concluded that the pseudo second-order kinetic model provided a good correlation for the biosorption of Se(IV) by *C. hutchinsiae* in contrast to the pseudo first-order model.

Table 2
Kinetic parameters obtained from pseudo first-order and pseudo second-order at different temperatures (Se concentration: 10 mg/L; pH: 5; biomass concentration: 8 g/L).

Temperature (°C)	$q_{e,exp}$ (mg/g)	Pseudo first-order			Pseudo second-order		
		k_1 (1/min)	$q_{e1,cal}$ (mg/g)	R^2	k_2 (g/mg min)	$q_{e2,cal}$ (mg/g)	R^2
20	3.08	44.8×10^{-2}	1.44	0.947	24.9×10^{-2}	3.02	0.999
30	2.88	17.5×10^{-2}	1.23	0.963	16.8×10^{-2}	2.85	0.992
40	2.76	15.9×10^{-2}	1.05	0.969	14.7×10^{-2}	2.70	0.993
50	2.54	10.2×10^{-2}	0.92	0.962	13.3×10^{-2}	2.50	0.997

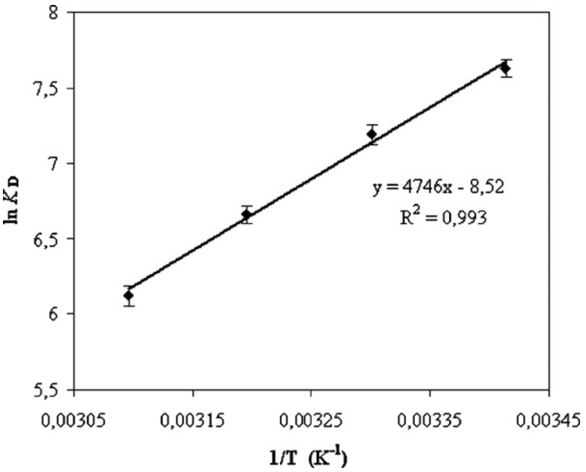

Fig. 10. Plot of $\ln K_D$ vs $1/T$ for the estimation of thermodynamic parameters for biosorption of Se(IV) by *C. hutchinsiae* biomass (pH: 5; biomass concentration: 8 g/L; contact time: 60 min).

3.8. Biosorption thermodynamics

In order to describe thermodynamic behavior of the biosorption of selenium by *C. hutchinsiae* biomass, thermodynamic parameters including the change in free energy (ΔG°), enthalpy (ΔH°) and entropy (ΔS°) were calculated from following equations

$$\Delta G^\circ = -RT \ln K_D \tag{8}$$

where R is the universal gas constant (8.314 J/mol K), T is temperature (K) and K_D (q_e/C_e) is the distribution coefficient [54].

The enthalpy (ΔH°) and entropy (ΔS°) parameters were estimated from the following equation

$$\ln K_D = \frac{\Delta S^\circ}{R} - \frac{\Delta H^\circ}{RT} \tag{9}$$

According to Eq. (9), the ΔH° and ΔS° parameters can be calculated from the slope and intercept of the plot of $\ln K_D$ vs $1/T$ yields, respectively (Fig. 10). Gibbs free energy change (ΔG°) was calculated to be −18.39, −18.12, −17.70, and −16.08 kJ/mol for 20, 30, 40, and 50 °C, respectively. The negative ΔG° values indicated thermodynamically feasible and spontaneous nature of the biosorption. The decrease in negative ΔG° values with increase in temperature shows an increase in feasibility of biosorption at higher temperatures. The ΔH° parameter was found to be −45.96 kJ/mol. The negative ΔH° indicates the exothermic nature of the biosorption processes at 20–50 °C. Furthermore, the negative value of ΔS° (−70.92 kJ/mol K) reveals the decreased randomness at the solid–solution interface during the fixation of the selenium ion on the active sites of the biosorbent.

4. Conclusions

This study focused on equilibrium, thermodynamic and kinetic studies on selenium biosorption from aqueous solution by *C. hutchinsiae* biomass. The operating parameters, pH of solution, biomass dosage, contact time, and temperature, were effective on the biosorption of Se(IV) using *C. hutchinsiae* biomass. The maximum biosorption capacity of *C. hutchinsiae* biomass was found to be 74.9 mg/g at pH 5, contact time of 60 min, biomass concentration of 8 g/L, and temperature of 20 °C. The mean free energy value (10.9 kJ/mol) calculated from the D–R model indicated that the biosorption of Se(IV) using *C. hutchinsiae* biomass was taken place by chemical ion-exchange. The highest recovery (95%) was achieved using 0.5 M HCI. The high stability of *C. hutchinsiae* permitted a slightly decrease about 20% in recovery of Se(IV) ions after ten times of adsorption-elution process. The negative ΔG° and ΔH° showed that the biosorption of Se(IV) onto *C. hutchinsiae* biomass was feasible, spontaneous and exothermic, respectively. The ΔS° parameter revealed the decreased randomness at the solid–solution interface during the fixation of the selenium ion on the active sites of the biosorbent. The experimental data was also fitted to the Lagergren's first-order and pseudo second-order kinetic models. The results revealed that the pseudo second-order reaction model provided the best description these data with coefficients of determination in range of 0.992–0.999. Based on all results, it can be also concluded that the *C. hutchinsiae* biomass can be evaluated as an alternative biosorbent for the treatment of wastewater containing Se(IV) ions, due to its being low-cost biomass and having a considerable high sorption capacity.

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