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Equilibrium, kinetics and thermodynamics study on biosorption of Cr(VI) by fresh biomass of *Saccharomyces cerevisiae*

YunHai Wu, Li Jiang, XianMiao Mi†, Bin Li, and ShiXun Feng

College of Environmental Science & Engineering, Hohai University, Nanjing 210098, China
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Abstract−The low cost fresh biomass of *Saccharomyces cerevisiae* (*S. cerevisiae*) was utilized for removal of Chromium ion from aqueous solution. The maximum biosorption was found to occur at pH 1.0. The biosorption capacity of *S. cerevisiae* was found to be 3.89 mg/g for a solution with initial Cr(VI) concentration of 50 mg/L at 35 °C. Several biosorption isotherms were used to fit the equilibrium data, indicating biosorption relied mainly on physical adsorption onto heterogeneous surface. Kinetic models were evaluated and we found that pseudo-second-order rate kinetic model showed better correlation, and the biosorption of Cr(VI) was governed by film diffusion as well as intraparticle diffusion. Thermodynamic constants indicated that the biosorption was spontaneous and endothermic. Fourier transform infra-red (FTIR) spectroscopy was used to reveal the main function groups of biosorption, which were hydroxyl, amine groups, C-H of the alkanes, C=O and S=O.

Key words: Biosorption, *Saccharomyces cerevisiae*, Chromium, Isotherm, Kinetic

INTRODUCTION

With rapid industrialization and increase in population, heavy metal pollution is well recognized to be detrimental because of its toxicity and wide spread occurrence [1]. Chromium is one of the most important heavy metal contaminants in the wastewater of industrial dyes and pigments, film and photography, galvanometry and electric, metal cleaning, plating and electroplating, leather and mining [2,3]. The effluents from these industries contain both Cr(VI) and Cr(III). Cr(VI) is known to be a strong oxidizing agent and potential carcinogen [4,5]. Therefore, the US EPA has set the discharge limit of Cr(VI) to surface water below 0.05 mg/L [6].

The removal of Cr(VI) from wastewater is important before it is discharged into the aquatic environments or onto land. To solve this problem, various conventional physico-chemical treatment methods were used including precipitation, filtration, oxidation-reduction, ion exchange and membrane separation [7]. However, these processes have the limitations of technical and/or economical viability. Therefore, there is a dire need of a removal method for Cr(VI) from wastewater which is simple, effective and inexpensive [8]. Biosorption has emerged as an alternative method of wastewater treatment with ecofriendly nature, excellent performance, and low cost domestic technique [9]. *Saccharomyces cerevisiae* is a sort of abundant cast-off coming from brew houses. It is abundant, low cost and non-polluting. So *S. cerevisiae* is a potential biosorbent for the removal of heavy metals from wastewater. Recently, various biosorbents have been reported for biosorption of Cr(VI) from wastewater. Some of them are waste acorn of *Quercus ithaburensis* [10], sawdust [11], *Agaricus bisporus* [12], non-living microbial biomass [13] and so on.

In the present study, the fresh biomass of *S. cerevisiae*, a low cost as well as non-hazardous material, was used as biosorbent for biosorption of Cr(VI). The objective of this study was to investigate the biosorption process of Cr(VI) from single component solution by *S. cerevisiae*. The influence of experimental conditions, such as pH, initial Cr(VI) concentration and temperature, were investigated. Several models such as biosorption isotherms, kinetic models and thermodynamic parameters were evaluated to analyze the biosorption mechanism of Cr(VI), which is very different from the study by Wang et al. [14], Ferraz et al. [15] and Bag et al. [16]. Fourier transform infra-red spectroscopy (FTIR) was used to find the main functional groups of biosorption. The effect of co-existing ions in the wastewater such as: Fe^{2+}, Pb^{2+} SO_4^{2-} and NO_3^- has not been investigated.

EXPERIMENTAL PROCEDURE

1. Preparation of Biomass

The biomass of *S. cerevisiae* was obtained from Jinling brew house (China). It was cultivated in a medium containing 3 g/L of yeast extract, 10 g/L of peptone, 20 g/L of dextrose and 1 g/L of various salts. After three days of incubation, the living *S. cerevisiae* was harvested. Immediately it was centrifuged at 3,500 rpm for ten minutes and washed several times with deionized water. After washing, the biomass was stored in icebox (4 °C) for the following experiments.

2. Preparation of Cr(VI) Solutions

Cr(VI) solutions were prepared by using $K_2Cr_2O_7$ (AR). Stock solution (100 mg/L) of Cr(VI) was prepared by dissolving 0.2829 g of $K_2Cr_2O_7$ in deionized water. For biosorption experiments, Cr(VI) solution with concentration of 1-50 mg/L was prepared and used.

3. Biosorption Experiments

The batch biosorption experiments were carried out in 250 ml erlenmeyer flasks containing 100 ml Cr(VI) solution, and shaken on a temperature controlled shaker at 130 rpm. After the solutions were agitated for a given period (15, 30, 60, 120, 180, 240, 330,

†To whom correspondence should be addressed.
E-mail: mixianmiao2008@yahoo.cn

420 min), solutions were centrifugated at 10,000 rpm for 3 min and then the supernatant solution was determined spectrophotometrically (UV1201 model) at 540 nm using diphenyl-carbazide reagent in acid solution as the complexing agent for Cr(VI) [17]. All the experiments were carried out in duplicates and the average values were used for further calculations.

3-1. Effect of pH

The pH of the solution varied from 1.0 to 10.0. It was adjusted by adding 0.1 mol/L HCl or 0.1 mol/L NaOH. *S. cerevisiae* (0.5 g) was added into 100 ml of solution having 20 mg/L of Cr(VI) in 250 ml Erlenmeyer flasks.

3-2. Effect of Initial Concentration

The effect of initial Cr(VI) concentration was studied. *S. cerevisiae* (0.5 g) was added into 100 ml of solution of Cr(VI) with the concentration ranging in 1 mg/L to 50 mg/L in 250 ml Erlenmeyer flasks at pH 3.0.

3-3. Effect of Temperature

The effect of temperature was studied in the range of 20 °C to 35 °C. *S. cerevisiae* (0.5 g) was added into 100 ml of solution having 20 mg/L of Cr(VI) in 250 ml Erlenmeyer flasks at pH 3.0.

4. FTIR Spectroscopy Analysis

The dried *S. cerevisiae* of natural and Cr(VI) loaded samples were analyzed by FTIR spectroscopy (Shimadzu IRPrestige-21 spectrometer). The biomass was oven-dried at 60 °C and mixed with KBr at a ratio of 1 : 100 in a carnelian mortar then powdered to particles with a carnelian pestle for making pellets under proper pressure [18]. The pellets were used for FTIR analysis.

THEORY

1. Biosorption Isotherms

Biosorption isotherms describe qualitative information on the nature of the solute-surface interaction as well as the specific relation between the concentration of biosorbate and its degree of accumulation onto biosorbent surface at constant temperature. Finding the suitable isotherm is an important step for design purposes. The present isotherm study was carried out by varying initial Cr(VI) concentrations (1-50 mg/L) at various temperatures (20-35 °C).

The Langmuir model describes the uptake of metal ions occurs on a homogeneous surface by monolayer biosorption without any interaction between biosorbed ions. The Langmuir isotherm is represented in the following equation:

$$C_e/q_e=C_e/Q_L+1/(bQ_L) \quad (1)$$

The essential characteristics of Langmuir isotherm can be explained in terms of dimensionless constant separation factor (R_L) which is expressed as [19]:

$$R_L=1/(1+bC_0) \quad (2)$$

The values of R_L from the different initial concentrations used are between 0 and 1 for a favorable biosorption, while $R_L>1$ represents an unfavorable biosorption, and $R_L=1$ represents the linear biosorption, while the biosorption operation is irreversible if $R_L=0$ [11].

According to the Freundlich isotherm the uptake of metal ions occurs on a heterogeneous surface by multilayer biosorption and that the amount of biosorbate biosorbed increases infinitely with an increase in concentration. [20] The linear form of Freundlich isotherm can be represented as:

$$\log q_e=\log K_F+1/n\log C_e \quad (3)$$

The Tempkin isotherm considers the effects of indirect biosorbent-biosorbate interactions on biosorption [21]:

$$q_e=\frac{RT}{b_T}\ln(A_T C_e) \quad (4)$$

The D-R isotherm is more general because it is not based on the assumption of homogeneous surface or constant adsorption potential, but it is based on envisaging the heterogeneity of the surface energies. The linear form of the D-R isotherm can be represented as:

$$\ln q_e=\ln Q_L-K\varepsilon^2 \quad (5)$$

$$\varepsilon=RT\ln(1+1/C_e) \quad (6)$$

The mean biosorption energy, E, which is defined as the free energy transfer of 1mol of solute from infinity of the surface of the biosorbent, can be calculated as:

$$E=\sqrt{2/K} \quad (7)$$

If the value of E is between 1 and 16 kJ mol^{-1}, then physical biosorption prevails; if the value is more than 16 kJ mol^{-1}, then chemisorption prevails [22].

2. Biosorption Kinetic

The biosorption kinetics describes reaction pathways along time to reach the equilibrium. It is useful in examining the rate-controlling mechanism of the biosorption process such as mass transfer and intraparticle diffusion. Pseudo-first-order, pseudo-second-order and Elovich kinetic models were applied to fit the experimental data. A kinetic study was also carried out in the initial concentration of Cr(VI) 20 mg/L at different temperature (20-35 °C).

The pseudo-first-order model is the first equation (Lagergren [23]) for the biosorption of liquid/solid system based on solid capacity. This model is expressed as:

$$\log(q_e-q_t)=\log q_e-(k_1/2.303)t \quad (8)$$

The pseudo-second-order model kinetics model based on equilibrium biosorption is expressed as [24]:

$$t/q_t=1/h+t/q_e \quad (9)$$

$$h=k_2(q_e)^2 \quad (10)$$

The Elovich equation is also used successfully to describe second-order kinetics, assuming that the actual solid surfaces are energetically heterogeneous [25]. The linear form of this equation is represented as:

$$q_t=\frac{1}{\beta}\ln(\alpha\beta)+\frac{1}{\beta}\ln t \quad (11)$$

This equation is by assuming $\alpha\beta>>t$ and by applying the boundary conditions $q_t=0$ at $t=0$ and $q_t=q_t$ at $t=t$.

Intraparticle diffusion study is used to describe the internal diffusion of solute. The rate constants of intraparticle diffusion (k_{id}) at different temperatures were determined using the following equation [26]:

$$q_t = k_{id} t^{1/2} + C \quad (12)$$

The kinetic data is further analyzed using the Richenberg model to check whether biosorption proceeds via external diffusion or intra-particle diffusion mechanism, which is expressed as the following:

$$B_b t = -0.4977 - \ln(1 - q_t/q_e) \quad (13)$$

If the plots of $B_b t$ vs. t pass through the origin, then it is indicative of biosorption processes governed by intraparticle-diffusion mechanisms; otherwise it is governed by film diffusion [27].

3. Thermodynamic Parameters

Thermodynamic parameters such as change in Gibbs free energy (ΔG), enthalpy (ΔH) and entropy (ΔS) were calculated using the following equations [28].

$$\Delta G = -RT\ln K_C \quad (14)$$

The equilibrium constant (K_C) of the biosorption is defined as:

$$K_C = C_{Ae}/C_e \quad (15)$$

The relationship between ΔG, ΔH and ΔS can be expressed as follows:

$$\Delta G = \Delta H - T\Delta S \quad (16)$$

Combined with Eq. (19) this results in the equation:

$$\ln K_C = \Delta S/R - \Delta H/RT \quad (17)$$

RESULTS AND DISCUSSION

1. Effect of pH

Earlier studies on heavy metal biosorption have indicated that pH is an important parameter affecting both metal chemistry and cell surface metal binding sites [29]. The experimental result of the relation between the initial pH of the solution and the percentage removal of Cr(VI) is shown in Fig. 1. It was observed that the extent of biosorption of Cr(VI) increased with decreasing solution pH. From pH 1.0 to 10.0 corresponding biosorption values were found to be 75.2% to 10.4%, respectively. The Cr(VI) in the solution exists in the form of oxy anions such as $HCrO_4^-$, $Cr_2O_7^{2-}$, CrO_4^{2-}, $Cr_4O_{13}^{2-}$, $Cr_3O_{10}^{2-}$. At a lower pH (1<pH<3), the dominant form of Cr(VI) was $HCrO_4^-$ while the function groups of the biosorbent surface were active and protonated to a higher extent [19,30]. This results in a stronger attraction for negatively charged chromium complex ions in the solution.

$$2H^+ + 2HCrO_4^- \leftrightarrow 2H_2CrO_4$$

Hence the solution pH after reaction was found to be 1.27, 2.32, 3.48, 5.75, 6.05 and 6.32 when the initial pH was 1.0, 2.02, 3.0, 4.03, 5.02 and 6.05, respectively. With the increase in pH of the solution, the degree of protonation of the surface reduces gradually [31]. Furthermore, CrO_4^{2-} is dominant (pH>6.0). There is dual competition of both the anions (CrO_4^{2-} and OH^-) to be biosorbed on the surface of the biosorbent of which OH^- predominates [32]. Hence, biosorption of Cr(VI) on the biosorbent is not significant at greater pH values. The FTIR spectroscopic analysis of *S. cerevisiae* cell demonstrated the involvement of hydroxyl and amino groups in Cr(VI) binding [17]. They may be more active at lower pH.

2. Effect of Cr(VI) Initial Concentration

The initial concentration of Cr(VI) in the solution markedly affected the equilibrium uptake of Cr(VI) at 30 °C. As shown in Fig. 2, when the initial concentration of Cr(VI) increased from 1 to 50

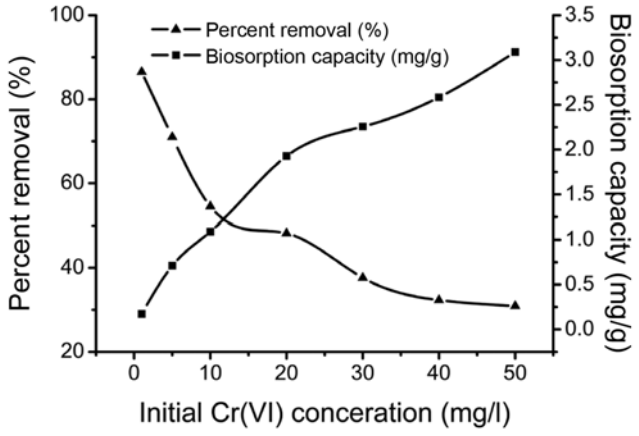

Fig. 2. Effect of initial concentration at T=30 °C, pH=3.0.

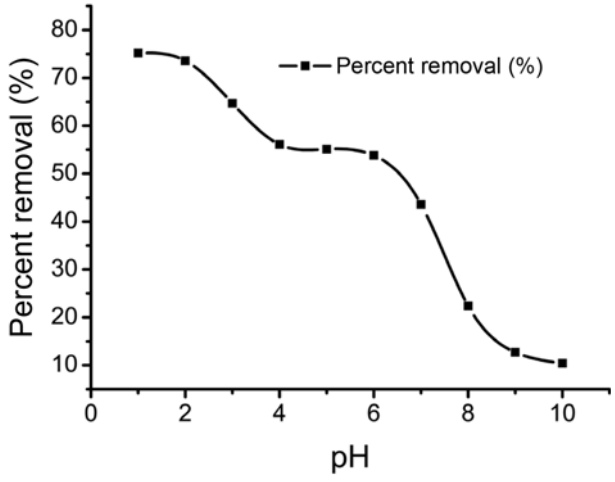

Fig. 1. Effect of initial pH on biosorption at concentration of 20 mg/L, T=30 °C.

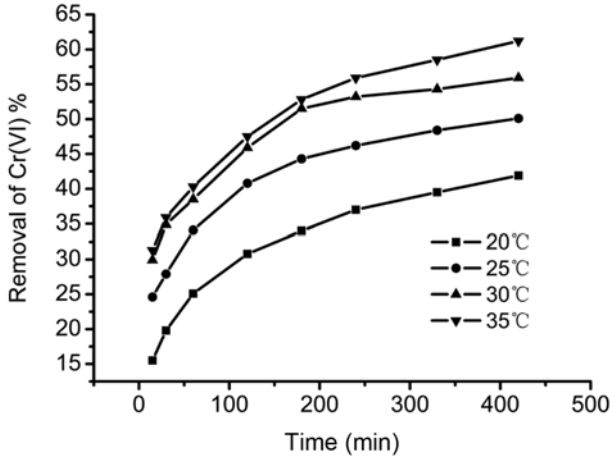

Fig. 3. Effect of temperature with time at concentration of 20 mg/L, pH=3.0.

mg/L, the biosorbent capacity increased from 0.173 to 3.29 mg/g, the percentage of Cr(VI) removal decreased from 86.5% to 32.9%. The increase in biosorption capacity with an increase in the Cr(VI) concentration may be due to the higher driving force to overcome mass transfer resistance of metal ions and the utilization of all the active sites available for the biosorption at higher concentration [33]. The decrease in the percentage removal of Cr(VI) can be explained with the fact that all the biosorbents had a limited number of active sites, which would have become saturated above a certain concentration.

3. Effect of Temperature

It is also observed that the biosorption of Cr(VI) increased with increasing temperature (Fig. 3). The reason for this phenomenon is probably that at higher temperature the energy of the system facilitates Cr(VI) attachment onto the cell surface. Secondly, at high temperature, due to bond rupture of function groups on biosorbent surface, there may be an increase in the number of active biosorption sites, which may also lead to the enhance of biosorption [10]. These indicated that the biosorption of Cr(VI) by *S. cerevisiae* may involve not only physical but also chemical biosorption [34].

4. Biosorption Isotherms

It is found that the value of correlation coefficients r^2 obtained from the Langmuir isotherm are from 0.9483 to 0.9796 which is lower than that from Freundlich isotherm as given in Table 1. The dimensionless parameter R_L is found in the range of 0.08726 to 0.8666 ($0<R_L<1$), which confirms the favorable biosorption process. Although the Langmuir isotherm is widely used, the obtained result indicates that the equilibrium data is not fitted well with the Langmuir isotherm.

The Freundlich isotherm shows the best fit to the experimental data with good correlation coefficients (0.9841-0.9929) compared with the other three biosorption isotherms. This result indicates that the uptake of Cr(VI) occurs on a heterogeneous surface by multilayer biosorption. The values of K_F are found to increase with increasing temperature, which suggests the biosorption process is endothermic [10]. The values of n between 1 and 10 represent favorable

Table 1. Isotherm parameters for the biosorption of Cr(VI) on *S. cerevisiae* at different temperatures

Isotherm parameters		Temperature (°C)			
		20	25	30	35
Langmuir	Q_L (mg/g)	2.8810	3.3625	3.8447	4.3122
	b (L/mg)	0.1581	0.1539	0.1754	0.2092
	r^2	0.9483	0.9558	0.9643	0.9796
Freundlich	K_f	0.4815	0.5195	0.6091	0.7161
	n	2.0777	1.9592	1.8986	1.0702
	r^2	0.9911	0.9929	0.9894	0.9841
Tempkin	A_T (L/mg)	5.2750	5.0053	5.7556	6.2343
	b_T (J/mol)	5611.6	4871.4	4460.2	3837.4
	r^2	0.8998	0.8944	0.9006	0.9262
D-R	Q_L (mg/g)	1.6114	1.7968	1.8995	2.3591
	K (mol^2/kJ^2)	0.0844	0.0889	0.0746	0.0784
	E (kJ/mol)	4.8679	4.7431	5.1778	5.0508
	r^2	0.8021	0.7830	0.8107	0.8169

Table 2. Kinetic parameters for the biosorption of Cr(VI) on *S. cerevisiae* at different temperatures

Kinetic parameters		Temperature (°C)			
		20	25	30	35
$q_{e,exp}$ (mg/g)		1.676	2.004	2.236	2.448
Pseudo-first-order	k_1 (1/min)	0.0074	0.0076	0.0092	0.0111
	$q_{e,cal}$ (mg/g)	1.1146	1.0452	1.1321	1.4990
	r^2	0.9968	0.9882	0.9859	0.9735
Pseudo-second-order	h (mg/g·min)	0.0404	0.0741	0.0970	0.0851
	$q_{e,cal}$ (mg/g)	1.7999	2.0938	2.3414	2.5621
	r^2	0.9944	0.9979	0.9983	0.9959
Elovich	α (mg/(g min))	0.1327	0.4223	0.7497	0.6080
	β (g/mg)	3.1270	3.1626	3.0248	2.7049
	r^2	0.9966	0.9932	0.9846	0.9879
Intraparticle diffusion	K_{id} (mg/g $h^{1/2}$)	0.0626	0.0603	0.0640	0.0728
	C	0.4703	0.8483	1.0558	1.0464
	r^2	0.9724	0.9480	0.9406	0.9782

$q_{e,exp}$: the q_e of experiment; $q_{e,cal}$: the q_e of calculation

biosorption. For the present study the values of n all presented the same trend, showing a beneficial biosorption.

The correlation coefficients of the D-R isotherm are the lowest compared to the other isotherm correlation coefficients, indicating that the D-R isotherm does not fit well with the equilibrium experimental data. The maximum biosorption capacity Q_m obtained using the D-R isotherm is 2.3591 mg/g, which is less than the value of Q_m obtained by using the Langmuir isotherm (4.3122 mg/g). The mean free energy of biosorption (E) was obtained as 4.8679-5.0508 kJ/mol (1<E<16), indicating that the biosorption of Cr(VI) on the surface of *S. cerevisiae* is mainly physical in nature.

5. Kinetic Studies

As seen from Table 2 the values of correlation coefficients for the pseudo-second-order kinetic model were higher and the $q_{e,cal}$ values better agreed with the values of $q_{e,exp}$ in comparison to the pseudo-first-order model at various temperatures [35]. These results indicate that the pseudo-second-order kinetic model can describe the pathway to reach the equilibrium better. The initial biosorption rate, h, has been widely used for evaluating the biosorption rates [36]. In the present study the value of h is 0.0404-0.0970. Similar results have been observed for Cr(VI) biosorption [37].

The Elovich kinetic correlation coefficients r^2 are obtained in the range of 0.984 to 0.997, which are found to be less than the values

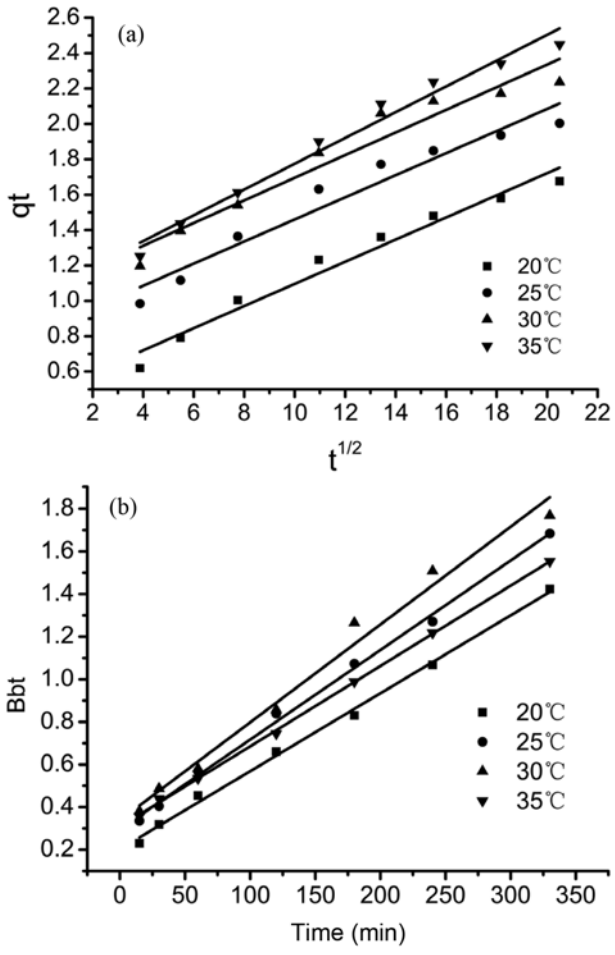

Fig. 4. (a) Intraparticle diffusion plots at different temperature, (b) Richenberg kinetic model plots at different temperature.

Table 3. Thermodynamic parameters for the biosorption of Cr(VI) on *S. cerevisiae* at different temperatures

Temperature (°C)	ΔG (kJ/mol)	ΔH (kJ/mol)	ΔS (J/(mol K))
20	−12.11	38.78	173.9
25	−13.14		
30	−13.94		
35	−14.73		

calculated using pseudo-first-order and pseudo-second-order kinetic models.

The intraparticle diffusion coefficient K_{id} for the biosorption of Cr(VI) was calculated from the slope of the plot q_t vs. $t^{1/2}$ (Fig. 4(a)). The intercept of the plot provides an estimation of the thickness of the boundary layer, i.e., the larger the intercept value the greater is the boundary layer effect [38]. If the regression of q_t vs. $t^{1/2}$ is linear and passes through the origin, the intraparticle diffusion is the sole rate-limiting step [9]. However, the linear plots at each temperature did not pass through the origin. This indicates that the intraparticle diffusion was not the only rate-controlling step.

Plots of B_t vs. t at various temperatures for the biosorption of Cr (VI) are shown in Fig. 4(b) which are straight lines with correlation coefficients (r^2) of 0.9968,0.9882,0.9859 and 0.9994, respectively, at 20-35 °C. The results indicate that film diffusion is the rate-limiting biosorption process because none of the plots pass through the origin at various temperatures.

This indicates the mechanism of Cr(VI) biosorption by *S. cerevisiae* is complex and both the film diffusion and intraparticle diffusion contribute to the rate determining step.

6. Thermodynamics

Table 3 shows these thermodynamic parameters for the biosorption of Cr(VI) at different temperatures. The ΔG indicates the degree of spontaneity of the biosorption process, where more negative values reflect a more energetically favorable biosorption process. We can find in Table 3 that the magnitude of ΔG increased with the rise in temperature and the value of ΔG was negative at all temperatures. It is also shown that better biosorption is actually obtained at higher temperatures. This is in agreement with the phenomenon of biosorption isotherms [35]. The invariable values of ΔH and ΔS at different temperatures were 38.78 kJ/mol and 173.9 J/(mol K), respectively (Table 3). The positive value of ΔH suggests that the biosorption is endothermic. The positive value of ΔS reflects the affinity of Cr(VI) for the *S. cerevisiate* [39,40].

7. FTIR Spectroscopic Analysis

To determine the main function groups of *S. cerevisiae* participating in Cr(VI) biosorption, the FTIR spectra of natural and Cr(VI) loaded *S. cerevisiae* samples were taken and presented in Fig. 5. The FTIR spectra of natural *S. cerevisiae* showed several distinct biosorption bands and peaks (Fig. 5(a)). The strong bands in the region of 3,200-3,500 cm^{-1} reflect O-H and N-H stretching vibrations, showing the presence of hydroxyl and amine groups on the biosorbent surface. The spectra of biosorbent displayed peaks at 3,076 cm^{-1} and 2,927.94 cm^{-1} are indicative of the existence of alkyl chains C-H stretching vibration. The peak at 1,627.92 cm^{-1} is the result of C=O stretching vibrations and at 1,224.80 cm^{-1} is the characteristic peak of S=O stretching vibrations. The band at 1,035 cm^{-1} was assigned to C-N stretching vibrations.

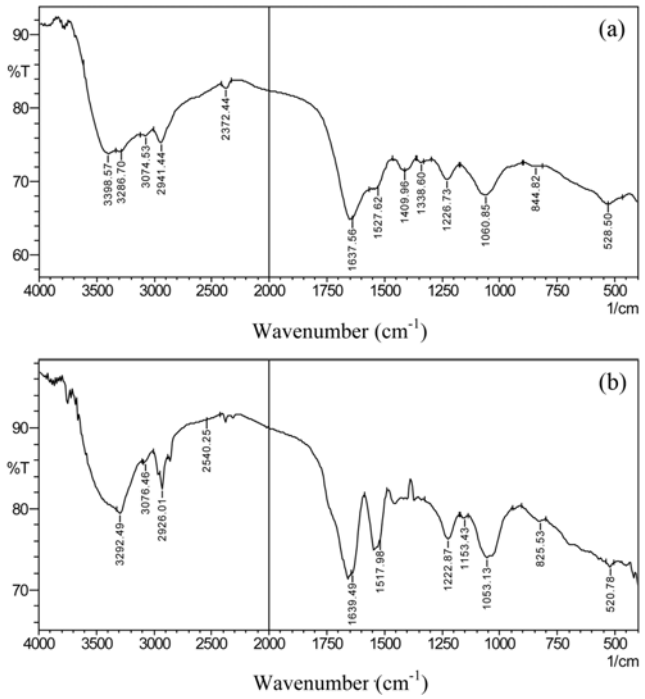

Fig. 5. (a) The FTIR spectra of *S. cerevisiate* before biosorption, (b) The FTIR spectra of *S. cerevisiate* after biosorption.

Compared with FTIR spectra before and after biosorption, there were clear band shifts, disappearances and intensity decrease at the above-mentioned bands (Fig. 5(b)). After biosorption of Cr(VI), the band at 3,076.46 cm^{-1} disappeared and the peak at 3,381.21 cm^{-1} shifted to 3,388.93 cm^{-1}, 2,927.94 cm^{-1} to 2,926.01 cm^{-1}, 1,627.92 cm^{-1} to 1,639.49 cm^{-1} and 1,224.80 cm^{-1} to 1,222.87 cm^{-1}. This result suggests that these function groups participated in the binding of Cr(VI). The changes in FTIR spectra confirm the complexation of Cr(VI) with function groups present in the biosorbent [37,38,41].

CONCLUSION

S. cerevisiae as a sort of biosorbent was investigated for the removal of Cr(VI) from aqueous solutions. It was observed that the biosorption was highly dependent on pH. The biosorption capacity increased as the initial concentration of Cr(VI) in solution and temperature increased.

The equilibrium biosorption data were best fitted with the Freundlich, isotherm which confirmed the multilayer biosorption mechanism of Cr(VI) on a heterogeneous surface. The mean free energy of biosorption (E) calculated with the D-R isotherm was found to be between 1 and 16 kJ/mol, suggesting that physical biosorption process is predominant.

The pseudo-second-order kinetic model provided a better description of biosorption kinetics of Cr(VI) than a pseudo-first-order and Elovich kinetic models. The film diffusion as well as intraparticle diffusion was found to be the rate determining steps. Thermodynamic investigation indicated the process of biosorption Cr(VI) was feasible, spontaneous and endothermic in nature.

The FTIR spectrum of *S. cerevisiae* has shown a clear difference in natural and Cr(VI) loaded forms. The biosorption of Cr(VI) was mainly due to Cr(VI) bound on hydroxyl, amine groups, C-H of the alkanes, C=O and S =O.

All these results suggest that *S. cerevisiae* can be used effectively for removal of Cr(VI).

NOMENCLATURE

A_T : Temkin constant [L/mg]
b : Langmuir constant related to the free sorption energy [L/mg]
B_b : Richenberg constant
B_T : Temkin constant
b_T : Temkin constant related to the heat of adsorption [J/mol]
C_{Ae} : equilibrium concentration of solute on biosorbent [mg/mg]
C_e : equilibrium concentration of solute in solution [mg/L]
E : free energy of biosorption [kJ/mol]
h : initial rate of pseudo-second-order biosorption [mg/g min]
K : D-R constant which relates to the adsorption energy [mol^2/kJ^2]
k_1 : rate constant of pseudo-first-order biosorption [L/min]
k_2 : equilibrium rate constant of pseudo-second-order biosorption [g/mg min]
K_C : equilibrium constant [L/mg]
K_F : Freundlich constant indicative of the relative biosorption capacity
k_{id} : rate constant of intraparticle diffusion [mg/g $h^{1/2}$]
n : Freundlich constant indicative of the intensity of biosorption
q_e : amount of solute adsorbed per unit weight of biosorbent at equilibrium time [mg/g]
Q_L : maximum amount of solute per unit weight of biosorbent [mg/g]
q_t : amount of solute adsorbed per unit weight of biosorbent at any time t [mg/g]
R : gas constant [8.314 J/(mol K)]
R_L : Langmuir separation factor
t : time [min]
T : absolute temperature [K]
$t^{1/2}$: time for half of the biosorption [min]
ΔG : Gibbs free energy change [kJ/mol]
ΔH : enthalpy change [kJ/mol]
ΔS : entropy change [(J/(mol K)]

Greek Letters

α : Elovich constant indicative of the initial sorption rate [mg/(g min)]
β : desorption constant of Elovich [g/mg]

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