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Enhanced Cr^{6+} biosorption from aqueous solutions using genetically engineered *Saccharomyces cerevisiae*

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ABSTRACT

Recombinant *Saccharomyces cerevisiae* (namely, M1) expressing metallothionein was designed for biosorption of chromium (VI). This paper demonstrates that recombinant *Saccharomyces cerevisiae* removes hexavalent chromium from a solution more effectively. The effects of different experimental conditions, such as solution pH, initial metal concentration, contact time, biosorbent dose and temperature on adsorption, were investigated. Bioadsorption equilibrium is quickly reached in approximately 30 min. The host strain and M1 showed the highest Cr^{6+} sorption capacity at an initial pH of 1.0. Biological adsorption increases with an increase in the initial concentration of chromium. The biological adsorption rate increases as the solution temperature rises. The presence of co-existing ions did not significantly affect the accumulation of Cr(VI). In addition, the saturated monolayer sorption capacity increased from 2.6 to 8.27 mg/g at 30°C. The adsorption kinetics was better described using a pseudo-second-order model, and the adsorption process could be well described using the Langmuir isotherm. Desorption is possible with 0.2 M NaOH. Yeast is reused for four adsorption-desorption cycles. Biological adsorbent functional groups were identified by FTIR. The morphology of the biological adsorbent was studied using SEM. The results indicate that the recombinant *S. cerevisiae* M1 should be useful for increasing the effectiveness of Cr(VI) biosorption in practice.

Keywords: Adsorption; Metals; Yeast; Proteins

1. Introduction

Heavy metal pollution is a serious and widespread environmental problem due to their toxicity, stability and bioaccumulation tendencies [1,2]. Chromium(VI) has received widespread attention and is classified as a high-priority toxic pollutant due to its high solubility in water [3,4]. Chromium affects human physiology by accumulating in the food chain and causes several health problems [5,6]. Human exposure to Cr(VI) compounds is associated with a higher incidence of respiratory cancer [7,8]. Chromium and its compounds are widely used in many industrial applications including electroplating, chromate manufacturing alloy repair industries, metal cleaning and processing, leather tanning and wood preservation [9,10]. As a result, the effluents of these industries may contain an elevated concentration of chromium. Wastewaters containing chromium must be treated to lower Cr(VI) to accepted limits before release into the environment. There is increasing interest in the development of new processes that remove heavy metals from wastewaters.

Conventional methods for removing toxic heavy metal ions include chemical precipitation, chemical oxidation or reduction, filtration, ion exchange, electrochemical treatment, application of membrane technology and evaporation recovery [11–14]. However, these technical processes have considerable disadvantages including incomplete metal removal, requirements for expensive equipment and monitoring system requirements, high reagent or energy requirements and generation of toxic sludge or other waste products that require disposal [15]. Therefore, there is a need for some alternative technique that is efficient and cost effective.

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Compared to conventional techniques, the biosorption process has emerged as an economical and efficient approach for the remediation of metal-bearing wastewater [16]. Various types of biomass, including bacteria, yeast, and algae have been studied as efficient biomass materials for Cr(VI) removal [17–19]. However, considering that the binding capacity of wild-type microorganisms is not high enough, recent research has focused on development of biomaterials with an increased affinity and capacity to target heavy metals.

Metallothionein (MT) is a family of low molecular weight metal-binding proteins rich in cysteine residues and is able to bind a variety of heavy metals including Cr(VI)[20–21]. Genetically engineered *Saccharomyces cerevisiae* expressing MT can improve its Cr(VI) resistance compared to the wild-type host strain [11]. The purpose of the present study is to evaluate the Cr(VI) bioaccumulation performance of a genetically engineered *Saccharomyces cerevisiae* strain from a dilute solution, including contact time, initial metal ion concentration, dose Cr(VI) uptake rate, and the effects of pH. Two kinetic models were used to correlate the experimental data. Two different isotherm equations were tested.

2. Materials and methods

2.1. Strains and culture conditions

The Saccharomyces cerevisiae strain GS115 was grown in YPD medium at 30°C. The recombinant *S. cerevisiae* strain containing the MT gene was constructed as described as previously described [22].

2.2. Preparation of yeast biosorbents

The recombinant M1 strain was grown in YPD medium and shaken at 30°C overnight. Cells were separated by centrifugation, rinsed with distilled water, and changed to YPD medium containing 2% glucose to obtain an OD600 of 0.4. Cells were harvested at 36 h after induction by centrifugation (1500 rpm, 5 min), washed twice in sterile water, and lyophilized for biosorption experiments. The wild-type S. cerevisiae strain was cultured and treated in the same way.

2.3. Preparation of stock solution

Stock solution was prepared by dissolving 1000 mg of potassium dichromate in one litre of de-ionised water; 1 N HCl/1 N NaOH was used to obtain different pH values for different experiments.

2.4. Characterisation of the host strain and M1

A scanning electron microscope (JSM-6490L V, Jeol) was used to study the surface morphology of the biosorbent. Energy-dispersive X-ray spectroscopy (JED-2300, Jeol) was used to analyse the distribution of elements on the biosorbent surface. Infrared spectra of the biosorbent were collected using a Fourier transform infrared spectrophotometer (Nicolet IS50; Thermo Scientific).

2.5. Biosorption experiments

Biosorption of Cr^{6+} was studied as a function of pH (0.5–5.0), contact time (0–30 min), initial chromium concentration (10–90 mg/L), biosorbents dosage (0.5–9 g/L) and temperature (20–40°C). The batch biosorption was performed in a reciprocating water bath shaker with a concussion speed of 200 rpm. In the experiments, 0.01 g sorbent was suspended in a 10 mL solution containing different concentrations of Cr^{6+} at different initial pH values. Other ions in the solution that affect the adsorption process were investigated. In a typical binary adsorption, absorbent was associated with a 10 mL solution, containing 50 mg/L of hexavalent chromium and other common ions in wastewater at 30°C and pH 5.0. The remaining hexavalent chromium concentration was measured.

The amount of Cr^{6+} adsorbed per unit mass of the host strain and M1 was calculated using Eq. (1)

$$q_e = (c_0 - c_e)\frac{v}{w} \tag{1}$$

where q_e is the adsorption capacity of the host strain or M1(mg/g), C_o and C_e are the chromium concentration in the initial and equilibrated solution (mg/L), respectively, V is the volume of the aqueous solution (L), and w is the mass of the host strain or M1 (g).

All the experiments were performed in duplicate to confirm reproducibility of the experimental results and relative deviations are on the order of +2.0% and +3.0%, respectively.

2.6. Adsorbent regeneration study

To test the reusability of the biosorbent, 10 mg of the biosorbent adsorbed 10 mL of 50 mg/L Cr(VI) solution for 30 min and then adsorbent separation from the solution was performed by centrifugation. Next, desorption was performed, adding 10 ml of 0.2 M sodium hydroxide followed by mixing for 30 min. After each biological adsorption–desorption, biosorbent was washed thoroughly with deionised water to neutralised dried and then prepared for running the biosorption process in the next cycle.

2.7. Determination of adsorption isotherms

The biosorbents were added to aqueous solutions containing Cr^{6+} ions at different initial concentrations over the range of 10–90 mg/L. The adsorption experiments were performed at 30°C, pH 5.0 and with shaking at 200 rpm. After adsorption equilibrium was reached, samples were collected from the solutions, and the residual metal concentration in the supernatant was measured using an UV/Vis spectrophotometer.

2.8. Biosorption kinetics

The kinetic studies were performed using bath biosorption experiments with different initial chromium concentrations. Samples were collected at different time points and analysed for their chromium concentration.

2.9. Analytical methods

The initial and equilibrated Cr^{6+} concentrations were measured using an UV/Vis spectrophotometer at 540 nm complexed with 1,5-diphenylcarbazide in an acidic medium. The biosorption capacities were then measured by mass balance calculations. All experiments were performed in triplicate and average values are reported.

3. Results and discussion

3.1. Characterisation of the host strain and M1

Biosorbent surface morphology was studied using SEM. As shown in Fig. 1a, the yeast is elliptical, the cell surface is smooth and a moderate porous structure was not observed. In Fig. 1b, some of the cavity can be observed and some porosity of various shapes and sizes was observed, which can lead to the increased adsorption properties of Cr (VI) in yeast.

Fig. 1c and d show the surface morphology of the host strain and M1 strain after Cr(VI) adsorption. After Cr(VI) adsorption, morphological changes have taken place in the yeast, such as a rough surface and unevenness, and the possible reason is that the material on the cell surface and Cr interacted, attaching to the cell wall and forming sediment. However, comparison of the M1 and host strains shows that surface shrinkage in the M1 strain is greater than in the host stain, demonstrating that metallothionein on the cell surface can promote heavy metal adsorption in yeast.

Therefore, EDX analysis has provided the direct evidence for the specific adsorption of Cr(VI) ions onto the surface of the host and M1 strains (Fig. 2).

FTIR analysis was used to investigate the functional groups on the surface of the host and M1 strains and to measure the vibration frequency change of the functional groups after biological adsorption of Cr(VI) (Fig. 3 a–d). The FTIR spectra of the host stain are shown in Fig. 3a. The absorption peak at 3270.25 shows the hydroxyl groups in the host strain. The absorption peak at 2923.12 is assigned to the C–H elastic vibration of the methylene group. At 1624.76 is the observed peak of C=O stretching and the absorption peak at 1517.72 is identified as the N–H bending vibration. The absorption peak at 1042.35 is C–OH and P–O–C elastic vibration, which exists on the surface structure of the yeast. Comparison of the infrared spectra of M1 and host yeast (Fig. 3 a,c) shows that some significant absorption peaks move at 3270.25, 1624.76, and 895.3. At 3270.25, the absorption peak shifts, demonstrating that metallothionein expression on the cell surface increases –NH/–OH binding in yeast.

Fig. 3 b,d are infrared spectrograms of the host and M1 strains after adsorption of Cr(VI), respectively. As shown in Fig. 3b,d, the –OH/NH absorption peak of the host and M1 strains shift 24.88 cm^{-1} and 85.37 cm^{-1}, respectively. The –OH absorption peak of the M1 strain after Cr(VI) adsorption shifts a wave number greater than in the host strain, suggesting that the amino and hydroxyl groups participated in the adsorption process of Cr(VI) and that metallothionein expression on the yeast cell surface promotes the binding of amino and hydroxyl groups with Cr(VI). The absorption peaks of the amide I band in the host and M1 strains also shift 3.66 cm^{-1}, 12.27 cm^{-1}, respectively, demonstrating that the offset in the M1 strain is four times that of the host strain from Cr adsorption and that metallothionein has an effect on the amount of C=O. The C–H absorption peak slightly shifts, indicating that C–H is involved in Cr(VI) adsorption.

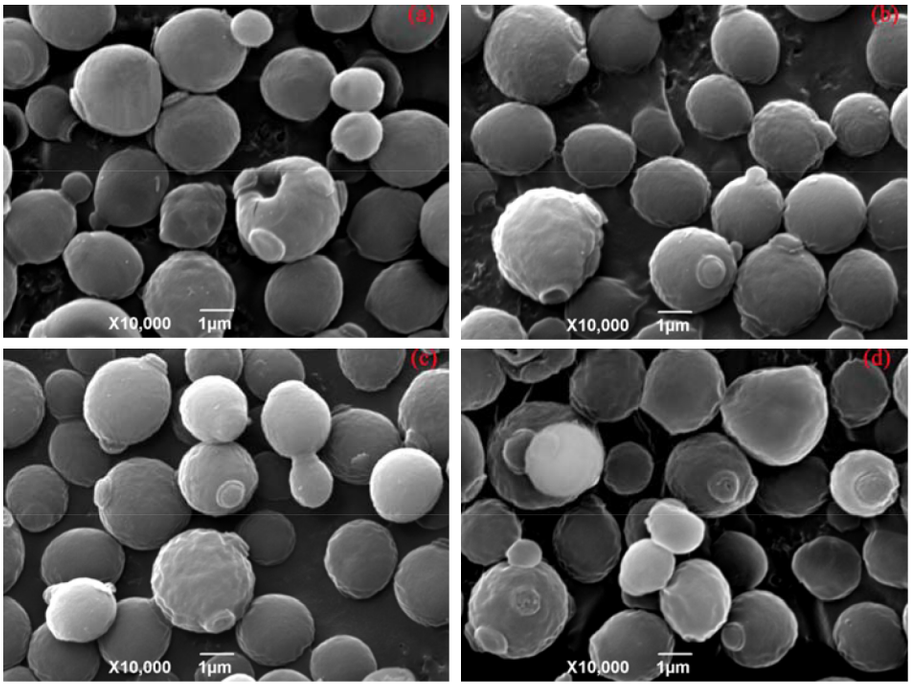

Fig. 1. Scanning electron micrograph images of (a) Host strain, (b) Cr(VI) loaded Host strain, (c) M1, (d) Cr(VI) loaded M1.

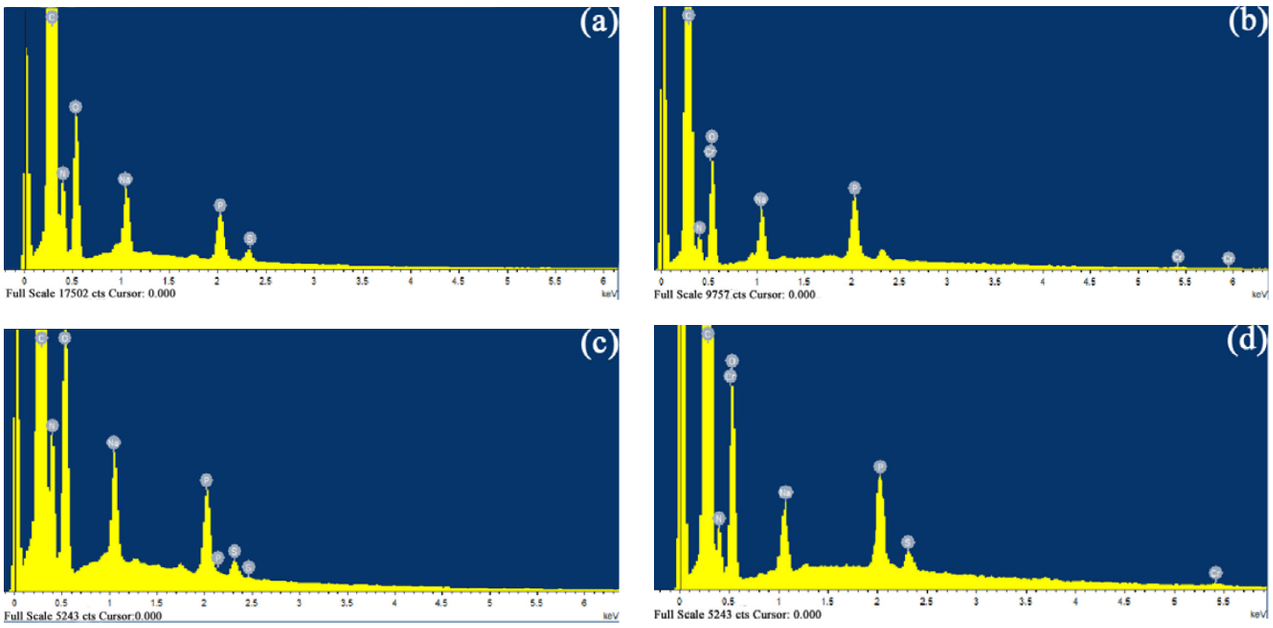

Fig. 2. EDX of (a) Host strain, (b) Cr(VI) loaded Host strain, (c) M1, (d) Cr(VI) loaded M1.

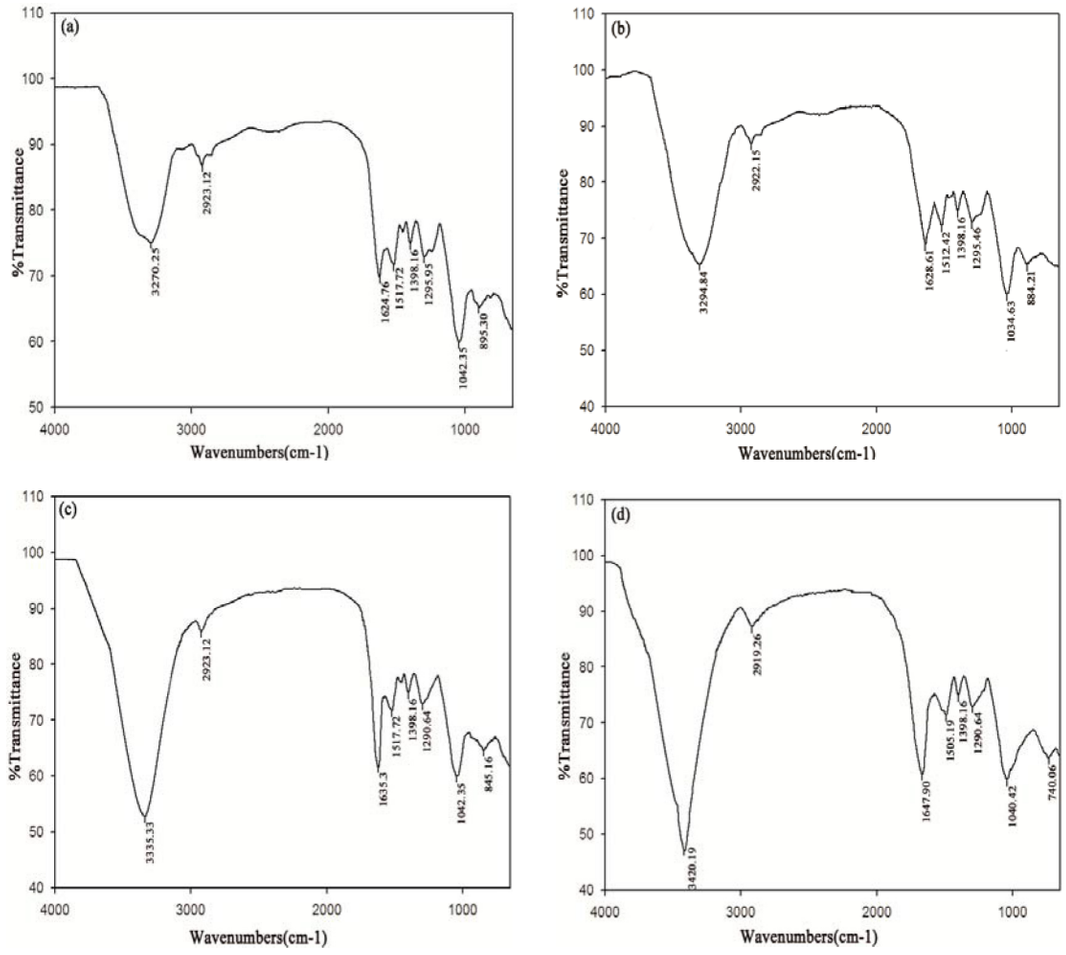

Fig. 3. FT-IR spectra of (a) Host strain, (b) Cr(VI) loaded Host strain, (c) M1, (d) Cr(VI) loaded M1.

In sugar, the C–OH stretching vibration peak, the P–O–C stretching vibration peak and the heavy atom stretching vibration peak and some deformation vibration peak also produces deviation, suggesting that C–OH and P–O–C also participate in the binding of Cr(VI). Thus, hydroxyl, amine, phosphoric acid and amide groups all play a role in Cr(VI) adsorption.

3.2. Effects of contact time on biosorption capacity

Contact time is also an important factor that can reflect the adsorption kinetics [23,24]. The variation of the adsorbed amount with contact time was studied using an initial Cr^{6+} concentration of 50 mg/L at pH 5.0 and 30°C. As shown in Fig. 4, the amount of Cr^{6+} adsorbed by the host strain and M1 strains increased sharply at the beginning, and then gradually reached equilibrium after 30 min. The faster adsorption rate at the beginning would be due to the larger concentration gradient [25]. Therefore, the contact time of 30 min was deemed sufficient to establish the sorption equilibrium and was used in all subsequent experiments.

3.3. Effects of pH on biosorption capacity

The effect of pH on Cr^{6+} adsorption in the host and M1 strains was investigated at pH 0.5, 1, 2, 3, 4, and 5, using an initial chromium concentration of 50 mg/L at 30°C. The adsorption capacity of Cr^{6+} was greatly dependent on solution pH (Fig. 5a). The uptake amount reached a maximum adsorption capacity of 9.08 mg/g (host strain) and 11.8 (M1) at pH 1.0. The reason for the increased chromium adsorption at low pH is that the negatively charged $[HCrO_4]^{2-}$, $[Cr_2O_7]^{2-}$, $[Cr_4O_{13}]^{2-}$ and $[Cr_3O_{10}]^{2-}$ ions are the dominant species under these conditions [26–27]. The surface of yeast cell walls at low pH is surrounded by hydronium ions (H_3O^+) [28]. The negatively charged ion species are thus effectively adsorbed

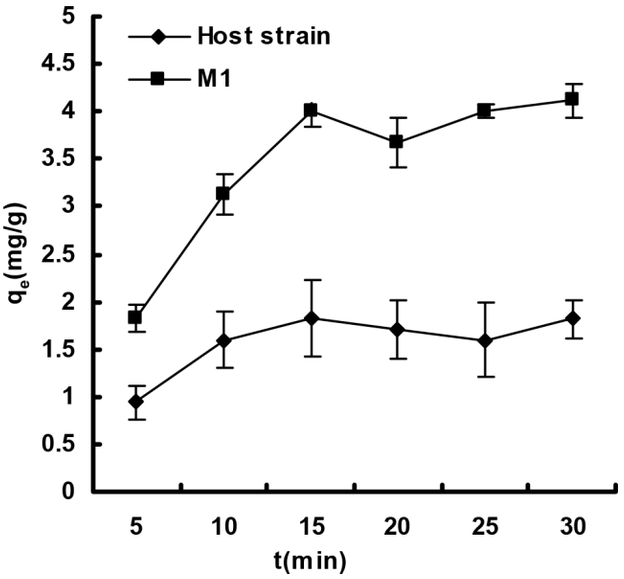

Fig. 4. Effect of contact time on Cr(VI) adsorption onto host strain and M1 (C_0 = 50 mg/L, V = 10 mL, pH = 5.0, m = 0.01 g, T = 30°C).

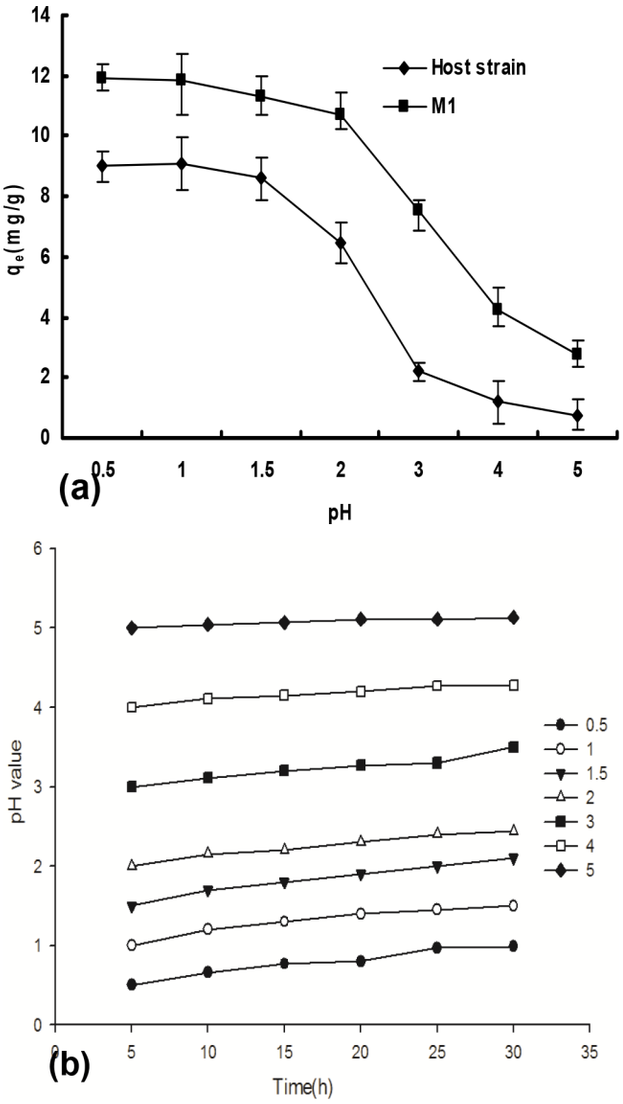

Fig. 5. (a)Effect of pH on Cr(VI) adsorption onto host strain and M1(C_0 = 50 mg/L, V = 10 mL, m = 0.01 g, T = 30°C) (b) The pH change during the adsorption.

by the positively charged active sites on the biosorbent. With an increase in pH, the binding of ions decreased on account of repulsive forces between the biosorbent and chromium. Therefore, a solution pH of 1.0 was used for further Cr^{6+} adsorption experiments on host and M1 strains.

At the same time, the effect of adsorption on solution pH was examined further. The results showed that there were no significant changes in pH with adsorption (Fig. 5b)

3.4. Effect of initial metal ion concentration on biosorption capacity

The effect of metal ion concentration on Cr^{6+} uptake by biomass was investigated using an initial metal ion concentration ranging from 10 to 90 mg/L. As shown in Fig. 6, the biosorption capacity (q_e) of Cr^{6+} by the host

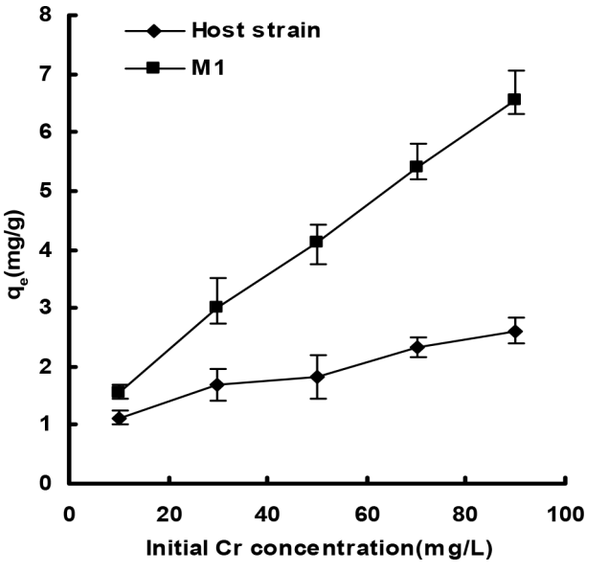

Fig. 6. Effect of initial Cr(VI) on Cr(VI) adsorption onto host strain and M1 (V = 10 mL, pH = 5.0, *m* = 0.01 g, *T* =30°C).

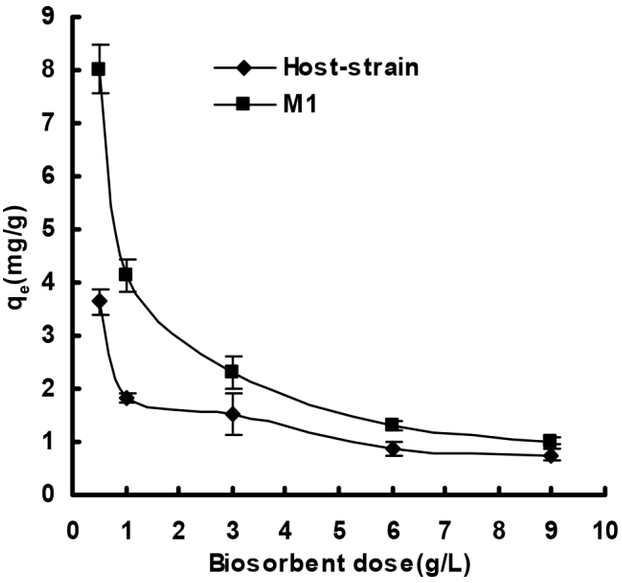

Fig. 7. Effect of biosorption dose on Cr(VI) adsorption onto host strain and M1 (C_0 = 50 mg/L, *V* = 10 mL, pH = 5.0, *T* =30°C).

and M1 strains increased with an increase in the initial Cr^{6+} concentration indicating that the initial concentration provided a dominant driving force to overcome the mass transfer resistance between the aqueous and solid phases [29,30]. Another reason for the increased biosorption capacity might be that by increasing the initial metal concentration there is increased probability of contact between chromium ions and the biosorbent [31,32]. Increased sorption capacity with increased sorbate concentration has been reported in biosorption studies of metals[33,34].

3.5. Influence of biosorbent dose on Cr^{6+} biosorption

The effect of biosorbent dose on the biosorption of Cr^{6+} ions was investigated using M1 and host strains doses at 50 mg/L with a constant Cr^{6+} concentration. If the M1 dose is increased at a constant Cr^{6+} concentration, the amount of Cr^{6+} adsorbed per unit mass of M1 decreases due to the decreased availability of Cr^{6+} ions. The results are presented in Fig. 7, and the maximum biosorption capacity is observed at 8.01 mg/g using a 0.5 g/L M1 dose. This result may be attributed to the higher biosorbent dose making the biosorbent surface area and pores volume more available, which will be available for biosorption, but at a lower optimal biosorbent dose, all types of sites are entirely exposed and the biosorption on the surface is saturated faster, showing a higher biosorption capacity [35,36].

3.6. Effect of temperature on biosorption capacity

The effect of temperature on biosorption of Cr^{6+} by the host and M1 strains was investigated by testing different temperatures ranging from 20 to 40°C. The results presented in Fig. 8 show that the biosorption capacity of M1 towards

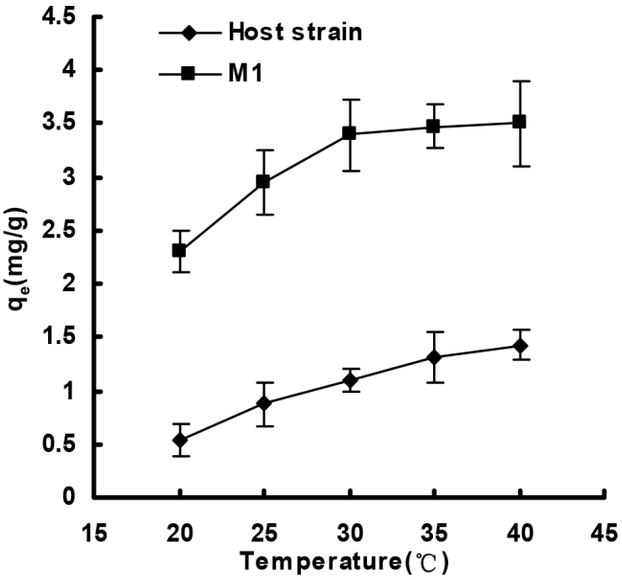

Fig. 8. Effect of temperture on Cr(VI) adsorption onto host strain and M1 (C_0 = 50 mg/L, *V* = 10 mL, pH = 5.0, *m* = 0.01 g).

Cr^{6+} removal was increased from 2.2 to 3.5 mg/g with an increase in temperature from 20 to 40°C, demonstrating that Cr^{6+} biosorption by M1 was an endothermic process. In addition, the biosorption capacity of host strains towards Cr^{6+} removal was increased from 0.5 to 1.4 mg/g with an increase in temperature from 20 to 40°C. The increase in biosorption capacity with an increase in temperature may be because of the formation of new biosorption sites on M1 or the increased kinetic energy of the $Cr_2O_7^{2-}$ ion, the dominant form of chromium under acidic conditions [37]. Most of the literature suggests an effective biosorption within a range of 30–35°C [38,39].

3.7. Adsorption isotherm

Langmuir [40,41] and Freundlich [42,43] isotherms were used to analyse the equilibrium distribution between adsorbed metal ions and ions in solution. The Langmuir isotherm equation is shown in Eq. (2)

$$\frac{1}{q_e}=\frac{1}{qbc_e}+\frac{1}{q} \tag{2}$$

where C_e is the equilibrium concentration (mg/L), q_e is the amount of solute adsorbed per unit weight of sorbent (mg/g), q is the Langmuir constant, which represents the saturated monolayer sorption capacity (mg/g), and b is a constant related to the energy of adsorption.

The Freundlich isotherm equation is shown in Eq. (3)

$$\ln q_e=\ln k+\frac{1}{n}\ln c_e \tag{3}$$

where C_e is the equilibrium concentration (mg/L), q_e is the amount of solute adsorbed per unit weight of sorbent (mg/g), k is the Freundlich constant related to the adsorption capacity, and n is relevant to the adsorption intensity.

The effect of the initial concentration on the Cr^{6+} adsorption by the host and M1 strains at 30°C is presented in Fig.6.

The linearised forms of the Langmuir and Freundlich adsorption isotherms collected at 30°C are presented in Figs. 9 and 10, respectively. The adsorption constants evaluated from the isotherms and the correlation coefficients (R^2) are shown in Table 1. The R^2 values show that the Langmuir isotherm model fitted better with the experimental data than the Freundlich isotherm model. The saturated monolayer sorption capacity (q) increased from 2.6 to 8.2 mg/g at 30°C after MT expression.

3.8. Adsorption kinetics

The pseudo-first-order [44–46] and pseudo-second-order kinetic [47,48] models were used to describe the kinetic

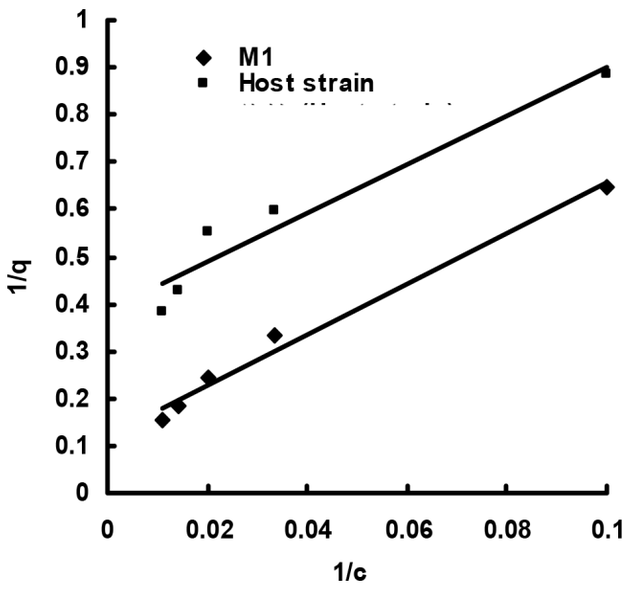

Fig. 9. Langmuir adsorption isotherm of host strain and M1.

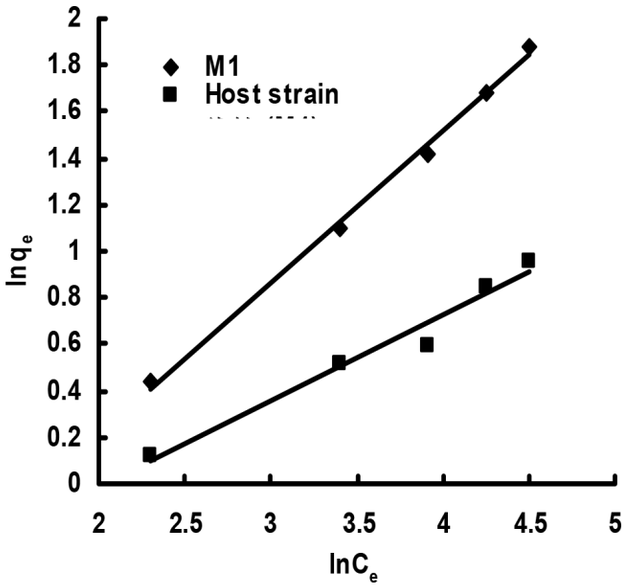

Fig. 10. Freundlich adsorption isotherm of host strain and M1.

Table 1
Adsorption isotherm parameters for Cr^{6+} adsorption onto host strain and M1

Adsorbent	Langmuir adsorption isotherm			Freundlich adsorption isotherm		
	b	*q*	R^2	*K*	*n*	R^2
Host-strain	0.074	2.604	0.936	0.34	1.53	0.9962
M1	0.0225	8.27	0.9848	0.47	2.71	0.969

characteristics of Cr^{6+} absorption by the host and M1 strains. The pseudo-first-order rate equation is shown by Eq. (4)

$$\log(q_e-q_t)=\log q_e-\frac{k_1}{2.303}t \tag{4}$$

where k_1 (min^{-1}) is the rate constant of the first-order adsorption, and q_e and q_t are the amounts of Cr^{6+} adsorbed (mg/g) at equilibrium and time t, respectively. The pseudo-second-order kinetic model is shown in Eq. (5)

$$\frac{t}{q_t}=\frac{1}{k_2q_e^2}+\frac{t}{q_e} \tag{5}$$

where k_2 (min^{-1}) is the rate constant of the second-order adsorption. and q_e and q_t are the amounts of Cr^{6+} adsorbed (mg/g) at equilibrium and time t.

The linear forms of the pseudo-first-order and pseudo-second-order models for Cr^{6+} adsorption are shown in Figs. 11 and 12. The biosorption kinetics of heavy metals provides the mechanism of the sorption reaction, describing the metal uptake, which in turn controls the time the metal remains at the solid-solution interface.

The square of the correlation coefficient (R^2) of the pseudo-second-order equation was better than the value for the pseudo-first-order equation (Table 2). Moreover, the amounts of Cr^{6+} adsorbed at equilibrium, q_e, calculated

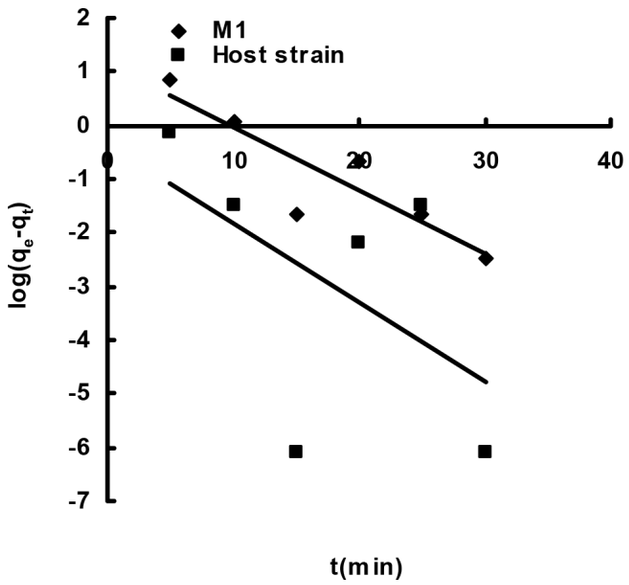

Fig. 11. Pseudo-first-order adsorption kinetics.

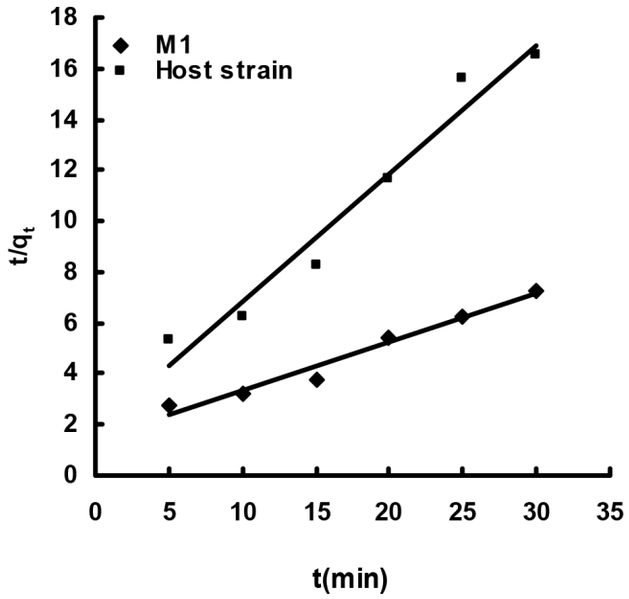

Fig. 12. Pseudo-second-order adsorption kinetics.

Table 2
Kinetic parameters of Cr^{6+} adsorption onto host strain and M1

Adsorbent	Pseudo-first-order kinetics			Pseudo-second-order kinetics		
	q_1/mg g^{-1}	k_1/ min^{-1}	R^2	q_2/mg g^{-1}	k_2/mg $g^{-1}min^{-1}$	R^2
Host-strain	0.72	0.34	0.2953	1.99	0.37	0.9624
M1	3.24	0.275	0.8064	5.22	0.16	0.9691

as 1.8 and 4.1 mg/g, were very close to the experimental values, q_e, empirically were 0.72 and 3.2 mg/g. Therefore, the adsorption process is better fitted by the pseudo-second-order-equation, indicating that the adsorption involves a chemical reaction in addition to the physical adsorption.

3.9. Effects of co-existing ions on Cr(VI) adsorption

Batch biosorption is performed to check the effect of co-existing ions on Cr (VI) adsorption. In real effluent, the main cations are Cu^{2+}, Cd^{2+}, Pb^{2+}, Na^+, K^+, and Ca^{2+}, and the main anions are Cl^-, NO_3^-, SO_4^{2-} and PO_4^{3-} [49,50]. The study of cations and anions shows that $CuSO_4$, $CdCl_2$, K_3PO_4, and especially $CaCl_2$, do not interfere with the biological adsorption of Cr (VI) (Fig. 13). However, $Pb(NO_3)_2$ and NaCl presented some low degree of interference. $Pb(NO_3)_2$ was found to produce 5.7% of the interference value, and NaCl was found to interfere at a rate of 6.3%. Thus, the results of this study clearly indicate that the M1 strain is suitable for the biological adsorption and removal of hexavalent chromium from real sewage.

3.10. Desorption and reuse studies

Biosorbent of reuse is very important for practical metal removal from sewage in industry. Rangabhashiyam et al. found that Cr (VI) can be desorbed well with NaOH [51]. Therefore, 0.2 M NaOH was used in the regeneration of yeast. Table 3 shows that the Cr (VI) adsorption capacity of the M1 strain is almost unaffected and that the biosorbent regeneration efficiency is generally high. The results show that the M1 strain can be effectively regenerated by NaOH for four cycles. Therefore, the high biosorption capacity and reproducibility make the M1 strain a potential biosorbent for removing Cr (VI) from effluent.

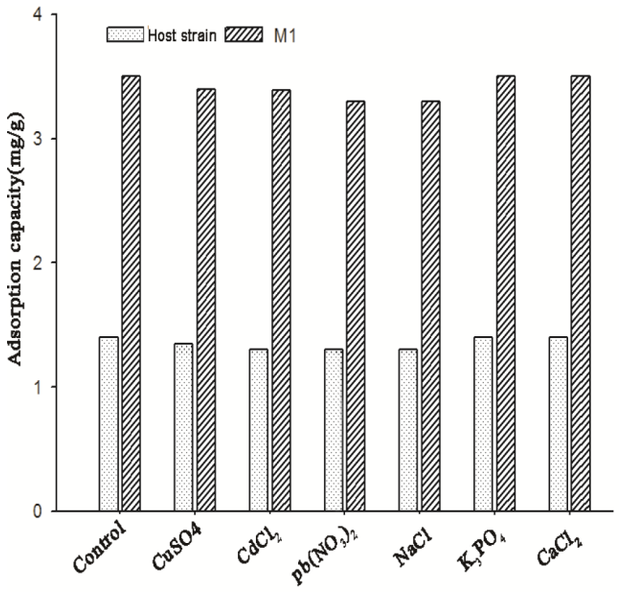

Fig. 13. The effect of co-existing ions on the adsorption of Cr(VI) ions by host strain and M1.

Table 3
The capacity of biosorption and desorption for Cr(VI) on M1 for four cycles

Times	Biosorption (mg/g)	Desorption (mg/g)	Recovery rate(%)
1	4.20 ± 0.11	3.73 ± 0.14	88.7
2	3.69 ± 0.16	3.22 ± 0.13	87.2
3	3.20 ± 0.19	2.49 ± 0.12	77.8
4	2.39 ± 0.14	1.83 ± 0.18	76.5

4. Conclusions

In the study, genetically engineered yeast that expresses MT has been evaluated for its accumulation of Cr(VI) from aqueous solutions.

The characteristics of the biosorbent were examined. SEM, EDX and FTIR show that the characteristics of the yeast were changed using transgenic technology. These changes lead to a different biosorption capacity between the recombinant yeast and the host strain. This research shows that the M1 strain has a higher Cr(VI) adsorption capacity than the host strain. The adsorption capacity is affected by many factors. Biological accumulation quickly reaches equilibrium within 30 min. The optimal pH and adsorption dose is 1 and 0.5 g/L, respectively. The Cr(VI) adsorption quantity increases with an increase in chromium ion concentration, and with an increase in temperature. Co-existing ions had no significant effect on yeast adsorption ability. Desorption studies show that NaOH can be used for Cr(VI) desorption and that yeast can be recycled. The Langmuir isotherm model provides a satisfactory explanation of the adsorption equilibrium data. Adsorption rates obey the pseudo-second-order model, with high R^2 values. M1 can accumulate 8.27 mg/g Cr(VI), which is more than twice that of the host strain in Cr(VI) absorption ability. Together, these results demonstrate that the recombinant yeast has potential for the removal and recovery of Cr(VI) from sewage. Further studies are needed to determine the optimal conditions for the treatment of industrial wastewater containing hexavalent chromium in a continuous packed bed column system.

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Symbols

k_1	—	Pseudo-first-order constant (min)
k_2	—	Pseudo-second-order constant (g/mg/min)
q_e	—	Amount of Cr(VI) ions adsorbed per unit mass of biosorbent (mg/g)
C_o	—	Initial Cr(VI) concentration (mg/L)
C_e	—	Cr(VI) concentration in solution at equilibrium (mg/L)
V	—	Volume of the solution (L)
W	—	Amount of biosorbent (g)
q	—	Monolayer coverage capacity (mg/g)
b	—	Langmuir isotherm model constant (L/mg)
k	—	Freundlich isotherm model constant $(mg/g)/(mg/L)^{1/n}$
q_t	—	Amount of Cr(VI) adsorbed at any time t(mg/g)
n	—	Adsorption intensity

Abbreviations

M1	—	Recombinant *Saccharomyces cerevisiae* expressing metallothionein
MT	—	Metallothionein
YPD	—	Yeast extract peptone dextrose

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