Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2019.24304

168 (2019) 252–260
November

Lead(II) biosorption from aqueous solutions by *Trichoderma* fungus: equilibrium and thermodynamic study

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Received 22 April 2018; Accepted 17 April 2019

ABSTRACT

Lead is one of the trace metal ions and environmental pollutants that can be hazardous to humans and other organisms. The present study was conducted to evaluate the efficiency of *Trichoderma* fungus in biosorption of lead ions (Pb^{2+}) from aqueous solutions. Hence, the optimal conditions for fungal growth were determined to investigate the effects of critical parameters affecting biosorption process, including pH, mixing rate, contact time, temperature and initial lead concentration. The findings of the experiments showed that the *Trichoderma* fungus could grow well within 24 h at pH and temperature equal to 5°C and 25°C, respectively. The highest growth rate in these conditions was 0.51 g/100 mL of broth medium. Maximum biosorption rate of Pb^{2+} (98.8%) occurred at pH = 6 and initial concentration of 25 mg/L Pb^{2+}. It was also found that mixing rate could have a positive effect on increasing the removal of Pb^{2+} by *Trichoderma* fungus. Evaluation of biosorption system behavior based on biosorption models determined that Langmuir model is the most appropriate one to explain the biosorption behavior. Under these conditions, the maximum biosorption capacity was obtained equal 25.05 mg Pb^{2+}/g, which is very close to the value predicted by Langmuir model.

Keywords: Biosorption; Lead; *Trichoderma* fungus; Isotherm

1. Introduction

Pollutants are considered among the most damaging factors to ecosystems. Trace metals, among these, are of great importance because of their physiological effects on living organisms, being non-biodegradable toxic in small quantities, and their affinity to accumulate in the tissues, among others [1,2]. These metals are found naturally in the environment at different amounts; however, there are various other emission sources of these metals. Nowadays, human activities such as production of large amounts of sewage and solid wastes in urban, industrial and agricultural areas, widespread use of fossil fuels and extensive use of trace metals in industrial processes have led to increased concentrations of these metals in the environment. As a result, contamination of water supplies with trace metals due to the discharge of urban and industrial sewage, runoff and improper management of solid wastes have led to the penetration of these metals into living organisms, including humans as final consumers [3–5].

Arsenic, lead, copper, cadmium, mercury, chromium, copper, silver, zinc and nickel are the most common trace metals found in wastewater [6]. Among these, in terms of emission rate, lead is the most extensive toxic heavy metal in the environment [7]. The widespread use of lead in gasoline, its use in the production of chemical fertilizers and production of large amounts of wastewater containing lead in industries such as printing, painting, batteries, glass, etc. have caused inevitable pollution arising from it in water resources and industrial wastewaters [8]. The presence of

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lead in the body can cause kidney and liver dysfunction, damage to the reproductive system, anemia, reduced intellectual quality (IQ), and many other metabolic complications. Hence, it is necessary to find effective ways to reduce and remove it from aqueous solutions [9]. In this regard, there are many methods, such as chemical precipitation [10], coagulation [10], ion exchange [11], membrane technology [12] and adsorption by various adsorbents (low-cost adsorbents and natural biomass) for removal of heavy metals from water and wastewater [13,14]. Each of these methods has its own advantages and disadvantages. Chemical pre-concentration and oxidation–reduction reactions have low efficiency at low concentrations of heavy metals, and generate high and persistent deposits. Ion exchange, membrane technology and adsorption on activated carbon are, on the other hand, expensive methods. Thus, recent investigations have led researchers to design and develop biosorption techniques aiming to obtain high-efficiency and low-cost approaches [15,16].

Biosorption is the ability of biomass to collect metal ions from wastewaters through indirect metabolic activities or physicochemical adsorption methods. Some important advantages of biosorption compared with other methods are cost-effectiveness, high efficiency, minimum biochemical deposits and the possibility of recycling the metal ions. Algae, molds, yeasts, bacteria and fungi are among these biosorbents [17,18]. The mechanism of metal ions biosorption by biosorbents is a complex process. Biosorbents structure, chemical properties of metal ion solution and environmental conditions affect the efficiency of biosorption mechanism. Metal biosorption by living cells is achieved in two stages. In the first phase, the metal ions are absorbed by the interaction between the metal ions and functional groups on the surface of cell walls. This step can be done quickly and independently through one of the bonding mechanisms, including coordination, complexation, ion exchange and physical biosorption. In the second phase, by means of active biosorption mechanisms, the metal ions penetrate into the cell membrane and enter into the cell. Thus, the first phase of the biosorption is passive and rapid, but the second phase is active and gradual [19,20].

Before crossing the cell membrane and penetrating into the cytoplasm, all metal ions pass through the cell wall. The cell wall contains a variety of polysaccharides and proteins. Therefore, the cell wall is composed of many sites which are capable to bond with metal ions. Because of the differences in the composition of the cell walls in living organisms, the type and level of metal ions that form the bonds are different [21,22]. Fungi are classified as a large group of eukaryotic organisms that are heterotrophs and need to breakdown organic compounds to get their energy and carbon for growth and proliferation. Among the various species of fungi, *Trichoderma* species are beneficial fungi that are found nearly in all soils [23]. These fungi are the most common species in cultivation, and are employed in agricultural sciences for biological control of soil pathogens as well [24]. Application of *Trichoderma* species in wastewater treatment have been reported by researchers. For example, treatment of tannery effluent [25], textile effluent [26] and wastewater containing pharmaceutically active compounds [27] have been studied by some researchers. Nevertheless, the performances of these fungi in biosorption of lead ions under critical operating variables such as pH, contact time, lead concentration and temperature have rarely been reported. Hence, this study was performed to investigate the biosorption of lead ions (Pb^{2+}) from aqueous solutions by *Trichoderma* fungus.

2. Materials and methods

2.1. Preparation of metal solution

All chemicals in this study were obtained from Merck (Germany). To prepare the stock solution of Pb^{2+} ion (1,000 mg/L), 1.6 g of $Pb(NO_3)_2$ was dissolved in 1,000 mL volumetric flask with double-distilled water. All the other metal ion concentrations were obtained by diluting this solution in double distilled water using volumetric flasks. Lactic acid and potassium hydroxide (3%) were used to adjust the pH of the samples.

2.2. Preparation of Trichoderma fungus

A *Trichoderma* fungus sample was obtained from Iranian Research Organization for Science and Technology (IROST) and was cultured in Mycology Laboratory of Medical School at Zahedan University of Medical Sciences, Iran. The sample was aseptically cultured in sterile petri dishes containing PDA (Potato Dextrose Agar, composition, autoclave-sterilized at 110°C for 10 min) and was incubated at 24°C for three to 4 d to form visible colonies on agar [28].

250 mL flasks containing 100 mL of broth medium (containing 250 g/L potato extract, 20 g/L dextrose and 0.25 g/L tetracycline antibiotic, autoclave-sterilized at 110°C for 10 min) were used to assess the influence of study parameters on the biosorption process. To achieve this, *Trichoderma* fungus single colonies on agar medium were picked to inoculate the sterilized media aseptically and the flasks were placed in the incubator shaker to permit fungus in broth medium to grow enough prior to contact with metal ions. At this stage, the parameters affecting growth, including pH, temperature, incubation time and mixing rate were examined to achieve optimal growth of the fungus (optimum biosorbent dosage). It must be noted that fungal growth was determined gravimetrically after drying in an oven at 80°C for 8 h, cooling it to room temperature in a desiccator and weighing [29]. All experiments were repeated three times and the calculated mean values were reported as the result.

2.3. Measurement of Pb^{2+} ions concentration and dependent variables

After determining the optimal conditions of growth, certain concentrations of Pb^{2+} ions were added aseptically to fungus cultured in broth medium grown to optimum biosorbent dosage. After setting variables according to the purpose of each phase, the flasks were placed back into the incubator shaker. In this study, in order to achieve optimal biosorption conditions, the effects of most important parameters that would have an impact on the process, including solution pH, initial concentration of Pb^{2+} ions, mixing rate, contact time and temperature were studied (Table 1). After the elapse of retention time, the biosorption rate of Pb^{2+} ions was measured by analyzing the supernatant by flame

Table 1
Range of experimental parameters

Parameter	Ranges
pH	2–8
Mixing rate (rpm)	150–350
Lead concentration (mg/L)	25–200
Temperature (°C)	20–35
Contact time (min)	30–270

atomic adsorption spectroscopy (FAAS) using a Shimadzu AA-6650 machine (Japan). The readings of remaining Pb^{+2} ions in the samples by FAAS were repeated three times. The obtained results were converted to concentration using the calibration curve and linear equation. Biosorption capacity of biosorbent and Pb^{2+} ion removal efficiency and were calculated according to the following equations:

$$q_e = \frac{\left(\left(C_0 - C_e\right) \times V\right)}{M} \tag{1}$$

$$\text{Removal efficiency}\left(E\right) = \left(\frac{\left(C_0 - C_t\right)}{C_0}\right) \times 100 \tag{2}$$

In Eq. (1) q_e is weight of metal ion biosorbed per gram of biomass (mg/g); C_0 and C_e are the initial and equilibrium liquid phase concentration of Pb^{2+} (mg/L), respectively; V is the volume of the solution (L); and M is the weight of biosorbent (g). In Eq. (2) E is the percentage of Pb^{2+} ion removal by the fungal biomass; C_0 and C_t represent the initial and final (after biosorption) lead concentrations (mg/L), respectively [30–32].

At the end of the experiments, the weight of biosorbent was calculated based on the weight of the water-free fungus as follows: the contents of each flask were centrifuged and the pellet was placed inside a glass desiccator at 105°C for 48 h, and then the weight was measured.

2.4. Biosorption process modeling

In the biosorption process in a solid–liquid system, the components of the solution will accumulate and concentrate on the solid surface, and this process will continue until equilibrium is reached. Two parameters including q_e (the equilibrium biosorption capacity) and C_e (the final equilibrium concentration of adsorbate after the equilibrium) are used to describe such equilibrium. Biosorption isotherm refers to the relationship between changes in the amounts of adsorbate and concentration of adsorbent remaining in the solution at a constant temperature and can describe the reaction mechanisms between adsorbate and adsorbent. A plot of C_e/q_e, that is, biosorption isotherms have various forms for different systems and thus are described using different models. In this study, biosorption system behavior was evaluated based on Langmuir, Freundlich, Dubinin–Radushkevich (DRK) and Temkin isotherm models. Linear equations for each of these models are shown below [33,34]. In Langmuir model (Eq. (3)), q_e (mg/g) is the amount of Pb^{2+} ions biosorbed per specific amount of biosorbent, C_e is equilibrium concentration of the Pb^{2+} ions in solution (mg/L), K_L (L/mg) is Langmuir constant, and q_m (mg/g) is the maximum amount of Pb^{2+} required to form a monolayer.

$$\left(\frac{1}{q_e}\right) = \left(\frac{1}{q_m}\right) + \left(\frac{1}{\left(q_m K_L\right)}\right)\left(\frac{1}{C_e}\right) \tag{3}$$

The Freundlich model (Eq. (4)) is an empirical relation between q_e and C_e. It is obtained by assuming a heterogeneous surface with non-uniform distribution of the biosorption sites on the biosorbent surface, and can be expressed by the following equation:

$$\log q_e = \log K_F + \frac{1}{n}\log C_e \tag{4}$$

where K_F and $1/n$ are the Freundlich constants related to biosorption capacity and biosorption intensity, respectively. The Freundlich constants can be obtained by drawing the $\log q_e$ vs. $\log C_e$ based on experimental data.

In Temkin model (Eq. (5)), the surface absorption theory was corrected considering possible reactions between adsorbent–adsorbent and adsorbent–adsorbate.

$$q_e = B\ln K_T + B\ln C_e \tag{5}$$

where K_T and B are Temkin constants, and B is related to the heat of biosorption.

The empirical equation of Dubinin–Radushkevich model (Eq. (6)) has been widely used to describe the adsorption of gases and vapors on microporous solids, and can be written as:

$$\log\ q_e = \ln q_m - \beta\varepsilon^2 \tag{6}$$

where β (mol^2/kJ^2) is a constant connected with the mean free energy of biosorption per mole of the adsorbate, q_m (mg/g) is the theoretical saturation capacity, and ε is the Polanyi potential.

3. Results and discussion

3.1. Optimization of biosorbent growth

Living and growing fungi cells are recruited as biosorbent; the quantities of biosorbent and available active sites on its surface are effective on the biosorption efficiency of metal ions. In other words, an improvement in the biosorbent quantity would increase the amount of available active sites and functional groups suitable for complex formation and metal ion extraction, leading to an enhancement of metal ion removal efficiency. Hence, as the first goal, determination of optimal conditions for growth of fungi cells, were studied. In this regard, effects of various parameters on fungal growth were evaluated (Figs. 1a–d). As is clear from Fig. 1, the maximum fungal growth rate for each parameter was as follows: pH = 5, contact time of 24 h, a temperature of 298 K and mixing rate of 250 rpm. When these optimum conditions were combined, a mean of 5.1 g of biomass per 1 L of broth

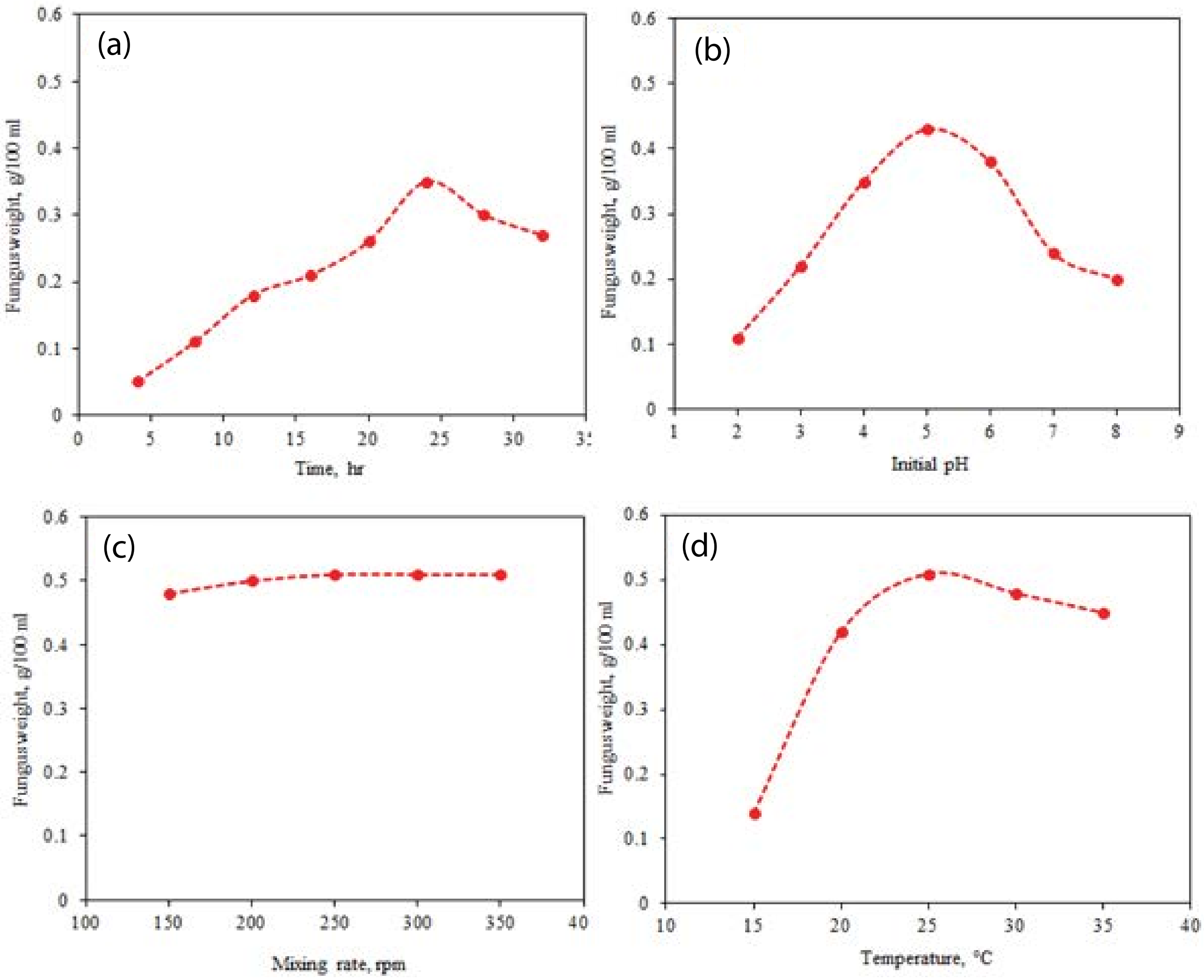

Fig. 1. Effect of various parameters on growth of *Trichoderma* fungus, (a) time, (b) pH, (c) mixing rate, and (d) temperature

medium (5.1 g/L) was gained, which was considered as the optimum biosorbent dosage in the following steps of the study.

3.2. Effect of solution pH on removal of Pb^{2+} by Trichoderma fungus

The solution pH is one of the most important parameters affecting the biosorption of metal ions by biosorbents. It can cause substantial changes in the efficiency of biosorption processes through acting on the cell wall of biosorbents and the chemistry of metal ions [35–37]. To investigate the effect of solution pH on the biosorption in the studied system, seven 250 mL flasks suitable for growth of the cultured *Trichoderma* fungus were selected and adjusted to the pH values of 2–8. The solution containing Pb^{2+} ions was added to the mentioned samples to achieve final concentration of 50 mg Pb^{2+}/L, and the samples were placed in the incubator shaker for 24 h.

Fig. 2 shows the effect of initial pH of solution on the removal of Pb^{2+} ions and the biosorption capacity of biosorbents. As it turns out, the highest rate of lead removal by biosorbents (82.4%) was obtained at pH equal 6, which was selected as the optimum pH. Similar to current results, in a study performed by Say et al. [38] on biosorption of metal ions using the filamentous fungus *Phanerochaete chrysosporium*, the highest removal rate was observed at pH = 6. Less biosorption was found at pH lower than 6, so that the lowest removal level (35.6%) was seen at pH = 2. This observation could be due to protonation of functional groups on the surface of fungi at acidic pH values. Hence, the total charge of the fungal surface would be positive in such conditions and repulsive forces between the fungal positive surface and metal ion positive charge could inhibit the ion biosorption on the surface of fungi. On the other hand, in acidic pH values, the protons in the environment could compete with metal ions in being absorbed on the surface of biosorbents, causing decreased biosorption. With increasing pH values, the total charge of the cell wall and the fungal surface would increasingly become more negative and anionic active sites will be created on its surface. This would lead to an increase in their ability to form complexes with lead(II) ions and thus higher removal efficiency will be achieved. The observed reduction in the biosorption process at pH values >6 can be attributed to the formation of hydroxide deposits or mixed hydroxide complexes that impede the metal ions biosorption on the adsorbent. Similar findings were reported by other researchers [14,16,39]. Similar findings were reported by Al-Homaidan et al. [40] for biosorption of cadmium by *Spirulina platensis* dry biomass (which maximum biosorption efficiency equal 78% was observed at pH 7–8). Also, the results of this study in agreement with the findings of Kariuki et al. [41] on biosorption of lead using rogers mushroom biomass '*Lepiota hystrix*', which found optimum pH of 4.5–6.0 for maximum lead biosorption from aqueous solutions.

3.3. Effect of mixing rate on Pb^{2+} ion biosorption by *Trichoderma fungus*

The appropriate and adequate contact of pollutant and adsorbent surface through suitable mixing in liquid medium can lead to accelerated biosorption of pollutants, improving the biosorption process, and reducing the equilibrium time. The present study examined the effect of mixing rate on Pb^{2+} ion biosorption at the mixing rate of 150–350 rpm with the concentration of 50 mg/L Pb^{2+} ion and at pH of 6 during a period of 90 min. As shown in Fig. 3, lead removal efficiency was improved from 83.6% to 92.8% by increasing the mixing rate from 150 to 250 rpm, and then it was nearly constant or reduced slightly at increased mixing rates. These findings can be interpreted as a result of breaking the bonds between metal ions and biosorbent surface at high mixing rates, or be due to occupation of the active sites on the adsorbent. These results agree with findings from the study of Foroutan et al. [42] regarding the lead biosorption from aqueous solution using shrimp peel. The results of their study showed that by increasing the mixing rate up to 200 rpm, the lead biosorption efficiency increased by 94.3% [42].

3.4. Effect of contact time on Pb^{2+} ion biosorption by *Trichoderma fungus*

Another parameter affecting the efficiency of metal ions biosorption on biosorbents is contact time, which determines the kinetics and time tested [43]. The effects of contact time on the Pb^{2+} ions biosorption was analyzed in a range of 30–240 min of contact time, concentration of 50 mg/L Pb^{2+} ions, pH = 6, mixing rate of 250 rpm and temperature of 25°C. Fig. 4 shows the effect of contact time on the biosorption efficiency of Pb^{2+} ions and absorptive capacity. According to Fig. 4, it is clear that both biosorption efficiency and biosorption capacity of adsorbent at the beginning of the experiment are rising with steep slope in a manner that within an interval of 30–120 min of contact time, biosorption efficiency and capacity rose from 71.6% and 7.02 mg/g to 96.8% and 9.49 mg/g, respectively. After 120 min, both factors remain almost constant. Concordantly, Abdel-Aty et al. [44] observed the highest amount of lead adsorbed by *Anabaena sphaerica* fungus after 120 min of testing. The high rate of Pb^{2+} ions biosorption at the beginning of the process can be attributed to the abundance of available active sites on the biosorbents and high concentration of metal ions. Biosorption efficiency is reduced over time with the occupation of the active sites by metal ions and a reduction in the concentration of ions. Thus, the contact time of 120 min in this study could be regarded as the equilibrium point of

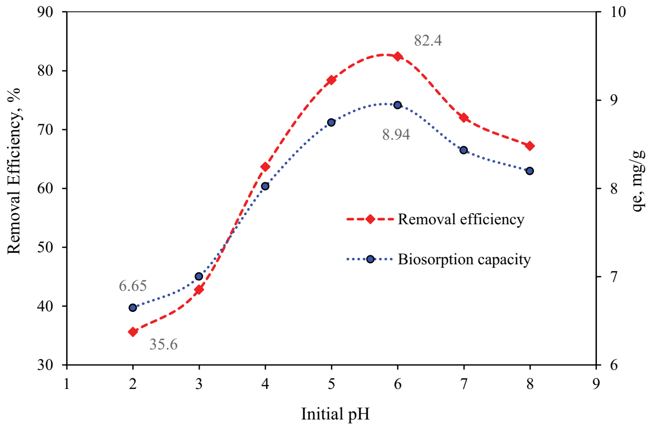

Fig. 2. Effect of initial pH on Pb^{2+} ions biosorption by *Trichoderma* fungus (at 25°C, mixing rate = 150 rpm, biosorbent dosage = 5.1 g/L, initial Pb^{2+} concentration = 50 mg/L, contact time = 90 min).

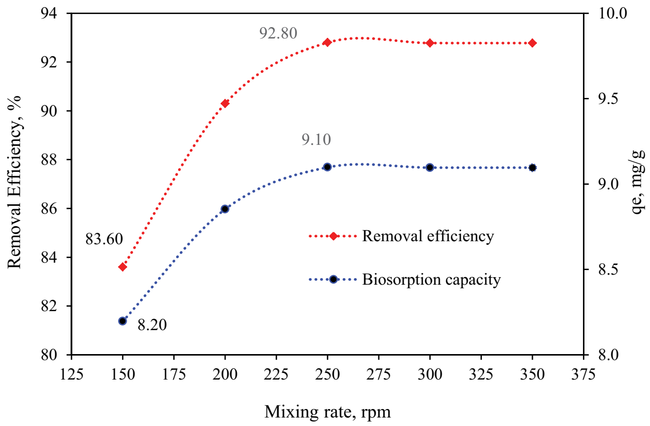

Fig. 3. Effect of mixing rate on Pb^{2+} ion biosorption by *Trichoderma* fungus (at 25°C, pH = 6, contact time = 90 min, biosorbent dosage = 5.1 g/L, initial Pb^{2+} concentration = 50 mg/L).

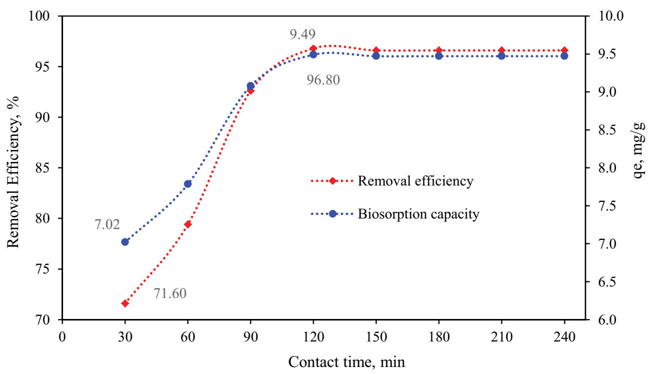

Fig. 4. Effect of contact time on Pb^{2+} ions biosorption by *Trichoderma* fungus (at 25°C, pH = 6, mixing rate = 250 rpm, initial Pb^{2+} concentration = 50 mg/L).

biosorption process, which could be considered as an optimum contact time for the rest of experiments.

3.5. Effect of initial Pb^{2+} ions concentration and temperature on its biosorption by *Trichoderma* fungus

Initial concentration of pollutants and temperature are always regarded as important parameters on biosorption process efficiency. Temperature can affect chemical reaction rate, and initial concentration of pollutant is the driving force in the mass transfer rate of adsorbate to the biosorbent surface. Fig. 5 indicates the effect of initial Pb^{2+} ions concentration on biosorption efficiency at different temperatures. As shown in Fig. 5 and similar to the results reported by Abdel-Aty et al. [44], the most biosorption efficiency at all temperatures was achieved at lower Pb^{2+} concentrations and, biosorption process efficiency was decreased by increasing the concentration of the Pb^{2+} ions. For example, at temperature 20°C, maximum removal efficiency equal 95.6% has been found at lower concentration of Pb^{2+} solution (25 mg/L) and a minimum removal efficiency of Pb^{2+} ions (equal 58.4%) has been obtained at initial concentration of 200 mg/L by *Trichoderma* fungus. Although, the biosorption process efficiency was decreased by rising concentrations of Pb^{2+} ions, biosorption capacity of biosorbent had an upward trend (Fig. 6). As shown in Fig. 6, the Pb^{2+} ions biosorption capacity of the *Trichoderma* fungus increased from 4.69 to 22.92 mg/g (at 20°C) as the initial Pb^{2+} concentration was varied from 25 to 200 mg/L. Similar trends were observed for other studied temperatures.

The increase of biosorption capacity of biosorbent with an increase in Pb^{2+} ions concentration is probably due to higher interaction between metal ions and the biosorbent. Similar findings were reported by Rathinam et al. [45] for cadmium biosorption by seaweed, and by Das and Guha [46] for chromium removal by biomass of *Termitomyces clypeatus*.

Analyzing the efficiency of temperature on the biosorption process indicates that removal efficiency was increased with increasing temperature from 20°C to 25°C. Probably due to increased diffusion coefficient of lead ions, their affinity was enhanced for complex formation and adhesion to the fungal surface. Thus, in the present study, the highest biosorption rate (98.8%) of Pb^{2+} ions occurred at 25°C and the concentration of 25 mg/L Pb^{2+}, and the lowest rate (58.45%) took place at 20°C and the concentration of 200 mg/L. Extraction efficiency is reduced at lower temperatures due to reduced mass transfer rate and diffusion coefficient. The removal efficiency was again declined slightly over 25°C. This could be due to high temperatures unsuitable for growing fungi and variations in the superficial active sites [16,31–33]. Findings of Al-Homaidan et al. [40] on biosorption of cadmium by *Spirulina platensis* dry biomass showed that maximum biosorption efficiency equal 87% was achieved at 26°C, which is in agreement with the results of this study.

3.6. Biosorption isotherms and kinetics

We further decided to study biosorption isotherms in our system, since the related findings could be helpful in understanding the mechanisms of the biosorption and pollutant affinity to adsorbent. In this regard, after plotting each of the biosorption models and determining their correlation coefficient, it can be observed which one of biosorption curves fits with empirical data of the biosorption process, indicating the type of equation governing process. Furthermore, biosorption intensity and adsorbent capacity to absorb pollutants can be measured according to the isotherm constants [16].

In the present study, Langmuir, Freundlich, Temkin and DRK biosorption isotherms were examined and the respective graphs were drawn on the basis of experimental data. Figs. 7a–d display the linear models of the studied isotherms and Table 2 presents the correlation coefficients and the aforementioned isotherm constants. Given the correlation coefficients for different biosorption models at the temperatures of 20°C–35°C, it can be concluded that the biosorption of Pb^{2+} ions by *Trichoderma* fungus is most consistent, in decreasing order, with Langmuir, DRK, Temkin and Freundlich models. Based on the experimental findings, the maximum biosorption capacities of the adsorbent were observed at 20°C, 25°C, 30°C and 35°C, respectively equal

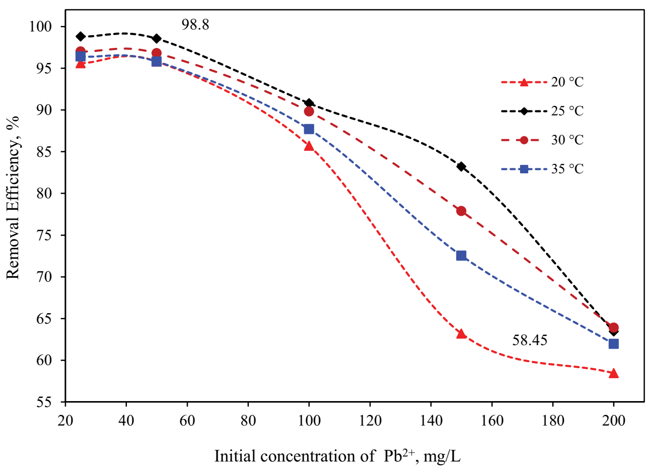

Fig. 5. Effect of initial concentration of Pb^{2+} ions on biosorption by *Trichoderma* fungus at different temperature (pH = 6, mixing rate = 250 rpm, contact time = 120 min).

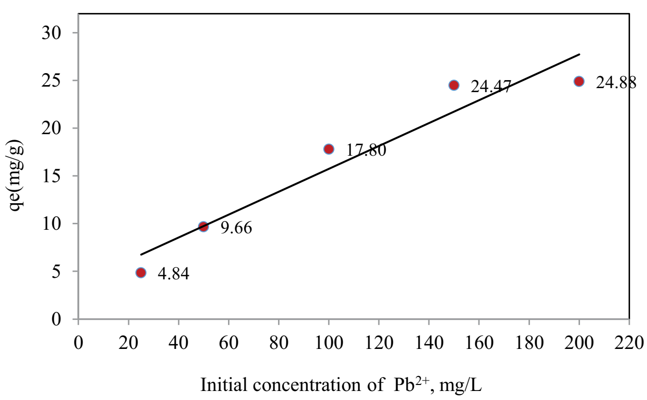

Fig. 6. Effect of initial concentration of Pb^{2+} ions on biosorption capacity by *Trichoderma* fungus at 25°C (pH = 6, mixing rate = 250 rpm, contact time = 120 min).

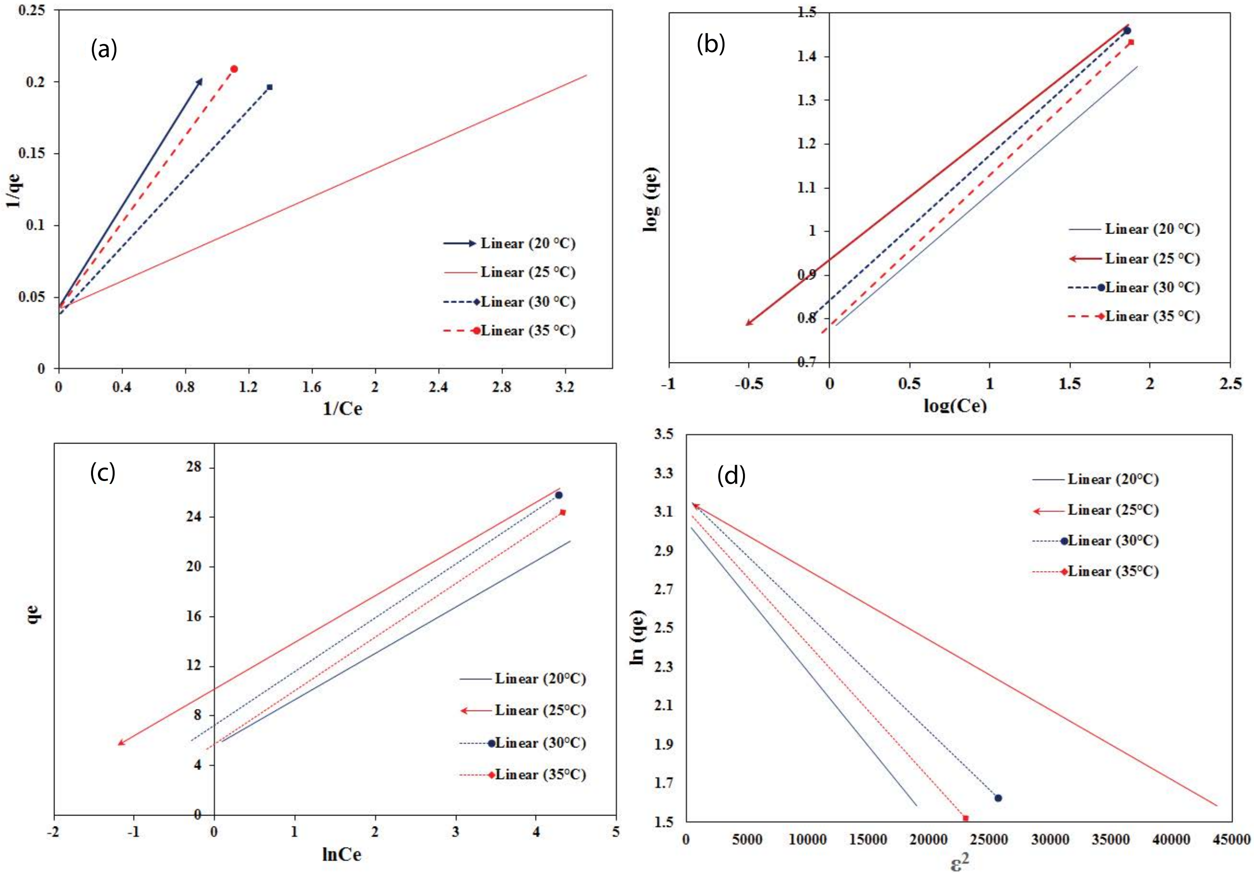

Fig. 7. Isotherms for biosorption of Pb^{2+} ions on *Trichoderma* fungus. (a) Langmuir isotherm, (b) Freundlich isotherm, (c) Temkin isotherm, and (d) DRK isotherm.

to 22.92, 24.88, 25.06 and 24.29 mg/g, which are very close to those obtained by Langmuir model. This is confirmed by comparing the empirical findings with the constants of Langmuir mode. Thus, it is concluded that the biosorption process on all active sites was based on an identical mechanism and biosorption occurs as a monolayer. Sari and Tuzen [47] and Morosanu et al. [48] have reported similar results. Findings of Morosanu et al. [48] have been shown that the calculated sorption capacities were in good agreement with the uptake capacity of Langmuir model. In addition, findings of Morosanu et al. [48] on biosorption of cadmium by *Spirulina platensis* dry biomass showed that Langmuir model to be in better correlation with experimental data ($R^2 = 0.92$). Furthermore, the results of Kariuki et al. [41] on biosorption of lead using rogers mushroom biomass '*Lepiota hystrix*' confirmed the suitability of Langmuir isotherm model.

Two kinetics models, namely pseudo-first-order and pseudo-second-order were used in this study to investigate the biosorption of Pb^{2+} ions on *Trichoderma* fungus (Table 3). Where q_t (mg/g) and q_e (mg/g) are the biosorption capacities of Pb^{2+} ions at time *t* (min) and equilibrium, respectively. k_1 (min^{-1}) and k_2 (g/mg min), are the rate constants of the pseudo-first-order and pseudo-second-order models, respectively. As it can be seen from Figs. 8, 9 and Table 3, the data well fitted with the second-order kinetics model ($R^2 > 0.99$). On the other hand, the pseudo-second-order models can well describe the experimental data, indicating that the biosorption process was controlled by chemical interaction. Based on the findings of Kariuki et al. [41] on biosorption of lead using roger's mushroom biomass

Table 2
Isotherm parameters for biosorption of Pb^{2+} ions on *Trichoderma* fungus at different temperatures

Isotherm model	Constant	Temperature, K			
		293	298	303	308
Langmuir isotherm	b	0.2442	0.8606	0.3138	0.2744
	q_m	23.25	23.8	26.66	24.15
	R^2	0.9696	0.9936	0.9581	0.9960
Freundlich isotherm	K_f	5.92	8.60	6.91	6.06
	n	3.16	3.46	2.99	2.89
	R^2	0.8918	0.9256	0.9078	0.9341
Temkin isotherm	B	0.2567	0.2583	0.2280	0.2313
	K_t	0.0056	0.00047	0.0079	0.0033
	R^2	0.9587	0.9738	0.9875	0.9958
DRK isotherm	β	0.0003	0.00006	0.00064	0.000075
	q_m	3.04	3.16	3.17	3.10
	R^2	0.9808	0.9776	0.9776	0.9868

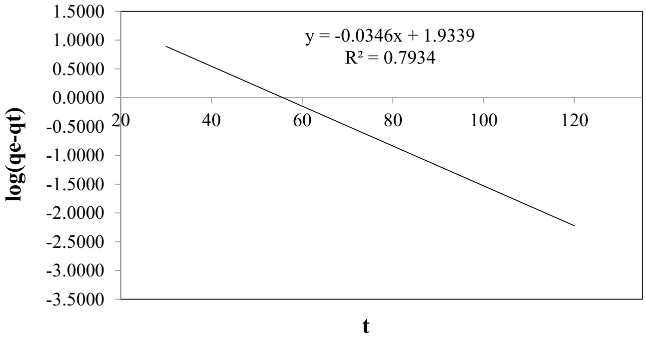

Fig. 8. Pseudo-first-order kinetic plots for Pb^{2+} ions biosorption on *Trichoderma* fungus.

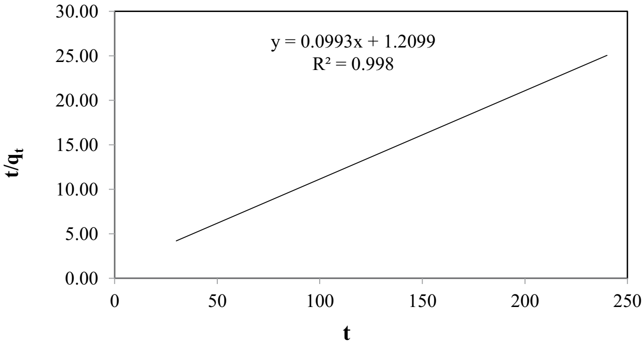

Fig. 9. Pseudo-second-order kinetic plots for Pb^{2+} ions biosorption on *Trichoderma* fungus.

Table 3
Kinetics parameters for lead biosorption on *Trichoderma* fungus

Kinetic models	Equations		Parameters	
	Non-linear	Linear		
Pseudo-first-order model	$q_t = q_e(1–\exp(–k_1 t))$	$\log(q_e – q_t) = \log(q_e) – (k_1/2.303)t$	K_1 (min$^{-1)}$ –0.07974	R^2 0.7934
Pseudo-second-order model	$q_t = (q_e^2 \times k_2 \times t)/(1 + q_e \times k_2 \times t)$	$t/q_t = (1/k_2 \times q_e^2) + (1/q_e)t$	K_2 (g/mg min) 1.2099	R^2 0.998

'*Lepiota hystrix*', the biosorption process follows second-order kinetics.

4. Conclusion

Being able to grow in most settings, *Trichoderma* fungus is one of the fungi used to remove pollutants from the environment. Studying the effects of variables related to the biosorption process determined that the maximum biosorption rate of lead ions (98.8%) occurs after 120 min of testing at pH equal 6 and the temperature of 25°C, which is close to the ambient temperature. Moreover, the removal efficiency was enhanced by increasing the mixing rate and was reduced by raising the concentration of Pb^{2+} ions. The biosorption system behavior was evaluated, and the suitability of the Langmuir model for the analysis of the biosorption process was demonstrated. Collectively, these results showed that *Trichoderma* fungus as a biosorbent has high biosorption capacity for the removal of Pb^{2+} ions from aqueous solutions.

Acknowledgment

The authors would like to thank Health Research Deputy of Torbat Heydariyeh University of Medical Sciences for financial support in carrying out this research (Project No: A-101350-1).

Symbols

B — Temkin constant
C_0 — Initial concentration in aqueous phase
C_e — Equilibrium concentration in aqueous phase
E — Removal efficiency
k — Rate constant
K_F — Freundlich constant
K_L — Langmuir constant
K_T — Temkin constant
M — Mass of biosorbents
n — Freundlich constant
q_e — Adsorption capacity at equilibrium
q_m — Maximum adsorption capacity
q_t — Adsorption capacity at time t
T — Temperature
V — Volume of the solution
β — Dubinin–Radushkevich constant
ε — Polanyi potential

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