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Biosorption of lead using *Penicillium notatum* dead biomass from aqueous solutions

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A B S T R A C T

Lead is one of the stable and biodegradable pollutants released from industrial, agricultural and technological development activities more than the permitted level in the environment. This metal, due to its toxicity, even at low concentrations, has adverse effects on the environment and health of living organisms. The aim of this study is to investigate the bio-absorption of lead by the fungus *Penicillium notatum* in aqueous solutions. For this purpose, the fungus *Penicillium notatum* PTCC 5074 was prepared from the Iranian Scientific Research Organization as lyophilisation and to culture and reproduce it in the culture medium of potato dextrose agar and sabouraud dextrose broth. In this study, the effect of some parameters such as lead concentration, ion intensity, biomass concentration, temperature and contact time on the rate of adsorption of lead by abiotic biomass at pH = 5 were evaluated. The maximum absorption rate was 180.75 mg g^{-1} under optimal conditions (concentration of metal = 228 mg L^{-1}, ion intensity = 43.2 mg L^{-1} Ca^{2+}, biomass concentration = 1.2 g L^{-1} of dry weight of biomass, temperature = 33°C, and contact time = 105 min). Absorption data were better fitted by Langmuir model R^2 = 0.9820). Also, due to the thermodynamic constants, it was found that lead absorption process is thermally abiotic by a biomass. Gibbs free energy values (ΔG) showed that all absorption processes are spontaneous and physical. The false quadratic equation (R^2 = 1) has the best compatibility with regard to kinetic data. BET, SEM and EDX tests were also used to determine the biomass characteristics.

Keywords: Biosorption; Lead; *Penicillium notatum*

1. Introduction

In recent years, much attention has been paid to managing environmental problems, including the risks of heavy metals [1]. The presence of heavy metals in wastewater from industries involved in manure production, paper production, car manufacturing, pesticide production, automobile and petrochemical production have harmful effects on the environment and health of living organisms, especially humans [2–4]. Because heavy metal ions accumulate in the environment due to their stability and degradability, their amount

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increases throughout the food chain [5]. Among the various metal ions, lead, mercury, cadmium and chromium have high toxicity and are at the top of the toxicity list [6,7]. Lead is a systemic poison, which affects more organs after being absorbed. Lead binds with sulfhydryl groups and is involved in the activity of enzymes that are dependent on sulfhydryl groups [8]. There are several methods for removing and separating heavy metal ions from aqueous solutions such as chemical deposition, ion exchange, reverse osmosis, membrane processes, solvent extraction, and surface adsorption by active carbon [1,5,9]. The ion exchange and reverse osmosis systems have high operational costs and most chemical processes require expensive and high-tech facilities which produce chemical sludge that is hardly refined. Also the relatively high cost of the active carbon process, which is related to the process of producing and recovering carbon, has limited its use. These problems have led to the consideration of bio-absorption method as a more appropriate option that is both economically and environmentally friendly [10].

The bio-absorption method involves all practical processes for absorbing heavy metals by the cell of microorganisms (bacteria, fungi, algae and etc.) and the accumulation of heavy metal ions in the outside and inside of the cell [9]. In this method, heavy metals are removed in two ways through biological absorption and biological accumulation. The advantages of bio-absorption method for removing metal ions compared with other physical and chemical methods include low cost and re-use of adsorbent, good absorption capacity due to high contact surface, selective absorption of metal ions and ability to be used under environmental conditions [5,11,12]. Among the microorganisms, the fungi have received considerable attention because of having a specific cell wall and the presence of various organic compounds such as carboxylic groups, sugars, fats and proteins and active sites that can bind metal ions [11,13,14]. The purpose of this study is to study the effect of lead concentration parameters, biomass, temperature, contact time and ion concentration on the removal of lead by the fungus *Penicillium notatum* and determine favorable conditions for biological absorption of lead ions.

2. Materials and methods

2.1. Preparation of Penicillium notatum dead biomass

In the study, the fungus *Penicillium notatum* PTCC 5074 was used which was purchased from Iran's Industrial Scientific Research Organization as lyophilization. The fungus was cultured on plates containing the specific environment of potato dextrose agar and incubated at 28°C for 48 h [15]. In order to increase the number of mycelia, we used 250 mL Erlenmeyer flask containing 100 mL of sabouraud dextrose broth culture. Several colonies with sterile loops were inoculated into this medium and placed in a shaker incubator at 120 rpm and 28°C for 72 h [15]. To isolate the biomass from the broth medium, we used a centrifuge machine with 3,000 rpm for 15 min [10]. Then the supernatant was discarded and the biomass was washed three times with distilled water and dried in an oven at 60°C for 24 h, then powdered, passed through a mesh of less than 100 μm and used as abiotic biomass [4,15].

2.2. Stages of performing absorption tests

Prior to the start of the experiments, all containers used for acid washing were placed in 10% nitric acid for 2 h, then washed with water and distilled water and dried in an oven [1].

For the preparation 1,000 mg L^{-1} of stock solution, we used lead nitrate salt $Pb(NO_3)_2$. Then, using this stock solution, we prepared various concentrations of 50–300 mg L^{-1} [1,16,17].

100 mL of the solution with different concentrations of lead (50, 123, 175, 228 and 300 ppm) was transferred to 250 mL Erlenmeyer flask and to adjust pH to 5 we used 1 M nitric acid and soda [8,15,16]. Also, to determine the effect of ion intensity at concentrations of 20, 43, 60, 77 and 100 mg L^{-1} of calcium we used stock solution of 1,000 mg L^{-1} of calcium made from $CaCl_2$ composition [17]. Dry biomass was added to the samples (0.05, 0.12, 0.17, 0.23 and 0.3), and placed in the incubator shaker at 120 rpm and different temperatures of 10°C, 23°C, 32.5°C, 42°C and 50°C for 30, 74, 105, 137 and 180 min. Finally, the samples were passed through Whatman No. 1 paper filter [14]. And the lead concentration of the sample was measured by atomic absorption device (VARIAN240). Then, using the following formula, the amount of lead absorption by this type of fungus was calculated in mg g^{-1} dry weight.

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

In the above equation, C_e is the balanced concentration of the absorbent substance in mg L^{-1}, C_0 is the initial concentration in mg L^{-1}, V is the volume of solution in liters, and m is the mass of the adsorbent in grams [2,14,18,19].

All chemicals used for solubilization were prepared from Merck Company (Germany).

3. Results and discussion

3.1. Effect of the initial concentration of lead ion on the metal adsorption capacity

In this study, we studied the absorption capacity of lead by abiotic biomass of the fungus *Penicillium notatum*, under the influence of various concentrations of lead in aqueous solutions in the range of 50–300 mg L^{-1}. The results showed that increasing the concentration of metal in the solution causes the absorption increased (Fig. 1). So that the average absorption at the concentration of 50 mg L^{-1} was 26.36 and 171. 68 mg L^{-1} biomass dry weight at the concentration of 300 mg L^{-1}. This is due to the fact that the active sites of the fungus are surrounded by metal ions, which leads to the maximum absorption capacity of metal ions [1,16]. On the other hand, increasing the concentration of the metal ion increases the number of collisions between the metal ions and adsorbent, which accelerates the absorption process [11]. The stages of optimizing the absorption of lead by the abiotic fungus *Penicillium notatum* biomass showed that the maximum absorption capacity of lead was 228 mg L^{-1} of lead. The results of Baysal et al. [9], Fan et al. [15] and Iram et al. [16] studies in 2009, 2008 and 2015 on the biological absorption

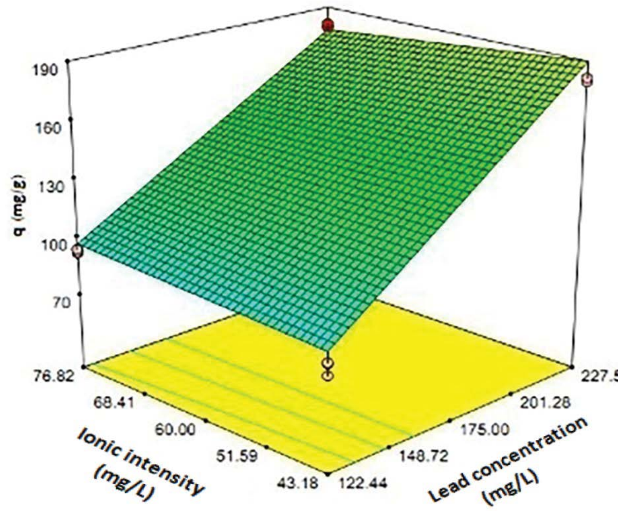

Fig. 1. Effect of lead concentration and ion intensity on the biosorption of *Penicillium notatum* (biomass concentration = 1.2 g L^{-1}, temperature = 33°C and contact time = 105 min).

of lead by the abiotic fungal biomass of *Penicillium*, *Aspergillus flavus* and *Aspergillus niger* and *Candida albicans* yeast are similar to the findings of this study. The optimal concentration of lead for these three studies was reported to be 250, 200 and 1,400 mg L^{-1}, respectively [9,15,16].

3.2. Effect of ion intensity on the metal absorption capacity

In this study, to determine the effect of ion intensity of calcium ion we used different concentrations of 20–100 mg L^{-1} calcium. The results of the present study showed that with increasing ion intensity, lead absorption capacity reduced by abiotic biomass (Fig. 1). So that the average absorption at the concentrations of 20 and 100 mg L^{-1} calcium ion by *Penicillium notatum* biomass was 101.46 and 84.58 mg g^{-1} biomass dry matter, respectively. This reduction could be due to the competition between calcium and lead ions in absorption positions [20]. These results are consistent with studies by Zhang et al. [4] and Lodeiro et al. [21]. In their studies, the reduction in metal absorption capacity was observed with increasing ion intensity due to the competition of electrolyte ions in adsorption sites [4,21]. In their study, El-Sayed et al. [22] also concluded that increasing 1 to 10 g per liter of salt (NaCl) slightly reduced the absorption of cadmium and nickel by rice bran. The study results of Glatstein and Francisca [23] showed that ion intensity had little effect on the removal of copper and lead from water by adsorbent sodium bentonite. Also, the study results of Nourmoradi et al. [24] showed that the increase in ion intensity in solutions had no significant effect on the removal of mono-aromatic hydrocarbons, including benzene, toluene, ethylbenzene and xylene. In contrast to the above results, the study by Jianwei et al [25]. showed that increasing the calcium ion from zero to 1 mL mol L^{-1} increased phosphorus uptake from 47.9 to 70.3 mg g^{-1} zirconium oxide. Similar to this study was also reported for ferrihydrite and oxide magnesium [25]. In this study, the maximum absorption capacity of metal at ionic concentration was 43.2 mg L^{-1} calcium ion.

3.3. Effect of biomass concentration on the metal absorption capacity

In this study, biomass was used at a concentration of 0.5–3 g L^{-1} (biomass dry weight). The results showed that with increasing the concentration of adsorbent, the biological absorption capacity of lead reduced (Fig. 2). The average absorption at the concentration of 0.5 g L^{-1} was 256.2 and 49.66 mg g^{-1} biomass dry weight at the concentration of 3 g L^{-1}. Because at high concentrations of the biomass, the cellular components' density leads to a reduction in the active sites of the adsorbing surface [11]. In other words, this effect is due to the interference with bonding sites at higher concentrations of the biomass. Also, the imbalance of dissolved metal ions in relation to the available sites for bonding in the adsorbent surface and the lack of complete coverage on these sites leads to a reduction in adsorption [14,16]. The results of this study are consistent with the study by Fan et al. [15] regarding the reduction of lead absorption by increasing *Penicillium* abiotic biomass from 0.1 to 0.6 g L^{-1}. Studies by Baysal et al. [9] and Marandy et al. [27] on the removal of heavy metals with different concentrations of fungal abiotic and biotic biomass are consistent with the findings of this study. Increasing the concentration of biomass has reduced the biological absorption of heavy metals [9,27]. In this study, the maximum absorption capacity of the metal was reported 1.2 g L^{-1} at the biomass concentration.

3.4. Effect of temperature on the metal biosorption capacity

In this study, we studied the effect of the temperature in the range of 10°C–50°C on the amount of lead absorption capacity. The results showed that with increasing the temperature, the absorption capacity of lead was first increased and then reduced (Fig. 3). The average absorption at 10°C, 23°C, 32.5°C, 42°C and 50°C, respectively, was 86.5, 98.45, 74.08, 87.103 and 75.55 mg g^{-1} of biomass dry weight, respectively. In this study, the optimal temperature for maximum

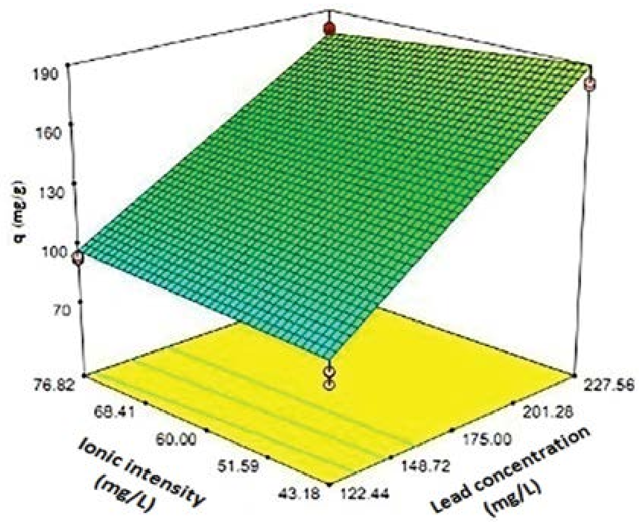

Fig. 2. Effect of lead concentration and concentration of biomass on biosorption by *Penicillium notatum* (ionic intensity = 43.2 mg L^{-1}, temperature = 33°C and contact time = 105 min).

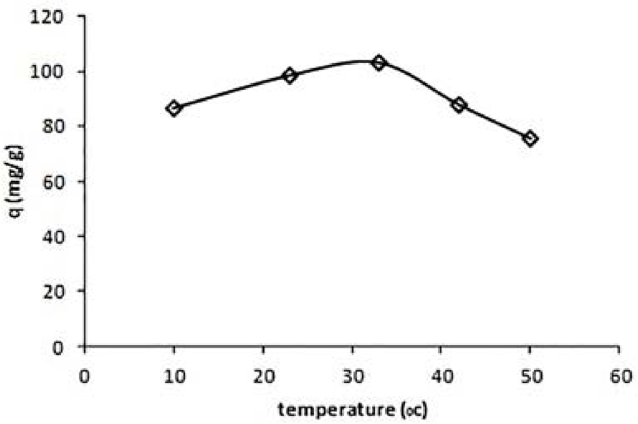

Fig. 3. Effect of temperature on the biosorption of lead by the fungus *Penicillium notatum*.

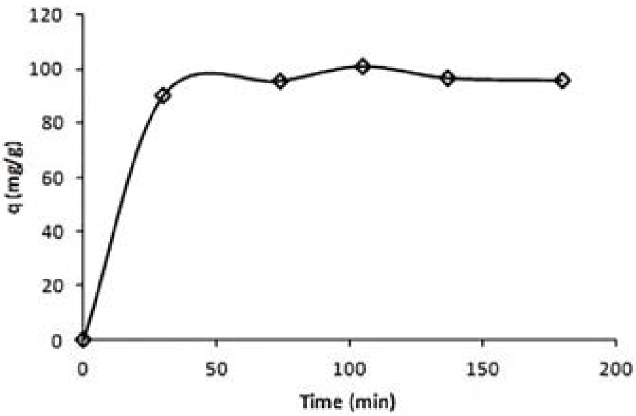

Fig. 4. Effect of contact time on the biosorption of lead metal by the fungus *Penicillium notatum*.

absorption was 33°C. Temperature in a certain range affects the absorption of metal ions. The reason for this may be the result of an increase in kinetic energy and contact surface of the adsorbent and lead [28,29]. However, given that the adsorption reactions are naturally thermosensitive, therefore, with increasing temperature, the ability of bio-absorption is reduced [8]. On the other hand, reducing the ability to absorb at higher temperatures suggests that the absorption of metal at very high temperatures is reduced due to changes in some of the metal binding sites at the cell surface [28,30]. Also, the active binding sites at the biomass level changes with increasing temperature. This phenomenon reduces the absorption at high temperatures [1,9,31]. Wang [28] stated that due to the thermal nature of the absorption, the increase in temperature would reduce the biomass absorption capacity. Fan et al. [15] reported the increase in the biological absorption of lead by *Penicillium simplicissimum* with increasing temperature from 20°C to 40°C and Baysal et al. [9] reported an increase in lead absorption by abiotic *Candida albicans* with an increase in temperature from 20°C to 45°C. Also, Marandy et al. [27] studied the biosorption of lead on *Phanerochaete chrysosporium* and concluded that increasing the temperature from 20°C to 45°C increased lead absorption, but this increase was negligible. The desirability of ambient temperature for the fungal activity makes it possible to implement the biological absorption process at ambient temperatures and shows the proper function of the fungus in the treatment of industrial wastewater.

3.5. Effect of contact time on the metal biosorption capacity

In this study, lead absorption capacity was investigated in the range of 30–180 min. it was found that with increasing contact time the absorption capability increased, but this increase in absorption was not statistically significant (p-value = 0.1458). So that the average absorption at 30, 74, 105, 137 and 180 min was 90.15, 95.46, 100.90, 96.55 and 95.73, respectively (Fig. 4). The findings of this study showed that the optimal contact time was 105 min, but the highest rate of metal adsorption has been observed in the first 30 min (90.15 mg g^{-1} biomass dry weight) and the absorption rate has been significant at the first 30 min (p-value ≤ 0.05). After that, the absorption rate was almost constant. This suggests that adsorption can be of a superficial type due to the availability of active adsorbent sites that reduced over time [1]. The short equilibrium time of about 30 min yields suitable fungal performance in industrial wastewater treatment, and this can indicate biological methods for the removal of heavy metals from industrial wastewater in the short term [32]. Similar to the obtained results, Baysal et al. [9] reported that the optimal time for maximum lead absorption by abiotic *Candida albicans* was 10 min and finally 20 min. Also, Marandy et al. [27] stated that the right time for maximum absorption of lead by abiotic biomass of *Phanerochaete chrysosporium* was 1 h. Contrary to the present study, Fan et al. [15] concluded that increased time resulted in increased absorption and optimal contact time for biological removal of lead by *P. simplicissimum* was 4 h.

3.6. Study absorption isotherms

Absorption isotherm is one of the important factors in the design of absorption systems. This parameter is a fundamental factor in determining the absorbent capacity and optimizing absorbent consumption [33]. In this study, two Langmuir and Freundlich adsorption isotherms are used to investigate the absorption mechanism and see which of these isotherms is followed by the process [32]. The linear equation of Langmuir isotherm is given in the following equation:

$$\frac{1}{q_e} = \frac{1}{q_m k_L C_e} + \frac{1}{q_m} \quad (2)$$

In this equation, q_e is the amount of absorbing material per unit mass of the adsorbent substance in mg g^{-1}, C_e is the equilibrium concentration of the absorbing substance in the solution after surface adsorption in mg L^{-1} and q_m and K_L are Langmuir constants obtained from plotting $\frac{C_e}{q_e}$ for C_e.

The linear equation for Freundlich isotherm is as follows:

$$\log q_e - \log K = \frac{1}{n}\log C_e \quad (3)$$

In this equation, q_e is the absorption capacity at the time of equilibrium in mg g^{-1}, C_e is the concentration of the absorbing substance in mg L^{-1}, and K and n are Freundlich constants, which are obtained from plotting log q_e diagram vs. log C_e [34].

Absorption isotherm experiments were performed on the abiotic fungus *Penicillium notatum* at pH 5, contact time 131 min, adsorbent values of 0.03–0.35 g/100 mL, initial concentration of lead 228 mg L^{-1}, ion concentration of 43.2 mg L^{-1} and temperatures of 23°C.

The results showed that absorption in abiotic biomass follows Langmuir's model (R^2 = 0.9820) and the maximum absorption is about 178.6 mg g^{-1} dry weight of the fungus (Table 1; Fig. 5).

This means that lead ion absorption occurs in certain homogeneous sites, and single-layer surface adsorption takes place on the surface of the synthesized absorbent. The results of this study are consistent with the study results of Ahmad et al. [2] and Iram et al. [16], but inconsistent with Marandy et al. [27] results, so that in Marandy et al.'s study, the process of absorbing lead and zinc by abiotic biomass of *Phanerochaete chrysosporium* followed two models namely Langmuir and Freundlich isotherms.

3.7. Thermodynamic parameters of lead absorption by abiotic biomass

Thermodynamic studies help understand the process of absorption and application of measures to increase the absorption efficiency. The thermodynamic parameters include Gibbs free energy variations $\Delta G°$, enthalpy $\Delta H°$ and entropy $\Delta S°$ which, respectively, indicate the feasibility and spontaneity of processes, thermal reactions and changes in entropy and irregularity during absorption action. For the determination of $\Delta G°$, we use Eq. (4):

$$\Delta G^\circ = -RT\ln b \tag{4}$$

where R is the global constant of the gases (J mol^{-1} K^{-1}), T is the temperature in K, and b is the process equilibrium constant. The values of $\Delta H°$ and $\Delta S°$ can be determined according to Van't Hoff equation with plotting ln (b) diagram in 1/T (Fig. 6) [4,9,15,35–37].

$$\ln(b) = -\frac{\Delta G^\circ}{RT} = \frac{\Delta H^\circ}{RT} + \frac{\Delta S^\circ}{R} \tag{5}$$

In this study, according to the obtained thermodynamic constants, it was found that the amount of free energy changes $\Delta G°$ of absorption of lead by the abiotic biomass of *Penicillium notatum* is negative (Table 2). The negative values of Gibbs free energy changes in each reaction indicate that the reaction is rapid, spontaneous and desirable. In addition, an increase in the values of $\Delta G°$ with increasing temperature in the abiotic biomass indicates a reduction in the rate of spontaneity of the adsorption process with increasing temperature. Gibbs free energy values in this study are greater than –20 kJ mol^{-1} and represent the physical processes of absorption [35]. The negative enthalpy of adsorption reactions in the abiotic biomass indicates that these processes are thermosensitive. And, according to Le Chatelier's principle, we have a reduction in the reaction progress with increasing temperature. Entropy changes in absorption are negative by the abiotic adsorbent and this indicates that the degree of freedom at solid-solution level is reduced during absorption [35]. Baysal et al. [9] and Fan et al. [15] thermodynamics studies showed that lead absorption on *Candidate albicans* and *P. simplicissimum, Penicillium* has been spontaneous and

Table 1
Constant and correlation coefficients of Langmuir and Freundlich isotherms

Adsorption isotherm	Adsorption equations	Isothermal constant and correlation coefficients		
Langmuir	$\frac{1}{q_e} = \frac{1}{q_m k_L C_e} + \frac{1}{q_m}$	q_m (mg g)	K_L	R^2
		178.6	0.011	0.982
Freundlich	$\log q_m = \log K + \frac{1}{n}\log C_e$	K	$\frac{1}{n}$	R^2
		6.7	0.6	0.8653

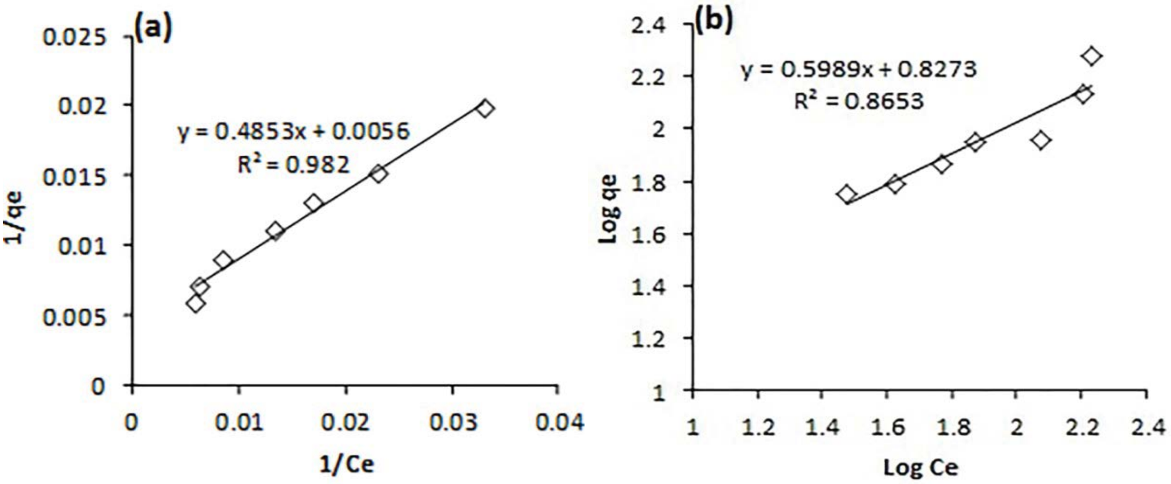

Fig. 5. Langmuir (a) and Freundlich (b) isotherm models biosorption of lead.

thermosensitive. However, Asadsangabi et al. [35] study on the thermodynamic parameters of adsorption of lead, copper and cadmium ions by plant adsorbents showed that the process of adsorption of metals by poplar is thermal. Also, Gibbs free energy values showed that all processes of absorption are spontaneous and of a physical type.

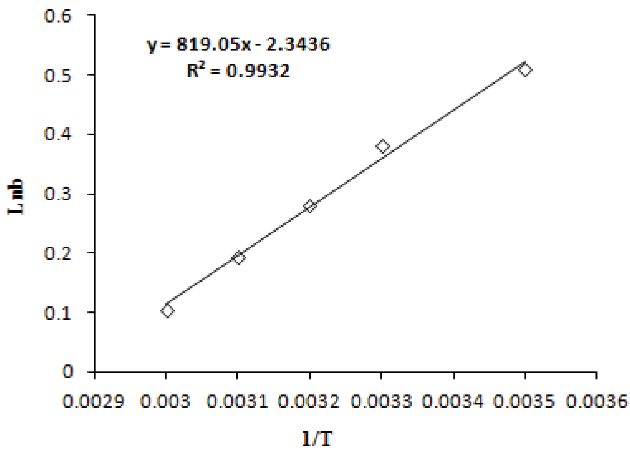

Fig. 6. Thermodynamic index biosorption of lead by *Penicillium notatum*.

Table 2
Thermodynamic parameters biosorption of lead by *Penicillium notatum*

ΔS° (J K⁻¹ mol⁻¹)	ΔH° (J mol⁻¹)	ΔG° (J mol⁻¹)	Temperature (K)
		−1,215.4	283
		−900.8	296
−19.48	−6,809	−658.8	306
		−441	315
		−247.4	323

3.8. Adsorption kinetics

The experimental data biosorption of lead using *Penicillium notatum* dead biomass can be described via two common kinetic models including pseudo-first-order and pseudo-second-order models. Pseudo-first-order kinetic model is shown by Eq. (6).

$$\ln\left(q_e - q_t\right) = \ln q_e - K_1 t \tag{6}$$

where q_t and q_e are the amount of lead adsorbed per mass of sorbent (mg g^{-1}) at any time and equilibrium, respectively, and K_1 is the rate constant of first-order sorption (min^{-1}). K_1 and q_e were calculated from the slope and intercept of the straight plotting ln $(q_e - q_t)$ vs. t, respectively. The pseudo-second-order model is expressed as Eq. (7).

$$\frac{t}{q_t} = \frac{1}{K_2 q_e^2} + \frac{t}{q_e} \tag{7}$$

where K_2 (the pseudo-second-order rate constant, g mg^{-1} min^{-1}) and q_e (sorption capacity at equilibrium, mg g^{-1}) can be obtained result from the intercept and slope of linear plotting t/q_t vs. t, respectively. The initial sorption rate is defined by Eq. (8) as follows:

$$h = K_2 q_e \tag{8}$$

where K_2 is the rate constant, q_e is the metal uptake capacity at equilibrium, mg g^{-1} [3,34,38,39].

Fig. 7 shows the linear plot of ln $(q_e - q_t)$ vs. t for the Lagergren pseudo-first-order model and t/q_t vs. t for the Lagergren pseudo-second-order model for the biosorption of Pb(II) for *Penicillium notatum* dead biomass.

According to the results of Table 3, adsorption kinetic studies showed that absorption kinetics followed the pseudo-second-order reaction ($R^2 = 1$). Similar to the obtained results, Ahmed et al. [2], Baysal [9] and Fan et al. [15] showed

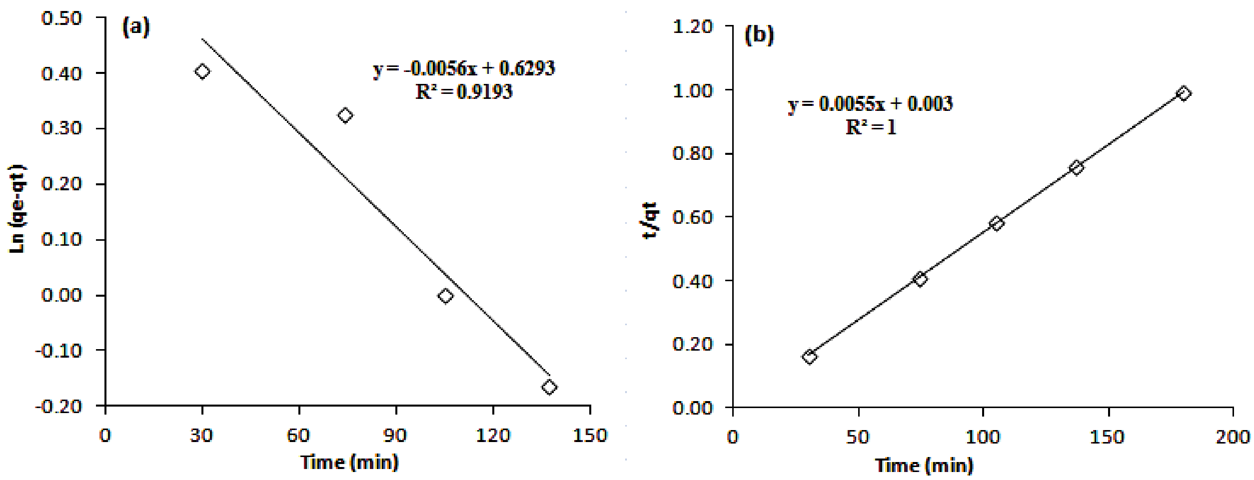

Fig. 7. Lagergren pseudo-first-order (a) and pseudo-second-order (b) kinetic biosorption for Pb(II) onto *Penicillium notatum* dead biomass.

Table 3
Kinetic parameters for the sorption of lead onto the adsorbents

Kinetic type	Adsorbent
Pseudo-first-order	
q_e (mg g^{-1})	1.87
K (min^{-1})	0.005
R^2	0.919
Pseudo-second-order	
q_e (mg g^{-1})	181.82
K (g mg^{-1} min^{-1})	0.01
R^2	1

that, the adsorption kinetics of heavy metal by *Candida utilis*, *Candida tropicalis* and *P. simplicissimum* followed the false-second-order equation.

3.9. Absorbent characteristics

The results of Brunauer–Emmett–Teller (BET), scanning electron microscopy (SEM), and energy dispersive X-ray microanalysis (EDX) tests showed that the specific surface of the abiotic fungus *Penicillium* was 0.739 g m^{-2} (Table 4). SEM images also showed that the porosity in the adsorbent has been completely covered by lead after the adsorption process (Fig. 8). The results of EDX analysis showed that, after absorption, the main elements were oxygen, phosphorus, potassium and lead adsorbents, and the weight percentage of lead absorbed on abiotic biomass was 68% and absorption was well done (Fig. 9; Table 5).

3.10. Determination of the absorbent surface charge

In order to determine the charge of the adsorbent surface, zero point charge (pH$_{pzc}$) test was performed under optimal

Table 4
BET test results

Absorbent type	Special surface area (g m^{-2})
Penicillium notatum	0.739

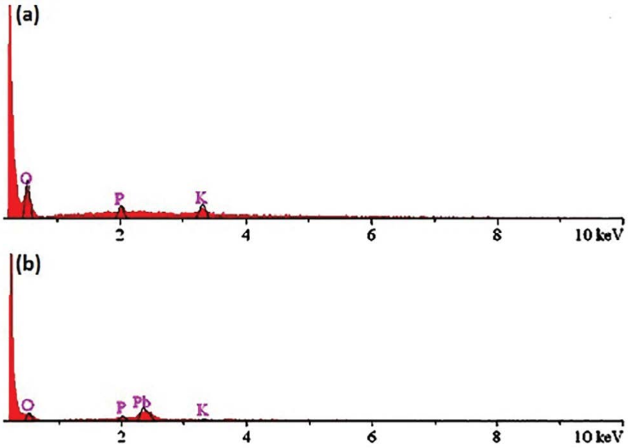

Fig. 9. EDX analysis of the abiotic fungus *Penicillium notatum* (a) before absorption and (b) after absorption.

Table 5
Percentage of weighted elements in abiotic absorbent structure of the fungus *Penicillium notatum*

After absorption (W%)	Before absorption (W%)	Elements
24.34	76.76	O
4.38	10.07	P
2.81	13.17	K
68.47	–	Pb

adsorption conditions (lead concentration of 228 mg L^{-1}, ion intensity of 43.2 mg L^{-1}, biomass concentration of 1.2 g L^{-1} and temperature 33°C) with initial pH 1, 3.5, 7 and 9. After pH adjustment with 1 molar nitric acid and soda, the samples were placed on a shaker for 48 h. Then, the secondary pH of the samples was measured and the absorbent surface charge was obtained to be 5.2 by plotting the initial pH diagram vs. the secondary pH (Fig. 10). At pH below pH$_{pzc}$, the adsorbent surface has a positive charge and is inappropriate for adsorption of lead cation. At pH higher than pH$_{pzc}$, the adsorbent surface has a negative charge, due to the increase in OH^- ions, sedimentation of lead hydroxide is formed and lead ion adsorption reduced by biomass [6,38].

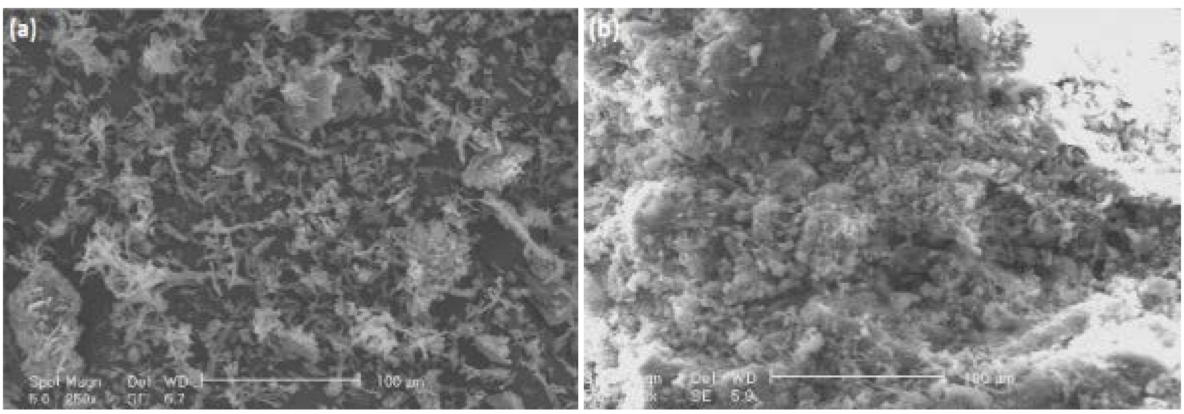

Fig. 8. SEM images of the abiotic fungus *Penicillium notatum* (a) before absorption and (b) after absorption.

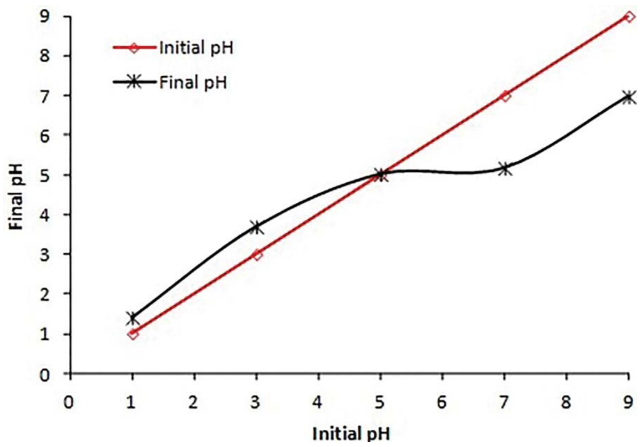

Fig. 10. Determination of abiotic absorbent surface charge.

4. Conclusion

In this study, the efficacy of abiotic biomass of the fungus *Penicillium notatum* was investigated as an absorbent for removal of lead from aqueous solutions. The results of this study showed that maximum absorption efficiency under optimal conditions was obtained for abiotic biomass equal to 180.75 mg g^{-1} dry weight of biomass. The mechanism of absorption process was more consistent with Langmuir adsorption isotherm. Regarding the obtained thermodynamic constants, it was found that lead absorption process is thermoplastic by abiotic biomass. The specific surface of the fungus *Penicillium notatum* was found to be 0.739 g m^{-2} as abiotic. Also, SEM images showed that the porosity in the adsorbent has been completely covered by lead after the adsorption process. The results of EDX analysis showed that, after absorption, the main elements were oxygen, phosphorus, potassium and lead, and the weight percentage of lead absorbed on abiotic biomass was 68% and absorption was well done. According to the results of this study, it can be said that the removal of lead using bio-absorption method by the abiotic fungus *Penicillium notatum* is very important due to low cost, high absorption capacity, simple implementation and environmental compatibility, ability to run under environmental conditions and the relatively desirable removal efficiency.

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