Bio-adsorption characteristics of *Pseudomonas aeruginosa* PAO1

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Abstract: Biosorption of Cd(II) and Pb(II) ions from aqueous solution using
lyophilized *Pseudomonas aeruginosa* PAO1 cells were observed under various
experimental conditions. The effect of pH, initial metal concentration, equilib-
ration time and temperature on bio-adsorption was investigated. The optimum
pH value for Pb(II) adsorption was found to be 5.0, and for Cd(II) 5.0–6.0. The
Pb(II) and Cd(II) bio-adsorption equilibrium were analyzed employing the
Freundlich and Langmuir Models using nonlinear least-squares estimations.
The experimental maximum uptake capacity of Pb(II) and Cd(II) was estimated
to be 164 and 113 mg g^{-1}, respectively. For a kinetic study of the biosorptions,
the pseudo second-order kinetic model was applied at various temperatures.
The temperature had no significant effect on Pb(II) bio-adsorption. In case of
Cd(II) bio-adsorption, the adsorbed amount decreased with increasing tem-
perature.

Keywords: heavy metals, kinetics, isotherm, temperature, atomic absorption
spectrometer.

INTRODUCTION

Heavy metal pollution is one of the most important environmental problems
today. In recent years, the biotechnology applied to control and remove metal
pollution has received much attention, and gradually, becomes a hot topic in the
field of metal pollution control because of its potential application. For heavy
metal removal, an alternative process is biosorption, which utilizes various cer-
tain natural materials of biological origin, including bacteria, fungi, yeast and
algae. These biosorbents possess metal-sequestering properties and can be used

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to remove rapidly heavy metal ions from dilute complex solutions with high efficiency; therefore, they are ideal candidates for the treatment of high volume and low concentration of complex wastewaters. In general, removal of chemical pollutants from aqueous solution is difficult at low pollutant concentrations. Most of the industrial techniques are ineffective and excessively expensive at the metal concentration less than 100 mg mL^{-1}.[1] Therefore, studies on biosorption have become an active field for the removal of metal ions or organic compounds.[2,3]

The capability of some living microorganisms to accumulate metallic elements was observed at first from a toxicological point of view. However, inactive/dead microbial biomass can also passively bind metal ions *via* various physicochemical mechanisms. The mechanisms responsible for biosorption may be one or combination of ion exchange, complexation, coordination, adsorption, electrostatic interaction, chelation and microprecipitation.[2,4] The uptake of heavy metals by biomass is usually classified into three categories: 1) cell surface binding, 2) intracellular accumulation and 3) extra-cellular accumulation.[2,5,6] Being metabolism-independent, the cell surface binding can occur in either living or in inactivated microorganisms, whereas the intracellular and extra-cellular accumulation of metals are usually energy-driven processes, and thus can occur in living cells. [7]

Several investigations have reported that *Pseudomonas aeruginosa* displays efficiency for metal uptake.[8–10] Chang and Chen studied the biosorption of copper(II), lead(II) and cadmium(II) ions on *P. aeruginosa* and the multi-metal adsorption results showed that lead(II) and copper(II) significantly inhibited the adsorption of cadmium(II), while the effects of cadmium(II) on the adsorption of copper(II) and lead(II) was limited.[11] They also reported the combined effects of two or more metal ions on inactivated *P. aeruginosa*, which depended on the number of the metals competing for binding sites, metal combination, levels of metal ion concentration, order of metal addition, and residence time.[11,12] Leung *et al.* selected *Pseudomonas* as a biosorbent for lead(II), copper(II) and nickel(II), among 12 bacteria isolated from activated sludge. They reported the maximum sorption capacities of 271.7 and 46.8 mg g^{-1} for lead(II) and copper(II) ions, respectively.[13] The order of affinity of the three metals toward *P. pseudoalcaligenes* was Ni < Cu < Pb. Gialamouidis *et al.* compared *Pseudomonas* sp. (Gram--negative) and *Staphylococcus xylosus* (Gram-positive) isolated from contaminated soil for the removal of Ni(II) in aqueous solution. Desorption experiments by treating biomass with 0.1 M HNO$_3$ solution resulted in more than 87 % recovery of the adsorbed Ni(II) ions from *Pseudomonas* sp. and almost 98 % from *S. xylosus*, indicating that Ni(II) could be easily and quantitatively recovered from biomass, as well.[14] Kang *et al.* studied Cr(III) and Cr(VI) biosorption onto the cell surface of *P. aeruginosa.* Batch experiments were conducted with various initial concentrations of chromium ions to obtain the sorption capacity and iso-

therm. It was found that the sorption isotherms of Cr(III) were described well by the Langmuir isotherm model, while Cr(VI) appeared to fit the Freundlich model. The results of FT-IR analysis suggested that the chromium binding sites on the bacterial cell surface were most likely carboxyl and amino groups. The bacterial surface of *P. aeruginosa* seemed to engage in reductive and adsorptive reactions with respect to Cr(VI) biosorption.[15] *Pseudomonas* genus plays an important role in bio-adsorption studies, a genus including members with well-characterized biochemical and genetic characteristics, and for which a considerable range of genetic tools are available. In addition, the resistance against antibiotics by many strains was well described.[16] *Pseudomonas* strains can protect plant roots from an excess of heavy metal ions in the soil.[17] However, many studies use *Pseudomonas* strains isolated from contaminated soil and water,[18–21] and in the case of living cells, the risk of multiplication of multi-resistant cultures is high.[22,23]

In this study, the biosorption characteristics of lyophilized *P. aeruginosa* PAO1 laboratorial bacterial strain for cadmium(II) and lead(II) ions in aqueous suspension is presented. The effect of pH, contact time and initial heavy metal concentrations on the biosorption were investigated for both cations. This micro-biologically well-characterized *P. aeruginosa* PAO1 laboratorial bacterial strain as biosorbent has not hitherto been studied for the sorption of lead(II) and cadmium(II). The effect of temperature is less studied field in the field of biosorption of metal cations.

EXPERIMENTAL

Bacterial strain and cultivation

The microorganism used in this study was *P. aeruginosa* PAO1. The strain was cultivated in Mueller–Hinton broth (Difco, Germany) using shaken flasks. They were incubated at 37 °C and the liquid cultures were agitated at 220 rpm. The reproduction curve was determined by spectrophotometry (Spectronic, Genesys 5, Milton Roy Company, USA) using the OD_{600} value (optical density at $\lambda = 600$ nm). The optical density of the bacterial cell suspension is presented against the incubation time in Fig. 1. The aim of broth dilution methods is to determine the lowest concentration of the assayed metal cations (minimal inhibitory concentration, *MIC*) that, under defined test conditions, inhibits the visible growth after overnight incubation of the bacterium under investigation. MIC values are used to determine the susceptibilities of bacteria to metal cations. For broth dilution, bacteria are inoculated into a liquid growth medium in the presence of different concentrations of metal cations.[24] The *MIC* values were determined by the broth dilution method using 96 mmol L^{-1} initial heavy metal concentrations. The concentrations were 96, 48, 24, 12, 6, 3 and 1.5 mmol L^{-1}. The *MIC* values were determined after solid plate cultivation and the colony formation was compared with that of a control culture.

Preparation of biosorbents

The cells were harvested by centrifugation (10000 rpm, 30 min) at the early-stationary phase of growth, after 38 h incubation. The cells were rinsed twice with physiological saline solution, centrifuged and then lyophilized at –40°C in a freeze drier (HETO, Dry Winner, Denmark).
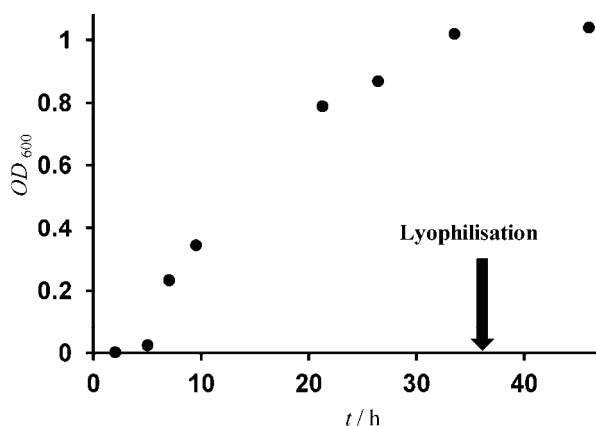
Fig. 1. Time-course profiles of the growth of *P. aeruginosa* PAO1 cells.

Preparation of heavy metal solutions

The heavy metal test solutions containing Pb(II) and Cd(II) ions were prepared from $Pb(NO_3)_2$ (Fluka, Germany) and $Cd(NO_3)_2 \cdot H_2O$ (Fluka, Germany) in the concentration range 5–250 mg L^{-1}. All employed chemicals were of analytical grade. The pH values of the adsorption systems were adjusted using 0.1 M NaOH and 0.1 M HCl solutions.

Analysis of heavy metals

The concentration of heavy metals in the solutions was measured by atomic absorption spectrometry (AAS, Perkin-Elmer 2380) at 217 nm for Pb(II) and 228 nm for Cd(II). Before measurement, the heavy metal solutions were diluted with deionized water to ensure that the heavy metal concentration in the sample was linearly dependent on the absorbance detected. The calibration of Cd(II) and Pb(II) was made with standard cadmium(II) and lead(II) solution (Scharlau, Germany) in the concentration range of 0–2.5 mg L^{-1} for Cd(II) and for Pb(II) 0–20 mg L^{-1}.

Effect of pH on biosorption

The effect of pH on the adsorption Cd(II) and Pb(II) by *P. aeruginosa* PAO1 biomass in aqueous suspension was investigated. To determine the optimum pH range of bio-adsorption, adsorption measurements with 25 and 50 mg L^{-1} solutions were performed for both Cd(II) and Pb(II) ions in the pH range of 3.0–8.0. The suspension concentration was 1 g L^{-1}. The expected pH was regulated with 0.1 M NaOH and 0.1 M HCl solutions, then the adsorption systems were agitated at 250 rpm. After 24 h, samples were taken from the adsorption systems and were spin-dried at 10,000 rpm for 10 min and diluted for analysis by atomic absorption spectrometry.

Kinetics study of biosorption

In the kinetics study of Cd(II) and Pb(II) biosorption by *P. aeruginosa*, the concentration of Cd(II) and Pb(II) ions were 50 mg L^{-1} at a suspension concentration of 1 g L^{-1}. Samples were taken from the solutions at desired time intervals and the metal concentrations of the supernatants were measured after centrifugation. The supernatants were spin-dried at 10,000 rpm for 10 min and diluted for analysis by flame atomic absorption spectrometry.

Determination of bio-adsorption isotherms

The biomasses (1 g L^{-1}) were suspended in heavy metal solutions in glass containers that were gently agitated at room temperature. Solutions in the concentration range 5–250 mg L^{-1} were used for the determination of adsorption isotherms for Pb(II) and Cd(II). After 24 h incubation, samples were taken from the suspensions, the biomass was separated from the heavy metal solution at 10,000 rpm for 5 min, and then the heavy metal content of the supernatant was measured by AAS. The metal uptake was calculated using the following equation:

$$q = \frac{(c_0 - c_e)V}{m} \tag{1}$$

where q is the adsorbed amount of heavy metals (mg g^{-1}), c_0 is the initial heavy metal concentration (mg L^{-1}), c_e is the heavy metal concentration at adsorption equilibrium (mg L^{-1}), V is the volume of the solution (L) and m is the mass of biosorbent (g).

All experiments were performed in triplicate.

For equilibrium modeling, the following isotherm equations were used:

Langmuir isotherm. The Langmuir isotherm is valid for monolayer adsorption onto a surface with a finite number of identical sites. It is given as Eq. (2):

$$q_e = \frac{q_{max}bc_e}{1+bc_e} \tag{2}$$

where b is the adsorption equilibrium constant including the affinity of the binding sites (L mg^{-1}), c_e and q_e are the non-adsorbed metal ions in solution and adsorbed metal ions on the biosorbent at equilibrium, respectively, q_{max} is the maximum amount of metal ion per unit weight of adsorbent required to form a complex monolayer on the surface (mg g^{-1}).[2,3,7,12,25]

Freundlich isotherm. The Freundlich Equation, based on sorption on a heterogeneous surface, is given as Eq. (3):

$$q_e = k_F c_e^{1/n} \tag{3}$$

where k_F and n are the Freundlich constants, which are indicators of the adsorption capacity and adsorption intensity of the sorbents, respectively. The Freundlich isotherm provides no information on the monolayer adsorption capacity, whereas the Langmuir model does.[26,27]

RESULTS AND DISCUSSION

Determination of the lowest inhibitory concentration for cadmium(II) and lead(II) ions

Free cells of *Pseudomonas aeruginosa* were cultivated in aqueous solutions containing heavy metals at various concentrations. The determined *MIC* values for cadmium(II) and Pb(II) were 20 and 12 mmol L^{-1}, respectively. These values are similar to that previously reported for *P. aeruginosa* (15 mmol L^{-1}) for Pb(II).[28] A growth medium having a complex rich composition (Mueller–Hinton broth) was used, which resulted in a high level of complexation between the metal cations and components of the growth medium. The residual concentrations of supernatant in the heavy metal stock solutions were determined after centrifugation. Due to precipitation, the *MIC* value was found to be 6 mmol L^{-1} for

cadmium(II) and 1.8 mmol L^{-1} for lead(II). The concentrations of metal cations employed in this study do not inhibit bacterial proliferation.

The effect of pH on cadmium(II) and lead(II) bio-adsorption

It has been shown that the affinity of cationic species towards functional groups present in the cellular surface is strongly dependent on the pH.[29] The results of Cd(II) and Pb(II) adsorption by *P. aeruginosa* bacterial cells as a function of pH at initial concentrations of 25 and 50 mg L^{-1} are summarized in Fig. 2a and b. In all cases, metal uptake by the biomass increased with increasing pH until a maximum was reached, after which the metal uptake decreased for Pb(II). For Pb(II), the results could be influenced by precipitation above pH 7. For Cd(II), the adsorbed amount did not decrease in the pH range 6−8. The bacterial cell wall contains negatively charged functional groups, such as carboxyl, phosphate, imidazole and amino groups. They are primarily responsible for the
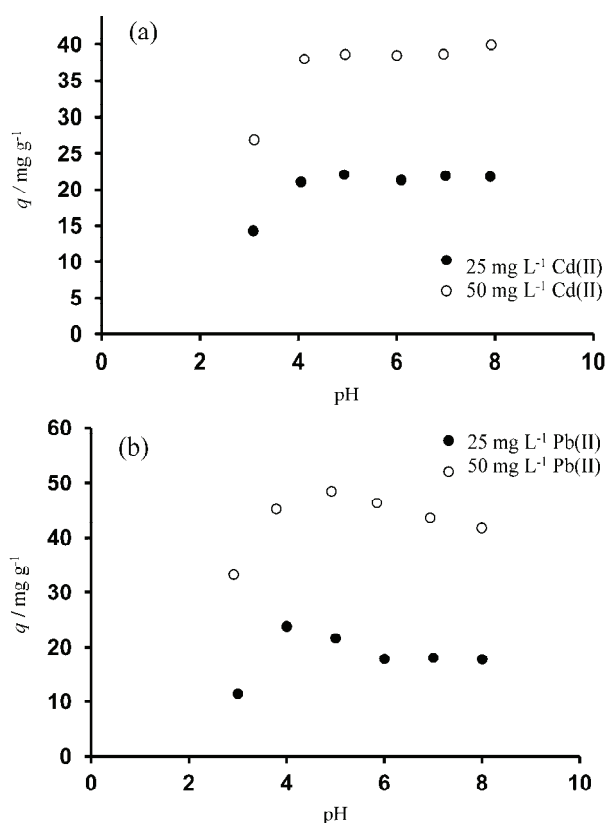

Fig. 2. Effect of pH on (a) Cd(II) and (b) Pb(II) biosorption by *P. aeruginosa* PAO1 bacterial biomass. Initial metal ion concentrations, 25 and 50 mg L^{-1}; contact time, 24 h; biomass concentration, 1 g L^{-1}; temperature, 285 K.

anionic character and metal binding capacity of the cell wall by Gram-negative bacteria.[30] With increasing pH, the negative charge on the cell surface increases, which favors the adsorption of the heavy metal cations. Strong acidic pH range (pH < 3) is not appropriate for adsorption due to protonation. In addition, metal ions undergo hydrolysis as the pH increases and highly alkaline pH values (pH > > 8) results in metal precipitation. Hence, the effect of pH was determined in the pH range 3.0–8.0. Optimum pH values were found to be 5.0–6.0 for cadmium(II) and about 5.0 for lead(II) biosorption. Other researchers, such as Chang *et al*. reported that the optimal pH values for inactivated and resting cells of *P. aeruginosa* PU21 were 5.5 for lead(II) and 6.0 for cadmium(II).[7,25] For *P. pudita*, the value was pH 6.0.[31] Gabr *et al*. found that the optimal pH value for Pb(II) bio-adsorption was 6 using *P. aeruginosa* ASU 6a.[25] There is no available information in the literature on the effect of pH in case of *P. aeruginosa* PAO1.

Effect of time on the bio-adsorption

The time-course profiles for the adsorption of Pb(II) and Cd(II) by lyophilized bacterial cells are shown in Figs. 3 and 4 at 285, 290 and 295 K. Figures 3 and 4 represent the adsorbed amounts of Cd(II) and Pb(II) by the biomass, res-
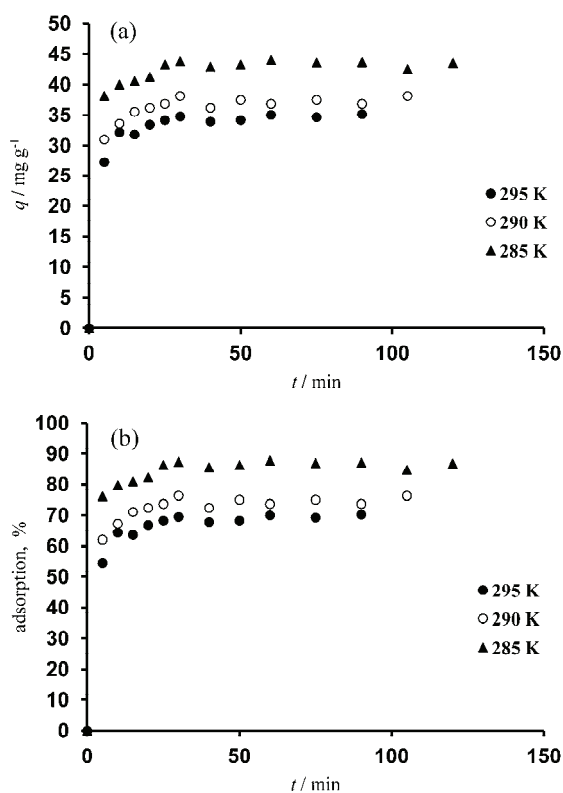

Fig. 3. Biosorption of Cd(II) by lyophilized cells of *P. aeruginosa* PAO1 (pH 6) as a function of time. Initial Cd(II) concentration, 50 mg L^{-1}; biomass concentration, 1 g L^{-1}; *T* = 285, 290 or 295 K.

pectively, a function of contact time. It was observed from figures that the uptake of heavy metals by biomass increased with increasing contact time. No significant increase in the sorption was found after 20 min, and the adsorption was rapid. The rapid adsorption was in agreement with the results of Gabr *et al.*, in which the time required for equilibrium was 30 min.[25] According to Chang *et al.*, metal concentration decreased rapidly during the first 30 min and remained nearly constant after 2 h of adsorption, suggesting that the bio-adsorption is fast and reaches saturation within 2 h.[7] The amount of bio-adsorbed Cd(II) decreased by increasing temperature and the adsorption efficiency decreased from 87 to 70 %. For Pb(II) bio-adsorption, the temperature had no significant effect; the adsorption efficiency decreased from 89 to 83 %.
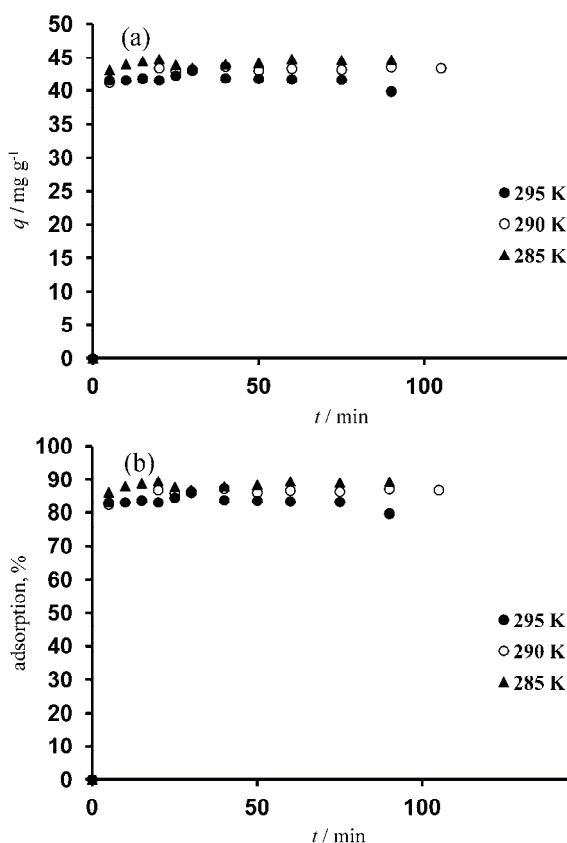

Fig. 4. Biosorption of Pb(II) by lyophilized cells of *P. aeruginosa* PAO1 (pH 5) as a function of time. Initial Pb(II) concentration, 50 mg L^{-1}, biomass concentration, 1 g L^{-1}; T = 285, 290 and 295 K.

This finding is in agreement with earlier studies.[7,25] The cells can accumulate metal ions on their surface and intracellular binding sites. The metal adsorption capacities of the lyophilized cells for Cd(II) and Pb(II) were 47.6 (95 %) and

46.6 mg g^{-1} (92 %), for an initial metal concentration of 50 mg L^{-1}, *i.e.*, the values for the two metal ions were not significantly different. There is no available information in the literature for the effect of temperature on the bio-adsorption of Cd(II) and Pb(II) by *P. aeruginosa* PAO1.

Modeling of the adsorption kinetics

Several kinetic models exist for the adsorption of heavy metals.[4] For the evaluation of the kinetics bio-adsorption of the heavy metals by lyophilized bacterial cells at 285, 290 and 295 K, the pseudo second-order model was used to fit the determined experimental data. The pseudo first-order model could not be used for modeling the biosorption kinetics.

The pseudo second-order kinetic rate equation can be written as follows:

$$\frac{\mathrm{d}q}{\mathrm{d}t} = k_{2,\mathrm{ad}} \left(q_{\mathrm{eq}} - q \right)^2 \tag{4}$$

where, $k_{2,\mathrm{ad}}$ is the rate constant of the second order bio-adsorption (g mg^{-1} min^{-1}), q is the adsorbed amount (mg g^{-1}) and q_{eq} is the adsorption capacity (mg g^{-1}) at equilibrium.

For the utilization of this model, it is not necessary pre-estimated the experimental value of q_{eq}. Straight lines were obtained by plotting t/q against t (Fig. 5a and b). The second-order rate constants $k_{2,\mathrm{ad}}$ and the theoretical adsorption capacities q_{eq} were calculated from the slope and intercept of the plots (Fig. 5a and b) and are summarized in Table I together with the corresponding correlation coefficients. The Cd(II) sorption rate constant $k_{2,\mathrm{ad}}$ varied in the range of 2.1×10^{-2}–2.4×10^{-2} g mg^{-1} min^{-1}, while the Pb(II) sorption rate constant $k_{2,\mathrm{ad}}$ varied in the range of 6.5×10^{-2}–7×10^{-2} g mg^{-1} min^{-1}. The temperature had no effect on the biosorption rate in the studied temperature range. The theoretical adsorption capacities $q_{\mathrm{eq,calcd.}}$ were 44.25 mg g^{-1} at 285 K, 37.45 mg g^{-1} at 290 K, and 35.46 mg g^{-1} at 295 K for Cd(II) and 44.84 mg g^{-1} at 285 K, 43.67 mg g^{-1} at 290 K and 40.48 mg g^{-1} at 295 K for Pb(II). The adsorbed amount of metal ions decreased with increasing temperature in the interval 285−295 K. The calculated adsorption capacities agreed well with the experimental data. The correlation coefficients for the second-order kinetic model were close to 1.0 in all cases. This suggests that the sorption of heavy metals by the bacterial biomass follow second-order kinetics.

Kong *et al.* performed kinetic and equilibrium studies for the adsorption process of Cd(II) and Cu(II) onto *P. aeruginosa* using the wave anodic stripping voltammetry method.[32] The kinetic characteristics of the adsorption process were studied and all the corresponding regression parameters were obtained by fitting the electrochemical experimental data to the pseudo second-order kinetic model. Lin *et al.* immobilized *P. aeruginosa* PU21 in chitosan and alginate. The Pb(II) bio-adsorption was studied by immobilized bacterial biomass in the temperature
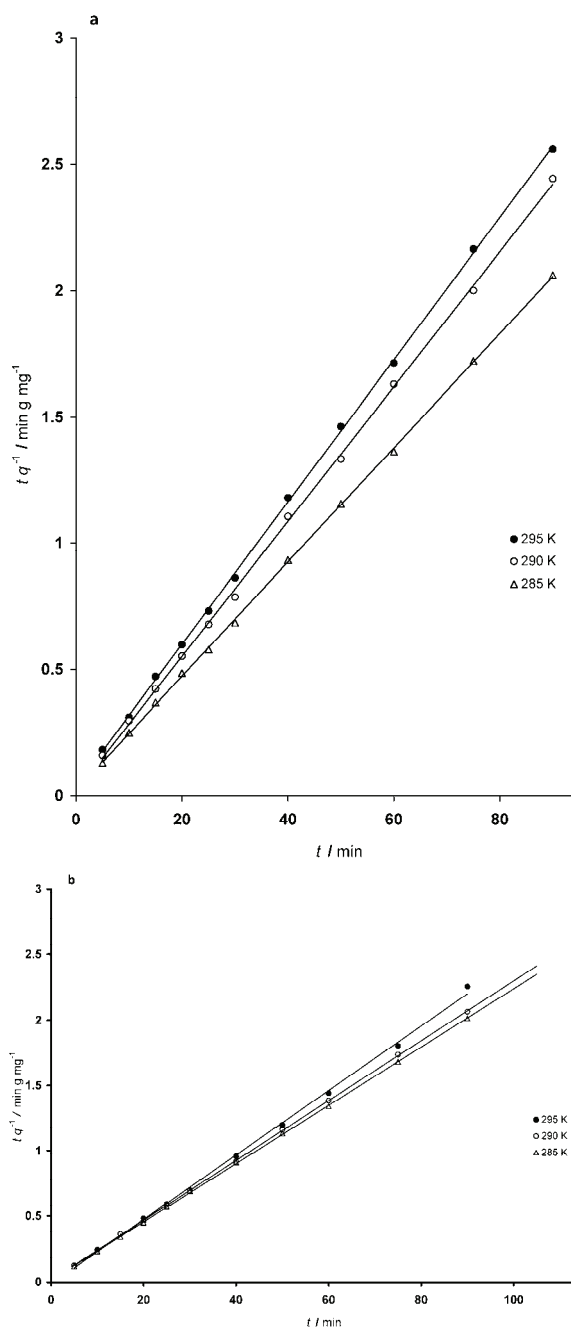
a

b

Fig. 5. Linearized pseudo second-order kinetic model for a) Cd(II) and b) Pb(II) adsorption by lyophilized cells of *P. aeruginosa* PAO1. Initial metal ion concentration, 50 mg L^{-1}; biomass concentration, 1 g L^{-1}; $T = 285$, 290 and 295 K.

range of 293–323 K. They found that the adsorption of Pb(II) onto optimized beads was consistent with a first-order/spontaneous reaction.[33] It is difficult to model

the kinetic experimental data in the studied temperature range, because the adsorption process is very fast. On the other hand, the pseudo second-order kinetic model using linearized presentation fitted the experimental data determined under these environmental conditions.

TABLE I. The pseudo second-order rate constants and the calculated equilibrium adsorption capacities for *P. aeruginosa* PAO1. Biomass concentration, 1 g L^{-1}; initial metal ion concentration, 50 mg L^{-1}; $T = 285$, 290 and 295 K

T / K	$k_{2,ad}$ / 10^{-2} g mg^{-1} min^{-1}	$q_{eq,cal}$ / mg g^{-1}	R^2	$q_{eq,exp}$ / mg g^{-1}
		Cd(II)		
285	2.4	44.25	0.999	43.90
290	4.0	37.45	0.999	38.13
295	2.1	35.46	0.999	35.16
		Pb(II)		
285	6.5	44.84	0.999	44.57
290	6.7	43.67	0.999	43.37
295	7.0	40.48	0.998	41.34

Bio-adsorption isotherms

Cadmium(II) and lead(II) sorption uptakes by the lyophilized bacterial cells of *P. aeruginosa* were determined by biosorption equilibrium measurements at initial concentrations of 5–250 mg L^{-1} for Cd(II) at pH 6.0 and for Pb(II) at pH 5.0. The biomass concentration was 1 g L^{-1}. The bio-adsorption isotherms determined for both heavy metals using batch technique showed the metal uptake by the bacterial biomass (Fig. 6). Thus, there was an increase in metal uptake as long as binding sites were free. A different adsorption mechanism could be observed for Pb(II) adsorption in comparison with the Cd(II) adsorption process. Experimental data were applied to adsorption models given by Langmuir and Freundlich and the adsorption constants were estimated using the nonlinear least-squares mathematical method.

Previous work[7] showed that resting cells of *P. aeruginosa* PU21 (harvested by centrifugation from early-stationary cultures and twice rinsed with deionized water) were able to adsorb 110 mg Pb(II) g^{-1} dry cell at pH 5.5 and 58 mg Cd(II) g^{-1} dry cell at pH 6.0. The Langmuir isotherm was used to describe the adsorption equilibrium of the heavy metals.[7] The results of Gabr *et al.*[27] demonstrated that for Ni(II) and Pb(II) biosorption by living and lyophilized *P. aeruginosa* ASU 6a cells, the adsorption equilibrium data fitted well the Langmuir and Freundlich models for metal ions in the 0−160 mg L^{-1} concentration range.

The nonlinearly fitted Langmuir and Freundlich adsorption isotherms of the heavy metals obtained using *P. aeruginosa* PAO1 biomass are shown in Fig. 6.

The estimated values of q_{max} and b are given in Table II. The maximum adsorption capacity q_{max} was 158.25 mg g^{-1} and Langmuir constant b was $2.7 \cdot 10^{-2}$ L mg^{-1} for Cd(II) biosorption, and q_{max} was 182.10 mg g^{-1} and b was $2.8 \cdot 10^{-1}$ L mg^{-1} for Pb(II) biosorption. The estimated q_{max} value obtained for Pb(II) was higher than that for Cd(II). The experimental q_{max} value for Pb(II) was 164 mg g^{-1}, while it was 113 mg g^{-1} for Cd(II). The values of the4 equilibrium constant b for Pb(II) and Cd(II) were calculated to be $2.8 \cdot 10^{-1}$ L mg^{-1} and $2.7 \cdot 10^{-2}$ L mg^{-1}, respectively, which indicates that the lyophilized cells of *P. aeruginosa* PAO1 possessed a higher adsorption affinity for Pb(II) ions than for Cd(II) ions. Such a fact led to the conclusion that the energy of adsorption was more favorable for Pb(II) than for Cd(II). The regression correlation coefficients of the Langmuir Model were 0.938 and 0.915 for Pb(II) and Cd(II) biosorption, respectively.
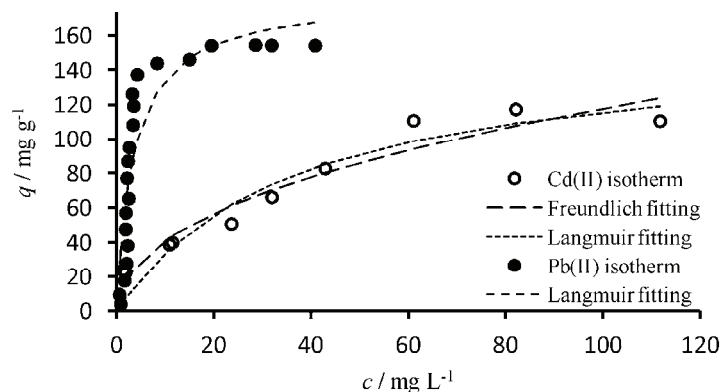

Fig. 6. Bio-adsorption isotherms of lyophilized *P. aeruginosa* PAO1 bacterial cells for Cd(II) and Pb(II) ions. The initial concentration of the metal ions varied between 5 and 250 mg L^{-1}. Biomass concentration, 1 g L^{-1}. pH$_{Cd(II)}$ 6; pH$_{Pb(II)}$ 5; T = 285 K.

TABLE II. The Langmuir and Freundlich isotherm constants for Cd(II) and Pb(II) adsorption by *P. aeruginosa* PAO1 lyophilized cells at 285 K

Metal	Freundlich isotherm model			Langmuir isotherm model		
	k_F / (mg g^{-1})(mg L^{-1})^n	n / L mg^{-1}	R^2	q_{max} / mg g^{-1}	b / L mg^{-1}	R^2
Cd(II)	14.60	2.20	0.936	158.25	0.027	0.915
Pb(II)	54.17	3.05	0.659	182.10	0.28	0.938

The estimated values of k_F and n are also given in Table II, together with the regression correlation coefficients. The parameter k_F related to the sorption capacity was 14.6 (mg g^{-1})(mg L^{-1})^n for Cd(II) biosorption. The exponent n of cadmium(II) biosorption was greater than unity, indicating that the heavy metal was favorably adsorbed by the bacterial cells. The regression correlation coefficient of Freundlich model was 0.936 for Cd(II) biosorption, suggesting that the Freundlich model was able to describe the adsorption equilibrium well. In the

case of Pb(II) biosorption, the Freundlich model could not be used to evaluate the adsorption equilibrium.

CONCLUSIONS

In this study, the high potential of lyophilized bacterial cells of *P. aeruginosa* PAO1 to adsorb Cd(II) and Pb(II) ions from aqueous solution was demonstrated. The optimum pH values were 5.0–6.0 for Cd(II) and about 5.0 for Pb(II) biosorption. A different adsorption mechanism could be observed for Pb(II) in comparison with that for Cd(II) adsorption. The Freundlich (Cd(II)) and Langmuir (Cd(II), Pb(II)) models exhibited good fits to the biosorption data. The heavy metal biosorption by bacterial biomass followed pseudo second-order adsorption kinetics. The second-order kinetic constants did not vary with increasing temperature, while the adsorbed amounts of heavy metals decreased in the case of Cd(II).

ИЗВОД

БИО-АДСОРПЦИОНЕ КАРАКТЕРИСТИКЕ *Pseudomonas aeruginosa* PAO1

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Биосорпција јона Cd(II) и Pb(II) из водених раствора коришћењем ћелија *Pseudomonas aeruginosa* (PAO1) посматрана је под различитим експерименталним условима. Испитани су утицај pH, почетне концентрације метала, времена уравнотежавања и температуре на биоадсорпцију. Нађено је да је оптимална pH вредност за адсорпцију Pb(II) једнака 5,0, а за Cd(II) износи 5 до 6. Равнотежне адсорпције Pb(II) и Cd(II) су анализиране Фројндлиховим и Лангмировим моделима, уз коришћење процене помоћу нелинеарне методе најмањих квадрата. Експериментално добијен максимум сорпционог капацитета за Pb(II) и Cd(II) је 164, односно 113 mg g^{-1}. За проучавање кинетике биосорпције примењен је модел псеудо-другог реда на више температура. Температура није показала значајан утицај на биоадсорпцију Pb(II). У случају биоадсорпције Cd(II), адсорбована количина се смањивала са растом температуре.

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