Desalination and Water Treatment
www.deswater.com

1944-3994/1944-3986 © 2011 Desalination Publications. All rights reserved
doi: 10/5004/dwt.2011.2235

28 (2011) 174–182
April

Evaluation of a deep-sea mesophilic bacteria exopolysaccharides in removal of low concentration Pb(II) from aqueous medium

Yan Qie[a], Jing Wang[a,b], Weizhi Zhou[a,c,*], Baoyu Gao[a], Yuzhong Zhang[c]

[a]*School of Environmental Science and Engineering, Shandong University, Jinan, China 250100*
[b]*Hebei Entry-exit Inspection and Quarantine Bureau Inspection and Quarantine Technical Center, Shijiazhuang, China 050051*
[c]*State Key Laboratory of Microbial Technology, Shandong University, Jinan, China 250100*
Email: wzzhou@sdu.edu.cn

Received 26 August 2010; Accepted 14 February 2011

ABSTRACT

Wangia profunda SM-A87, representative of a new genus of family *Flavobacteriaceae*, was isolated from deep-sea sediment samples near the southern Okinawa. The exopolysaccharides (EPS) produced by *W. profunda SM-A87* was used as an absorbent of Pb(II) from low concentration solution in this paper. The effect of various parameters such as EPS concentration, pH, temperature, contact time, ionic strength and the competitive adsorption of Pb(II), Cu(II), Cd(II) were evaluated in batch technique. The adsorption kinetic and isotherm were also calculated. The preferences biosorption conditions were, EPS dosage at 0.1~0.2 mg/l, pH value at 5.5, temperature at 20~30°C and contact time for 60 min, respectively. Coexistent cations decreased Pb(II) uptake in the order of $K^+<Na^+<Ca^{2+}<Mg^{2+}$. The maximum adsorption capacity of Pb(II) was 357 mg/g at 30°C which was much higher than those of other biosorbents. The adsorption data fitted better to the Langmuir equation than Freundlich equation. The pseudo second-order kinetic model provided the better correlation for the adsorption process, compared with the pseudo first-order kinetic model. The competitive biosorption results indicated that Cu(II) had a greater effect on Pb(II) biosorption compared with Cd(II). Functional groups (—OH, —COO and C—O—C) of SM-A87 EPS possibly involved in Pb(II) biosorption process signed by the FT-IR spectrum. This paper indicates that SM-A87 EPS could be applied in wastewater treatment as a promising Pb(II) absorbent.

Keywords: Wangia profunda SM-A87; Exopolysaccharides; Biosorption; Pb(II)

1. Introduction

With the rapid development of various industries, wastes containing heavy metals have brought serious environmental pollution and human health damage, mainly for their high toxicity even at low concentrations and bio-circle accumulation [1,2]. Lead (Pb) is considered one of the most toxic and prevalent heavy metals in aquatic environment as a result of major anthropogenic emission and improper waste disposal. It can be accumulated along the food chain and is not liable to biological degradation and even cause adverse health effects to human beings such as anemia, encephalopathy, hepatitis and nephritis syndrome [3,4].

In the past few years, biosorption method has attracted researchers' interests in heavy metal removal from aquatic environment, which utilized various natural materials of biological origin, including bacteria, fungi, yeast, algae, etc. These biosorbents have metal seizuring properties, and more attractively than chemi-physical methods, are able to decrease the concentrations of heavy metal ions in solution from ppt to ppb level [5,6,7]. Hence biosorbents, possessing both high sorption ability and high biomass yield, are ideal candidates for the treatment of

---

*Corresponding author.

high volume and low concentration complex heavy metal wastewaters. Many kinds of biosorbents have been used for removal and recovery of Pb(II) from aqueous solutions [8,9,10]. Biopolymers, which are biodegradable and the degradation intermediates, are used as biosorbents in wastewater treatment and showed good performance at most common conditions. Heavy metal cations are more liable to combine with the negative charged exopolysaccharides (EPS) produced by microorganisms originated from soil or wastewater sludge. And the adsorption process is considered non-metabolic, energy independent and can be caused by interaction between metal cations and negative charge of acidic functional groups of EPS [11,12]. The EPS is also convenient for industry producing, transportation and wide application compared to viable cells. However, the EPS yields of most microorganisms are very low, much less high negatively charged EPS.

Deep sea is a major component of the earth's biotopes. It has been reported that some deep-sea bacteria secrete a large amount of EPSs, which may help to concentrate proteinaceous particles and metal ions [13]. Due to their attractive chemical and rheological properties, the EPSs from deep-sea bacteria have been applied in biotechnology, pharmaceutical industry, food industry, and so on [14,15]. However, study on application of deep-sea bacterial EPSs in environmental protection has been rarely published. *W. profunda* SM-A87, a species of family *Flavobacteriaceae*, was isolated from deep-sea sediment samples near the southern Okinawa [16]. It has been reported that the yield of the EPS secreted by SM-A87 reached 8.76 mg/g (dry weight) at optimal experiment conditions [17], which was higher than that of the EPSs produced by other psychrotrophic microorganisms[18]. The low-nutrient consuming and high-EPS-yielding indicates SM-A87 might be a low-cost biosorbent producer. The performance of Cu(II) and Cd(II) adsorption onto EPS SM-A87 could partly proved the above hypothesis[19]. In this paper, better performance of the EPS SM-A87 biosorption of Pb(II) at low concentration wastewater was reported, and the mechanism was also investigated.

2. Materials and methods

2.1. Cultivation of W. profunda (SM-A87) and preparation of EPS SM-A87

Strain *SM-A87* was cultivated in basal medium and the polysaccharides was separated following the method described in reference [19].

2.2. Batch biosorption tests

Stocked Pb(II) solution of 10 mg/l used in this study was prepared by dissolving $Pb(NO_3)_2$ in deionized water. The initial pH of the working solutions was adjusted by addition of HNO_3 or NaOH solution.

SM-A87 EPS solution was added in a 250 ml flask containing 50 ml Pb(II) solution and then the flasks were shaken at 200 rpm at 20°C for 60 min using a Enviro-Genie mechanical shaker. The solution was then filtrated by a 0.45 μm cellulose acetate membrane after equilibrium, and the filtrate was analyzed by atomic absorption spectrophotometer (TAS-990, Purkinje General) with an air–acetylene flame.

The metal uptake (Q) was determined as follows:

$$Q = \frac{V(C_i - C_e)}{W} \tag{1}$$

where V is the volume of solution in flask (ml), W is the mass weight of adsorbent EPS A87 (g); C_i and C_e are the initial and equilibrium concentrations of metal in solution (mg/l).

Standard Pb(II) solution and standard Pb(II) samples were applied for quality controlling. Otherwise, in this study, all chemicals used were in analytical grades and distilled, deionized water was employed. Blank test was also examined as the above proscribed procedure except for deionized water substituted for SM-A87 EPS, respectively. Each determination was conducted at least three times and the average values were reported.

2.3. Competitive biosorption

Competitive biosorptions were performed at an initial pH of 5.5 at 20°C. The initial concentration of Pb(II), Cu(II) and Cd(II) were fixed at different ratios of 1:0:0, 1:1:0, 1:0:1 and 1:1:1, respectively. The same procedures described in Section 2.2 are performed, respectively.

2.4. Adsorption isotherms

Adsorption isotherms were studied by equilibrium tests at different temperatures. SM-A87 EPS dosage of 0.1 g/l was controlled at 50 ml Pb(II) solutions of initial concentration varied from 0 to 500 mg/l.

The samples were shaken end-over-end for 12 h to guarantee the biosorption equilibrium reached. Then the solutions were filtered and measured following the same procedures described in Section 2.2. The isotherm experiments were duplicated and the average values were reported.

2.5. Adsorption kinetics

For kinetic measurements, biorsorption tests were contacted at different intervals and the other procedures were as the same described in Section 2.2.

2.6. FT-IR spectrum

Both the dried EPS samples before and after Pb(II) adsorption were pressed into KBr pellets at sample: KBr ratio of 1: 100, then tested by a Fourier transform infrared spectrometer (VERTEX-70, BRUKER, FT-IR). The spectra were recorded in transmittance mode over the wave number range of 4000–400 cm^{-1}, at a resolution of 4 cm^{-1}.

3. Results and discussion

3.1. Effect of SM-A87 EPS concentration, pH, temperature and contact time

The economic possibility of a biosorbent is one of the major concerns in its application. This could be partly estimated by the dosage of the biosorbent. The dosage effect was investigated at initial lead concentration of 10 mg/l and pH value of 5.0, respectively. Fig. 1(a) shows the biosorption amounts and removal efficiency obtained at various dosages of SM-A87 EPS. The EPS exhibited the maximum biosorption of Pb(II) to be 314 mg/g at the lowest dosage of 0.02 mg/l, and with the increasing dosage of EPS, the biosorption amounts decreased. At constant lead concentration of 10 mg/l, a higher biosorption capacity at a lower dosage could be attributed to an increased ratio of metal to available adsorption sites. The biosorption is lower at a higher EPS dosage for the biosorption sites are superabundant while the amount of lead is limited. Similar results were observed when other biomasses were employed as biosorbents to remove lead, such as lead biosorption by *Citrobacter* strain MCMB-181[20] and by *Penicillium simplissimum* [21]. However, the efficiency of Pb(II) removal increased sharply from 57.7% to 96.5% with the dosage increasing from 0.02 to 0.1 mg/l, then remained complete Pb(II) removal at higher dosage, implying Pb(II) deficiency in solution at higher EPS concentration. It is clear that biosorbent SM-A87 EPS exhibits great potential of Pb(II) adsorption. On the consideration of both economical and technical requirement, 0.1 mg/l EPS dosage was selected in the following tests without explication.

The solution pH is an important parameter for adsorption experiments as it strongly influences the metal species, the activity of functional groups on the biosorbent and the competition of ions for the binding sites. To understand the effect of pH on Pb(II) uptake onto SM-A87 EPS, the biosorption was carried out at pH values from 2 to 7.5, respectively. The result was shown in Fig. 1(b). The adsorption results at pH values above 7.5 were not shown due to the limited solubility of lead ion at higher pH values, which makes true sorption studies impossible. As shown in Fig. 1(b), the biosorption capacity strongly depends on the initial pH of simulated lead wastewater. With the increasing of pH from 2 to 4.5, the biosorption capacity increased sharply

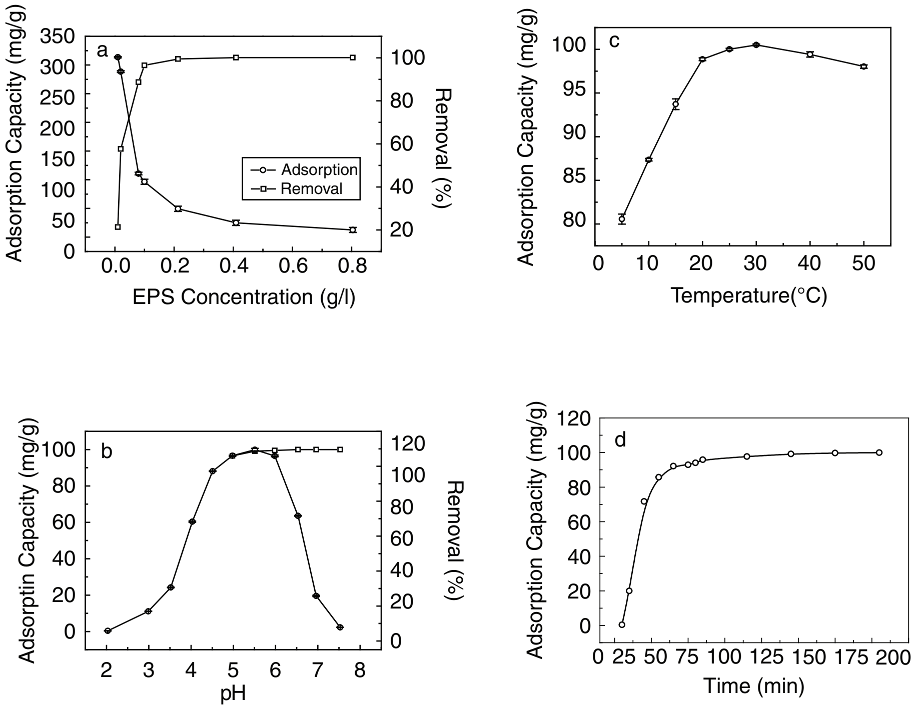

Fig. 1. Effect of different parameters on Pb(II) biosorption (a) EPS concentration; (b) pH; (c) Temperature; (d) Contact time.

from 0.45 to 88.1 mg/g. After this the rate slowed down, and the biosorption capacity reached the maximum value of 99.9 mg/g at a pH of 5.5, and then decreased at higher pH values. The same trend has been observed in the Pb(II) removal at pH 2–5.5, that is, the removal efficiency increased from 0.3% to 99.1% with the increasing of pH from 2 to 5.5. In contrast to the biosorption capacity, Pb(II) removal efficiency did not decrease, but remained constant at higher pH values. As it is well known, the biosorption capacities of biosorbents depend on the available binding sites provided by the functional groups existing at the surface of the biosorbents. At low pH, such sites on the EPS were not available due to the competition between Pb^{2+} and H_3O^+ ions. At increasing pH of the solution, the deprotonation of acid functional groups, such as carboxyl, phosphonate and phosphodiester, were strengthened and the attraction increased between negative charge on biomass and positive metal cations [22]. On the other hand, the zeta potential of EPS became more negative at increasing pH (Fig. 2), suggesting EPS should have the higher potential to adsorb positively charged Pb^{2+}, which is corresponding to the enhancement of biosorption onto the EPS surface. At higher pH values, the decrease of biosorption together with the unchangeable efficiency of Pb(II) removal could be explained by the formation of insoluble precipitates from the solution, which is in agreement with the earlier studies by Fan et al. [21] and Li et al. [23]. To get the maximum lead adsorption and avoid the interference from precipitation, subsequent experiments were carried out at pH 5.5.

The influence of temperatures in the range of 5–50°C on Pb(II) biosorption onto SM-A87 EPS was shown in Fig. 1(c). The biosorption capacity increased when the temperature increased from 5 to 30°C, and then decreased slightly with increasing temperature. However, the biosorption capacities obtained at 15~40°C were higher and the Pb(II) removal rates were about 93~100%, suggesting Pb(II) biosorption on EPS was favorable at general temperatures encountered in practical water treatment. All the same, the temperature for Pb(II) biosorption on SM-A87 EPS was preferred at 20~30°C.

Biosorption of Pb(II) on SM-A87 EPS as a function of contact time is shown in Fig. 1(d). Pb(II) biosorption increased rapidly at the first 30 min of contact time then maintained a constant level with time increasing. From Fig. 1(d), the biosorption of heavy metal ions consisted of two phases: an initial rapid phase contributing significantly to the equilibrium uptake, and a slower second phase whose contribution to the total metal biosorption was relatively small. The occupation of the remaining vacant sites will be difficult as time going on due to the repulsive forces between the Pb(II) ions on the solid and the liquid phases [24,25]. The similar contact time trends of lead binding onto other sorbents have been reported in earlier works [21,26,27].

3.2. Effect of ionic strength

Influence of ionic strength on the Pb(II) biosorption was studied by changing ionic strength from 0 to 0.5 mol/l NaCl, KCl, $MgCl_2$, $CaCl_2$ at pH 5.5, respectively. As shown in Fig. 3, biosorption capacity of SM-A87 EPS decreased significantly with the increase in ionic strength of the salt solutions, and the relatively large change in biosorption capacity occurred at lower ionic strength, implying the formation of lead chloride and the existence of cation exchange in the solution. Increasing ionic strength will increase the ratio of chelation to ion exchange and at very high salt concentration, ion exchange will become very small [28]. A corresponding decrease in the biosorption capacity with increasing

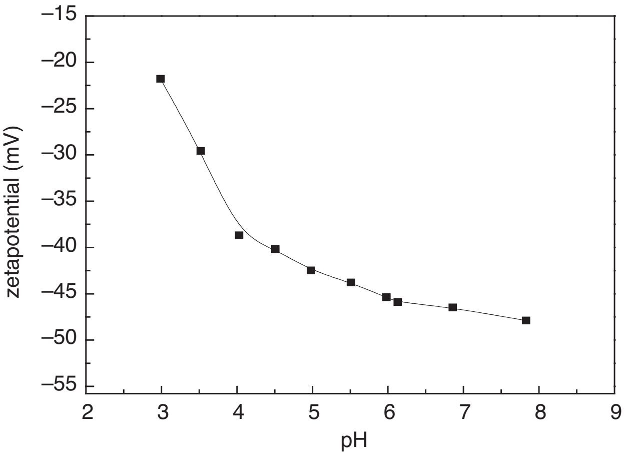

Fig. 2. Zeta potential of SM-A87 EPS.

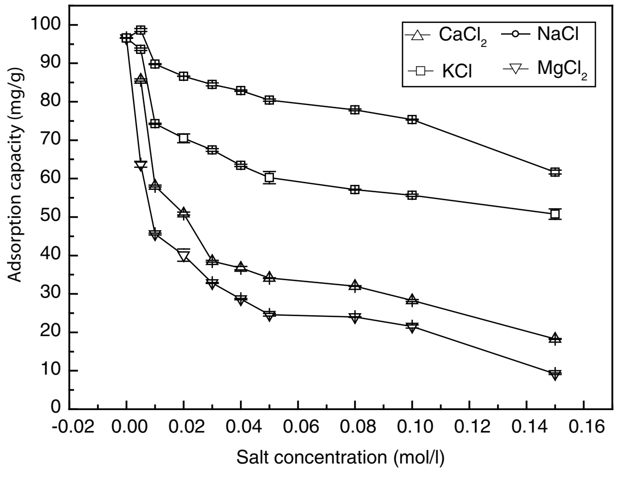

Fig. 3. Effect of ionic strength on Pb(II) biosorption.

ionic strength could be attributed to (1) increasing Na^+, K^+, Mg^{2+}, Ca^{2+} concentration with increasing ionic strength and therefore increasing competition for the sorption sites on EPS surface and, (2) changing either solute activity or diffuse electrical double layer thickness and therefore limiting the lead transfer from solution onto EPS surface.

Salt cations had discrepant effects on Pb(II) biosorption. For the four tested salt cations, Mg^{2+} and Ca^{2+} had greater depression than Na^+ and K^+ on Pb binding onto the EPS. This could be due to the fact that Ca^{2+} and Mg^{2+} brought two times ionic strength compared with that of K^+ and Na^+ at the same salt concentration. So, their effects on electrical double layer and consequently on the Pb(II) biosorption are much stronger than K^+ and Na^+. On the other hand, the ionic radius is dominated to affect the metals uptake through competition biosorption. Due to the smaller ionic radius of Na^+ than K^+, it is easier for Na^+ to compete with Pb(II) for binding sites on SM-A87 EPS, and consequently the influence of Na^+ on Pb(II) biosorption is stronger than that of K^+. Similarly, the inhibitory effect of added bivalent ions on Pb(II) biosorption was greater for Mg^{2+} than Ca^{2+}, which is due to the much smaller ionic radius of Mg^{2+} as compared with Ca^{2+}.

3.3. Competitive biosorption in solution

The competition among the heavy metals onto the biosorbent can affect the mobility and the removal efficiency of heavy metals from such multi-component solutions. Metal biosorption capacities of SM-A87 EPS in single- and multi-solute systems (lead, copper, and cadmium) were investigated. The initial metal ion concentration was equal of 10 mg/l for each metal ion. As shown in Fig. 4, trends of the biosorption capacities in multi-solute system were similar to that in single-solute system but the biosorption capacities was significantly reduced due to the presence of adsorption competition among heavy metals. In the binary systems, the capacities of Pb(II) biosorption were less for Pb(II)-Cu(II) mixture than Pb(II)-Cd(II) mixture at all tested times, indicating Cu(II) had a greater effect on Pb(II) biosorption compared with Cd(II). However, the adsorption capacity of Pb(II) is higher in the simultaneous presence of Cu(II) and Cd(II) compared with the presence of copper alone. This phenomenon was difficult to understand but has been observed in several reports as to remove Pb(II) at the presence of Cu(II) and Zn(II) [29,30]. This may be attributed to the presence of Cd(II), which competes with Cu(II) instead of Pb(II). Cu(II) and Cd(II) are all transition elements, which may enhance their competition for the same available adsorption binding sites on the EPS and consequently lessen the competitive effect on Pb(II).

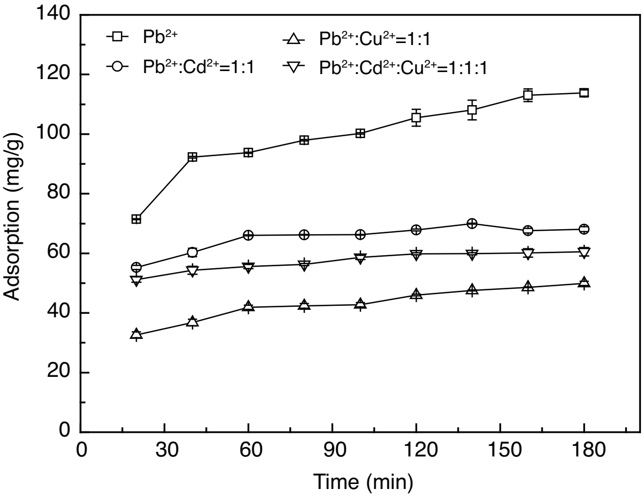

Fig. 4. Competitive adsorption of Pb(II), Cu(II), and Cd(II) on SM-A87 EPS.

3.4. Adsorption isotherms

Several isotherm equations have been used for equilibrium models of biosorption systems. The two most commonly used isotherm equations, the Langmuir and Freundlich have been applied for this study.

The Langmuir biosorption isotherm has been successfully applied to many monolayer sorption processes. A basic assumption of the Langmuir theory is that sorption occurs at specific homogenous sites within the adsorbent. The Langmuir model is represented by equation (1):

$$\frac{C_f}{q_e} = (\frac{1}{q_{max}})b + \frac{C_f}{q_{max}} \tag{2}$$

where q_e and q_{max} are the equilibrium and maximum uptake capacities (mg/g biosorbent) respectively; C_f is the equilibrium concentration of metal in solution (mg/l); and b is the equilibrium adsorption constant, and is related to the affinity of the binding sites. q_{max} represents a practical limiting adsorption capacity when the surface is fully covered with metal ions. It allows the comparison of adsorption performance, particularly in cases where the adsorbent was not fully saturated.

The Freundlich isotherm is an empirical equation employed to describe heterogeneous systems. The equation for the linear fitting is

$$q_e = K_f C_f^{\frac{1}{n}} \tag{3}$$

where K_f and n are Freudlich constants characteristic of the system, indicating the adsorption capacity and adsorption intensity of the adsorbent, respectively.

Table 1
Isotherm parameters obtained from Langmuir, Freundlich models for Pb(II) biosorption on the EPS SM-A87

T (°C)	Langmuir			Freundlich		
	q_{max} (mg/g)	b	r_L^2	n	K_f	r_F^2
10	144.9	8.07	0.973	2.23	19	0.803
20	159.25	9.9	0.981	2.40	21	0.869
30	357	12	0.973	2.03	37	0.885
40	312	19	0.940	2	3	0.731

All the parameters correlating with Langmuir and Freundilch evaluated from the isotherms and also the corresponding correlation coefficients are given in Table 1.

As can be seen from Table 1, the relative coefficient (r^2) revealed that the sorption data of EPS fit both models, especially the Langmuir model ($r_L^2 > r_F^2$). Based on the Langmuir isotherm, the increase in the value of b with increase in temperature up to 40°C indicated the endothermic nature of the process, and the maximum biosorption amount (q_{max}) of EPS for Pb(II) was found to be 357 mg/g at 30°C. However, the adsorption data also fitted well to the Frendlich equation. The values of K_f showed easy uptake of metal ion with high adsorptive capacity of SM-A87 EPS. On the other hand, since the values of n were higher than 1.0, the strength of metal adsorption by the biosorbent was quite intense, indicating that Pb(II) is favorably adsorbed by SM-A87 EPS at the temperatures studied [31].

To confirm the favorability of the adsorption process, the dimensionless separation factor R_L has been calculated, which is given by the following equation:

$$R_L = \frac{1}{1 + bC_i} \tag{4}$$

C_i is the initial metal concentration (mg/l), b is Langmuir equilibrium constant (L/mg). The smaller R_L value indicates a highly favorable adsorption. If R_L<1 unfavorable, R_L=1 linear, 0<R_L<1 favorable, and if R_L=0 irreversible. The calculated values of R_L for Pb(II) biosorption onto SM-A87 EPS were found to be between 0 and 1 and confirm that the ongoing biosorption process is favorable.

3.5. Adsorption kinetics

The models of adsorption kinetics are correlated with the solution uptake rates, which would allow an estimation of the amount of metal ions that would be adsorbed within a specific time. In this study, the pseudo-first-order equation and the pseudo-second-order equation were tested to fit experimental data obtained from batch metal biosorption experiments.

The pseudo-first-order model is given as:

$$\log(Q_e - Q_t) = \log Q_e - \frac{k_1 t}{2.303} \tag{5}$$

The pseudo-second-order model is given as:

$$\frac{t}{Q_t} = \frac{1}{k_2 Q_e^2} + \frac{t}{Q_e} \tag{6}$$

where k_1 (min^{-1}) and k_2 (g/mg min) are the rate constants of pseudo-first-order model and pseudo-second-order model, respectively. Q_e and Q_t (mg/g) are the amounts of metal adsorbed on SM-A87 EPS at equilibrium and at time t, respectively. Linear plots of ln (Q_e–Q_t) versus t indicate the applicability of pseudo-first-order model. The plot t/Q_t versus t should give a straight line if pseudo-second-order kinetics is applicable.

Plots of linearized forms corresponding to pseudo-first-order and pseudo-second-order kinetics models were shown in Fig. 5. Kinetics parameters and correlation coefficients of the kinetic models were also shown in this figure. The correlation coefficient (R_2^2) of pseudo-second-order equation was better than that of the pseudo-first-order equation, indicating that the pseudo-second-order model could better explain the biosorption kinetic behaviors of Pb(II) onto SM-A87 EPS.

3.6. FT-IR spectrum

FT-IR is an important tool to identify the functional groups. The assignment of FT-IR bands and detailed wave number shifts for the biosorbent SM-A87 EPS are shown in Fig. 6 There were several functional groups found in the structure of EPS such as carboxylic acid groups. Three shifts (more than 10 cm^{-1}) in wave number of dominant peaks were observed comparing fresh-dried EPS with metal-loaded EPS. These shifts in the wave number showed that there was a metal binding process taking place on the surface of EPS.

The carboxylic group contained the following minor groups: O-H stretching, O-H bending, C=O stretching and C-O stretching. The O-H stretching group, C=O stretching group and O-H bending group were observed to shift clearly from 3417 cm^{-1}, 1654 cm^{-1}, 1401 cm^{-1} to 3433 cm^{-1}, 1637 cm^{-1}, 1412 cm^{-1}, respectively. These indicated that there were a high potential O-H stretching group, C=O stretching group and O-H bending group from carboxylic acid, which have been found involved with the adsorption of Pb(II) [32,33]. The wave numbers of the other groups such as: C-H group(shift from 2928 cm^{-1} to 2922 cm^{-1}), C-O group(shift from 1037 cm^{-1} to 1031 cm^{-1}) were also changed. All these changes may be

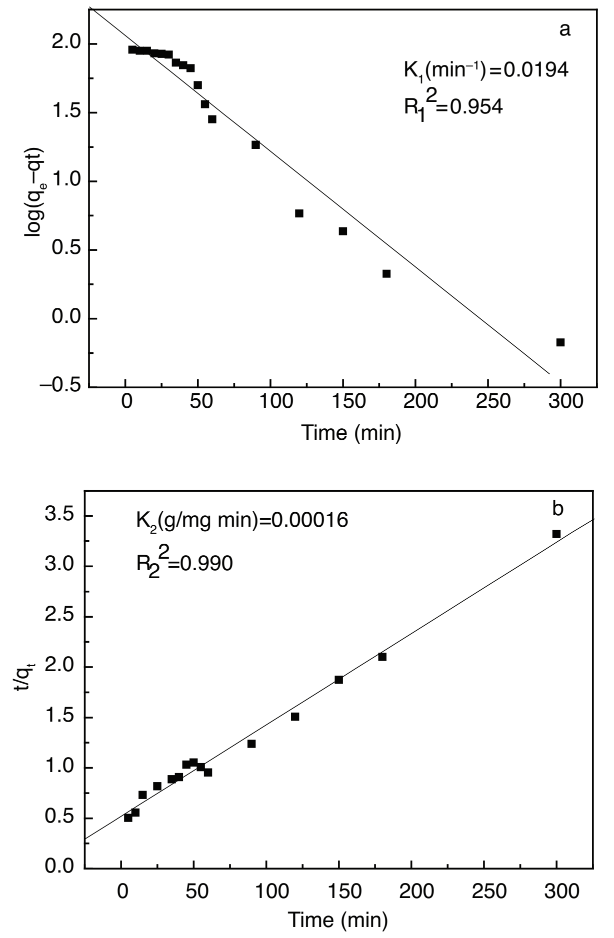

Fig. 5. Kinetics models for lead biosorption onto EPS SM-A87 (a) Pseudo-first-order model; (b) Pseudo-second-order model.

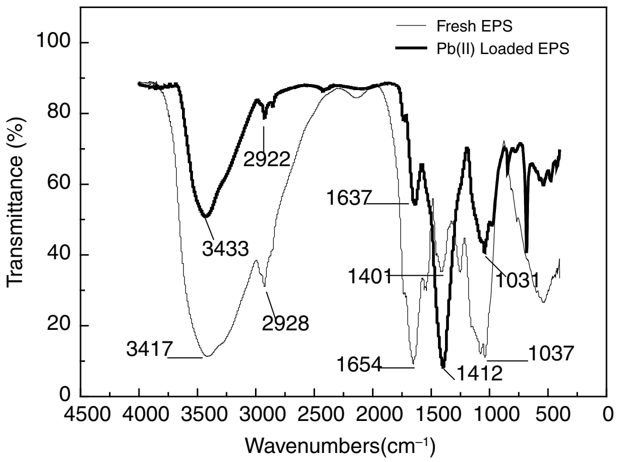

Fig. 6. FT-IR spectra of fresh EPS and Pb(II) loaded EPS.

Table 2
Pb(II) biosorption capacities of reported biosorbents

Biosorbents	Biosorption capacity (mg/g)	Dosage (g/l)	pH	Reference
Calophyllum inophyllum	34.51	20	4	Lawal et al. [34]
Modified peat-resin particles	47.39	10	4.5	Q.Y. Sun et al. [35]
Parmelina tiliaceae	75.8	4	5	Uluozlu et al.[32]
Penicillium simplicissimum	87.72	1	5	Fan et al. [21]
Green algae *Spirogyra* sp.	140.84	0.5	5	Gupta and Rastogi[36]
Oedogonium sp.	145	0.5	5	Gupta and Rastogi [26]
Formaldehyde treated acorn waste	164.2	1	5	Örnek et al. [37]
Pseudomonas putida	270.37	1	5.5	Uslu and Tanyol [38]
PAAc-functionalized chitosan	294.12	0.5	4	Li and Bai [39]
SM-A87	357	0.1	5.5	This study

relevant to a metal binding process taking place on the surface of SM-A87 EPS.

3.7. Comparison of sorption capacity of SM-A87 EPS with other biosorbents

As it is well known, a direct comparison with EPS and other reported biosorbents presents different values due to the varying experimental conditions employed. Here, SM-A87 EPS has been compared with other biosorbents based on their maximum adsorption capacity for Pb(II) and dosage as shown in Table 2. It can be observed that the maximum biosorption amount (q_{max}) of EPS for Pb(II) was 357 mg/g at an EPS dosage of 0.1 g/l with optimum pH of 5.5, which was much higher than those of other biosorbents reported in literature. Therefore, SM-A87 EPS as a biosorbent exhibits great potential to remove lead ions from wastewater.

In this study, we have also examined the biosorption capacity of whole cells (both viable and dead cells) in our lab. The main limitation of viable cells of A87 application in lead adsorption is the pH. The bacteria can not stand the pH value lower than 6.0 which is secure for Pb(II) with no precipitation. As to dead cells, it is not satisfied with the low biosorption capacity. This is mainly because the EPS had been previously separated to get the dried cells. On the other hand, there are more advantages to use the EPS than the whole cells: (a) the biosorption capacity is much higher than other biosorbents as shown in this study; (b) The EPS yields of A87 are very high and it can be reused by immobilization technology. This can lower the cost to some extent. (c) EPS is convenient for industry producing, transportation and wide application compared to viable cells; (d) we do purified the EPS strictly to understand the influence and the mechanism of biosorption. However, the materials used in the purification process, such as alcohol, chloroform and butyl alcohol, can be reused in industry, which makes the cost of purification lower. Besides the EPS purification is not compulsory for EPS application in water treatment practice.

4. Conclusions

Based on the results obtained in this study, the main conclusions are as follows:

1. The biosorption of Pb (II) on SM-A87 EPS were affected greatly by solution pH, temperature, EPS concentration and ionic strength. Pb (II) at low concentration can be removed almost completely from the water by SM-A87 EPS adsorption at controlled condition as EPS dosage of 0.1 mg/l or upper, pH of 5.5, temperature of 20~30°C, and contact time of less than 60 min, respectively. Coexistent cations and other heavy metal depressed the biosorption capability differentially.
2 The adsorption data fitted Langmuir model better than Freundlich model, which indicated that the removal process of Pb(II) by SM-A87 EPS was monolayer biosorption.
3. The biosorption capacity of EPS SM-A87 is much higher than other biosorbents. The maximum adsorption of 357 mg/g at 30°C and the R_L value between 0 and 1 confirms that the biosorption is favorable.
4. The biosorption kinetics for Pb(II) can be well described by pseudo-second-order kinetic model. The FT-IR analysis verified the possible functional groups (O–H, C=O etc.) contribute to the binding of heavy metals.

Comprehensively, EPS SM-A87 may be applied as a good adsorbing medium for Pb(II).

Acknowledgement

This work was supported by National Natural Science Foundation of China (50878120), Natural Science Foundation of Shandong province of China (Z2008B09), Key Scientific and Technological Projects of Shandong province of China (2010G0020606), University Independent Innovation Projects of Jinan of China (201004041) and Interdisciplinary Foundation of Shandong University (2009JC017).

References

[1] P.L. Bishop, Pollution prevention: fundamentals and practice, Tsinghua University Press, Beijing, 2002.

[2] Y.N. Mata, M.L. Blazquez, A. Ballester, F. Gonzalez and J.A. Munoz, Biosorption of cadmium, lead and copper with calcium alginate xerogels and immobilized *Fucus vesiculosus*, J. Hazard. Mater., 163 (2009) 555–562.

[3] M. Nadeem, A. Mahmood, S.A. Shahid, S.S. Shah, A.M. Khalid and G. Mckay, Sorption of lead from aqueous solution by chemically modified carbon adsorbents, J. Hazard. Mater. B, 138 (2006) 604– 613.

[4] S. Qaiser, A.R Saleemi and M. Umar, Biosorption of lead from aqueous solution by Ficus religiosa leaves: Batch and column study. J. Hazard Mater., 166 (2009) 998–1005.

[5] M.Y. Arica, Y. Kacar and O. Gene, Entrapment of white-rot fungus Trametes ver-sicolor in Ca-alginate beads: preparation and biosorption kinetic analysis for cadmium removal from an aqueous solution, Bioresource Technol., 80 (2001) 121–129.

[6] B. Volesky, Biosorption of heavy metals, CRC Press, Florida, 2000.

[7] S.S. Ahluwalia and D. Goyal, Microbial and plant derived biomass for removal of heavy metals from wastewater, Bioresource Technol., 98 (2007) 2243–2257.

[8] S. Tunali, A. Cabuk and T. Akar, Removal of lead and copper ions from aqueous solutions by bacterial strain isolated from soil, Chem. Eng. J., 115 (2006) 203–211.

[9] V.J.P. Vilar, C.M.S. Botelho and R.A.R. Boaventura, Infuence of pH, ionic strength and temperature on lead biosorption by *Gelidium* and agar extraction algal waste, Process Biochem., 40 (2005) 3267–3275.

[10] K.K. Wong, C.K. Lee, K.S. Low and M.J. Haron, Removal of Cu and Pb by tartaric acid modified risk husk from aqueous solutions, Chemosphere, 50 (2003) 23–28.

[11] W.W. Li, W.Z. Zhou, Y.Z. Zhang, J. Wang and X.B. Zhu, Flocculation behavior and mechanism of an exopolysaccharide from the deep-sea psychrophilic bacterium *Pseudoalteromonas* sp SM9913, Bioresource Technol., 99 (2008) 6893–6899.

[12] S.Y. Kim, J.H. Kim, C.I. Kim and O.K. Oh, Metal adsorption of the polysaccharide produced from *Methylobacterium organophilum*, Biotechnol. Lett., 18 (1996) 1161–1164.

[13] G.K. Qin, C.Y. Sun, L.Z. Zhu, X.L. Chen, P.G. Wang and Y.Z. Zhang, Structural characterization and ecological roles of a novel exopolysaccharide from the deep-sea psychrotolerant bacterium *Pseudoalteromonas* sp. SM9913, Microbiol., 153 (2007) 1566–1572.

[14] S. Colliec-Jouault, P. Zanchetta, D. Helley, J. Ratiskol, C. Sinquin, A. M. Fischer and J. Guezennec, Microbial polysaccharides of marine origin and their potential in human therapeutics, Pathol. Biol. (Paris), 52 (2004) 127–130.

[15] K.N. Kirschner and R.J. Woods, Solvent interactions determine carbohydrate conformation, Proc. Natl. Acad. Sci., 98 (2001) 10541–10545.

[16] Q.L. Qin, D.L. Zhao, J. Wang, X.L. Chen, H.Y. Dang, T.G. Li, Y.Z. Zhang and P.J. Gao, *Wangia profunda* gen. nov., sp. nov., a novel marine bacterium of the family *Flavobacteriaceae* isolated from southern Okinawa Trough deep-sea sediment, FEMS Microbiol. Lett. , 271 (2007) 53–58.

[17] G.K. Qin, Structure, ecological roles and biosynthesis gene cluster of EPS from deep-sea psychrotrophic bacterium *Pseudoalteromonas* sp. SM9913, Shandong University Doctoral Dissertation, 2007.

[18] C.A. Mancuso Nichols, S. Garon, J.P. Bowman, G. Raguenes and J. Guezennec, Production of exopolysaccharides by Antarctic marine bacterial isolates. J. Appl. Microbiol., 96 (2004) 1057–1066.

[19] W.Z. Zhou, J. Wang, B.L. Shen, W.G. Hou and Y.Z. Zhang, Biosorption of copper(II) and cadmium(II) by a novel exopolysaccharide secreted from deep-sea mesophilic bacterium, Colloid Surface B, 72 (2009) 295–302.

[20] P.R. Puranik and K.M. Paknikar, Biosorption of lead, cadmium and zinc by *Citrobacter* strain MCMB-181: characterization studies, Biotechnol. Prog., 15 (1999) 228–237.

[21] T. Fan, Y.G. Liu, B.Y. Feng, G.M. Zeng, C.P. Yang and M. Zhou, Biosorption of cadmium(II), zinc(II) and lead(II) by *Penicillium simplissimum*: isotherms, kinetics and thermodynamics, J. Hazard. Mater., 160 (2008) 655–661.

[22] G.Q. Chen, G.M. Zeng, L. Tang, C.Y. Du, X.Y. Jiang, G.H. Huang, H.L. Liu and G.L. Shen, Cadmium removal from simulated wastewater to biomass byproduct of *Lentinus edodes*, Bioresource Technol., 99 (2008) 7034–7040.

[23] X.M. Li, D.X. Liao and X.Q. Xu, Kinetics studies for the biosorption of lead and copper ions by pencillium simplicissimum immobilized within loofa sponge. J. Hazard. Mater., 159 (2008) 610–615.

[24] S.T. Akar, A. Gorgulu, B. Anilan, Z. Kaynak and T. Akar, Investigation of the biosorption characteristics of lead(II) ions onto Symphoricarpus albus: batch and dynamic flow studies. J. Hazard. Mater., 165 (2009) 126–133.

[25] A. Saeed, M.W. Akhtar and M. lqbal, Removal and recovery of heavy metals from aqueous solution using papaya wood as a new biosorbent, Sep. Purif. Technol., 45 (2005) 25–31.

[26] V.K. Gupta and A. Rastogi, Biosorption of lead from aqueous solutions by green algae *Spirogyra* species: Kinetics and equilibrium studies, J. Hazard. Mater., 152 (2008) 407–414.

[27] X.L. Tan, P.P. Chang, Q.H. Fan, X. Zhou, S.M. Yu, W.S. Wu and X.K. Wang, Sorption of Pb(II) on Na-rectorite: Effect of pH, ionic strength, temperature, soil humic acid and fuluic acid, Colloid Surface A, 328 (2008) 8–14.

[28] A.A. EI-Bayaa, N.A. Badawy and E.A. Alkhalik, Effect of ionic strength on the adsorption of copper and chromium ions by vermiculite pure clay mineral, J. Hazard. Mater., 170 (2009) 1204–1209.

[29] Changzhou Yan, Guoxin Li, Peiying Xue, Qunshan Wei, Qingzhaoli. Competitive effect of Cu(II) and Zn(II) on the biosorption of lead(II) by Myriophyllum spicatum, J. Hazard. Mater., 179 (2010) 721–728.

[30] M.H. El-Naas, F. Abu Al-Rub, I. Ashour 1 and M. Al Marzouqi, Effect of competitive interference on the biosorption of lead(II) by Chlorella vulgaris, Chem. Eng. Process., 46 (2007) 1391–1399.

[31] Z. Aksu, Determination of the equilibrium, kinetic and thermodynamic parameters of the batch biosorption of Pb(II) ions onto Chlorella vulgaris, Process Biochem., 38 (2002) 87–99.

[32] O.D. Uluozlu, A. Sari, M. Tuzen and M. Soylak, Biosorption of Pb(II) and Cr(III) from aqueous solution by lichen (Parmelina tiliaceae) biomass, Bioresource Technol., 99 (2008) 2972–2980.

[33] Y.N. Mata, M.L. Blazquez, A. Ballester, F. Gonzalez and J.A. Munoz, Characterization of the biosorption of cadmium, lead and copper with the brown alga Fucus vesiculosus, J. Hazard. Mater., 158 (2008) 316–323.

[34] O.S. Lawal, A.R. Sanni, I.A. Ajayi and O.O. Rabiu, Equilibrium, thermodynamic and kinetic studies for the biosorption of aqueous lead(II) ions onto the seed husk of Calophyllum inophyllum, J. Hazard. Mater., 177 (2010) 829–835.

[35] Q.Y. Sun, P. Lu and L.Z. Yang, The adsorption of lead and copper from aqueous solution on modified peat-resin particles, Environ. Geochem. Hlth, 26 (2004) 311–317.

[36] V.K. Gupta and A. Rastogi , Biosorption of lead from aqueous solutions by green algae Spirogyra species: Kinetics and equilibrium studies, J. Hazard. Mater., 152 (2008) 407–414.

[37] A. Örnek, M. Özacar and I.A. engil, Adsorption of lead onto formaldehyde or sulphuric acid treated acorn waste: Equilibrium and kinetic studies, Biochem. Eng. J., 37 (2007) 192–200.

[38] G. Uslu and M. Tanyol, Equilibrium and thermodynamic parameters of single and binary mixture biosorption of lead(II) and copper(II) ions onto Pseudomonas putida: Effect of temperature, J. Hazard. Mater., 135B (2006) 87–93.

[39] N. Li and R.B. Bai, Highly enhanced adsorption of lead ions on chitosan granules functionalized with poly(acrylic acid), Ind. Eng. Chem. Res., 45 (2006) 7897–7904.