

Optimization of lead (II) biosorption in an aqueous solution using chemically modified aerobic digested sludge

R. Darvishi Cheshmeh Soltani, A. Rezaee, Gh Shams Khorramabadi and K. Yaghmaeian

ABSTRACT

Biosorption of Pb(II) by using digested sludge obtained from a municipal wastewater treatment plant in Tehran was examined. The aims of this investigation were biosorption of Pb(II) ions onto chemically treated digested sludge with hydrogen peroxide (H_2O_2) solution and determination of kinetic and isotherm of biosorption. Biosorption capacity of two types of sludge (treated and untreated) for biosorption of Pb(II) ions was investigated as function of initial Pb(II) concentration and pH using batch biosorption systems. The equilibrium biosorption capacity increased with increasing of initial metal ion concentrations and pH for both of digested sludge. The pseudo-second order kinetic model was found to be slightly suitable than the pseudo-first order kinetic model to correlate the experimental data for two types of digested sludge ($R^2 > 0.9$). Regarding the applicability of the isotherm models, the freundlich model was found to be suitable than the other isotherm models. According to obtained q_{max} from Langmuir isotherm, biosorption of Pb(II) by H_2O_2 treated digested sludge was found to perform better than untreated digested sludge. The maximum biosorption capacity was given 185.19 and 144.93 mgg^{-1} for H_2O_2 treated and untreated digested sludge, respectively. Also, the constant of energy (B) between the Pb(II) ions and the adsorbent surface, calculated using BET isotherm model, obtained 5401 and 3401 for H_2O_2 treated and untreated digested sludge, respectively. These results indicate the usefulness of H_2O_2 treated digested sludge as a biosorbent for Pb(II) biosorption.

Key words | biosorption, digested sludge, isotherm, kinetic, Pb(II)

R. Darvishi Cheshmeh Soltani
(corresponding author)

A. Rezaee
Environmental Health Dept,
Faculty of Medical Sciences,
Tarbiat Modarres University,
P.O.Box: 14115-178,
Tehran,
Iran
E-mail: rezadarvish86@yahoo.com;
abbasrezaee@yahoo.com

Gh Shams Khorramabadi
Environmental Health Dept,
Faculty of Health,
Lorestan University of Medical Sciences,
P.O.Box: 441,
Khorramabad,
Iran
E-mail: shams_lums@yahoo.com

K. Yaghmaeian
Environmental Health Dept,
Faculty of Health,
Semnan University of Medical Sciences,
P.O.Box: 373,
Damghan,
Iran
E-mail: k_yaghmaeian@yahoo.com

INTRODUCTION

Heavy metal ions present in some industrial effluents have detrimental effects on the environments such as water and soil (Gulnaz *et al.* 2005; Kargi & Cikla 2006; Yunus Pamukoglu & Kargi 2006). Lead causes severe damage to kidney, liver, brain and reproductive system in human. Lead contamination exists in effluent of many industries, such as battery manufacturing, printing and pigment, metal finishing, glass industries and steel manufacturing (Kumar Naiya *et al.* 2009). Conventional methods for removal of heavy metals from industrial wastewater such as: chemical precipitation, ion-

exchange, adsorption, solvent extraction were found to be ineffective or expensive and require high capital and operating costs, also may result large volumes of sludge causing disposal problems (Utgikara *et al.* 2000; Aksu *et al.* 2002; Al-Qodah 2006; Kargi & Cikla 2006). Therefore, recent researches have been focused on use of non-conventional alternative including different biomaterials such as: waste sludge, algae, yeast and fungal biomass (Kargi & Cikla 2006; Tokcaer & Yetis 2006; Yunus Pamukoglu & Kargi 2006). Biomaterials are ecosystem-friendly, cost-effective,

highly selective, high biosorption capacity and high efficiency in detoxifying industrial wastewater (Utgikara *et al.* 2000; Jalali *et al.* 2002; Al-Qodah 2006; Kargi & Cikla 2006). Biosorption of metal ions is the passive binding of heavy metal ions to biopolymers on the cell wall of organisms. On the other hand, passive binding of heavy metal ions was defined as biosorption and active binding on the cell wall of live organisms defined as bioaccumulation (Aksu *et al.* 2002; Kargi & Cikla 2006; Yunus Pamukoglu & Kargi 2006). Dead biomaterials are more applicable than living biomaterial, because living systems require nutrients and maintenance of living biomass in high toxicity environment is very difficult. In addition, dead biomaterials can be easily regenerated (Aksu *et al.* 2002; Jalali *et al.* 2002; Al-Qodah 2006). Waste sludge as a biomaterial, for removal of heavy metal ions can be used because of low cost and its availability (Wang *et al.* 2006; Xuejiang *et al.* 2006). Waste activated sludge consists of microbial population such as bacteria and protozoa (Yunus Pamukoglu & Kargi 2006). Bacterial biomass in waste sludge is a natural biosorbent for heavy metal ions because of its negative cell wall charge. Cell wall of bacteria consists of polymeric substances that contain negatively charged functional groups, such as carboxyl, phosphate and sulfate (Yuncu *et al.* 2006). In a few researches, biosorption of heavy metal ions onto treated digested sludge (as a waste sludge) have been studied (Tokcaer & Yetis 2006). Cell debris will remain in final product from aerobic digestion as a result of endogenous respiration. Therefore, cell wall as a significant portion of the cell mass is not dissolved and remains as the most effective matter in the system containing functional groups for metal ions biosorption (Metcalf & Eddy 2003). In this study aerobic digested sludge was treated with hydrogen peroxide solution for biosorption of Pb(II) ions and the kinetic and isotherm models of the biosorption were investigated.

Theoretical background

Isotherm models. The equilibrium, established between adsorbed metal ions and unadsorbed metal ions in solution can be described by adsorption isotherm models (Aksu *et al.* 2002). There are different isotherm models such as Langmuir, Freundlich, Freundlich-langmuir and BET for describing adsorption equilibrium. The linear form of the Langmuir isotherm model is

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

where q_e (mgg^{-1}) is the amount of biosorbed metal ions per unit weight of biosorbent and C_e (mg^{-1}) is unbiosorbed metal ions concentration in solution. Q_m (mgg^{-1}) is the maximum amount of the biosorbent per unit weight of biosorbent to form a monolayer on the surface of biosorbent and K (lmg^{-1}) is related to the affinity of the binding sites (Loukidou *et al.* 2004; Norton *et al.* 2004). The linear form of the Freundlich isotherm model is:

$$\log q_e = \log K_F + \frac{1}{n} \log C_e \quad (2)$$

where n and K_F are indicators of sorption intensity and sorption capacity, respectively (Aksu 2001; Xuejiang *et al.* 2006). The linear form of the Freundlich-langmuir equation is as follow:

$$\log \left(\frac{1}{q} - \frac{1}{q_m} \right) = \log \left(\frac{1}{bq_m} \right) + \frac{1}{n} \log \left(\frac{1}{C_e} \right) \quad (3)$$

And the linear form of the BET equation is as below:

$$\frac{C}{(C_s - C)q_e} = \frac{1}{BQ^0} + \left(\frac{B-1}{BQ^0} \right) (C/C_s) \quad (4)$$

where C_s is the saturation concentration of the dissolved metal ions (mg^{-1}) and C is concentration of the dissolved metal ions at equilibrium. Q^0 is amount of metal ions adsorbed forming a complete monolayer (mgg^{-1}) and B is the constant of energy between the metal ions and the adsorbent surface.

Kinetic models. The pseudo-first order and pseudo-second order kinetic models were used in order to evaluate the mechanism of biosorption. The linear form of pseudo-first order kinetic equation is:

$$\log(q_e - q) = \log q_e - \frac{k_{1,ad}}{2.303} t \quad (5)$$

where q (mgg^{-1}) is the amount of adsorbed metal ions on the biosorbent at time t and $k_{1,ad}$ (min^{-1}) is the rate constant. A straight line of $\log(q_e - q)$ versus time suggests the suitability of pseudo-first order model. The linear form of pseudo-second order kinetic equation is:

$$\frac{t}{q} = \frac{1}{k_{2,ad}q_e^2} + \frac{1}{q_e} t \quad (6)$$

where $k_{2,ad}$ ($\text{gmg}^{-1} \text{min}^{-1}$) is the rate constant. If the pseudo-second order kinetic be suitable, the plot of t/q against t of Eq.(6) should give a linear form (Aksu 2001; Liu *et al.* 2004; Yunus Pamukoglu & Kargi 2006). The linear form of the

saturation or mixed-order model is as below:

$$\frac{1}{t} \ln \frac{C_0}{C_t} = -\frac{k_0}{K} - \frac{1}{K} \left(\frac{C_0 - C_t}{t} \right) \quad (7)$$

where C_0 is the concentration of adsorbate at t_0 (mg l^{-1}) and C_t is the concentration of adsorbate (mg l^{-1}) at t . k_0 is the constant of equation (mg min^{-1}) and also K is a constant.

METHODS

Experimental procedure

Digested sludge was obtained from aerobic digester effluent of a municipal wastewater treatment plant in Tehran. Digested sludge was washed with deionized water and dried at 60°C until constant weight, reground and sieved by using standard sieves (particle size between 0.2–0.3 mm). The dried digested sludge was treated using 1% H_2O_2 solution in order to activate the functional groups for binding Pb(II) ions. For pretreatment, 200 ml of 1% H_2O_2 solution were mixed with 2 g of dried digested sludge in a 250 ml erlenmeyer flask and placed on a shaker at 150 rpm for 6 h (Kargi & Cikla 2006; Yunus Pamukoglu & Kargi 2006).

Experimental system

Batch system was performed using 250 ml erlenmeyer flask and shaker at 150 rpm at room temperature (25°C) for 240 min to achieve sorption equilibrium time for experiments. Lead(II) ions (in form of $\text{Pb}(\text{NO}_3)_2$) and dried digested sludge were added to the flasks to obtain desired concentrations of Pb(II) ($10\text{--}500 \text{ mg l}^{-1}$) and dried digested sludge (1 g l^{-1}) in the solution. In selected experiments the biosorbent and Pb(II) concentration were 1 g l^{-1} and 50 mg l^{-1} , respectively. The pH was adjusted to 4 in all selective experiments. After shaking, samples were removed from the erlenmeyer flasks for analysis. A control flask, without biosorbent, was used to determine Pb(II) removal in the absence of the biosorbent. All biosorption experiments were carried out in triplicates to check the precision of results.

Analytical methods

The withdrawn samples from the erlenmeyer flasks were filtered. Samples were analyzed for Pb(II) ion concentrations by an atomic adsorption spectroscopy (BRAIC-WFX-130)

according to method no.3111B from standard methods for the examination of water and wastewater (APHA 1998).

RESULTS AND DISCUSSION

Determination of equilibrium time

Variations of adsorbed Pb(II) with time are depicted in Figure 1 for two types of digested sludge. In Figure 1 was shown that adsorbed Pb(II) ions increased with time and reached equilibrium after 2 h for both of biosorbents.

Effect of initial Pb(II) concentration

The influence of Pb(II) ion concentrations on biosorption was investigated by changing the initial concentrations in the range of $10\text{--}500 \text{ mg l}^{-1}$. In Figure 2 was shown that biosorption rate (as mg g^{-1}) increased with increasing concentration of Pb(II) ions. The results are in agreement with the literature reporting high metal ion biosorption at high metal ion concentrations. As the metal ion concentrations increased, more binding sites on sludge surface were occupied by metal ions yielding larger biosorbed ions as mg g^{-1} (Xuejiang *et al.* 2006; Yunus Pamukoglu & Kargi 2006). However, in Figure 2 was exhibited that with increasing Pb(II) ion concentrations, removal percentage of Pb(II) ions decreased. The maximum equilibrium capacities of dried digested sludge at 500 mg l^{-1} ion concentration were 166.22 and 119.11 mg g^{-1} for H_2O_2 treated and untreated sludge, respectively.

Effect of pH

The pH of solution affects the charge on the surface of the biosorbent. In Figure 3 variations of biosorbed Pb(II) ion concentrations versus pH of solution was presented. The biosorbed metal ion concentrations increased with increasing

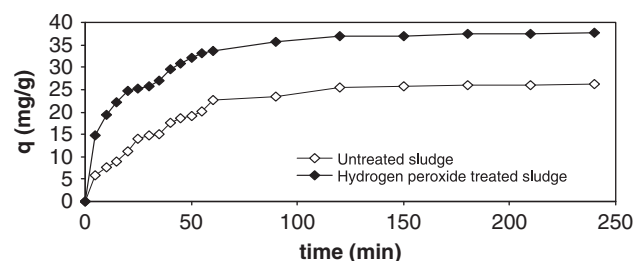


Figure 1 | Variations of biosorbed Pb(II) concentration versus time using two types of digested sludge, pH = 4, mixing speed = 150 rpm, biosorbent mass = 1 g l^{-1} , contact time = 240 min, metal concentration = 50 mg l^{-1} .

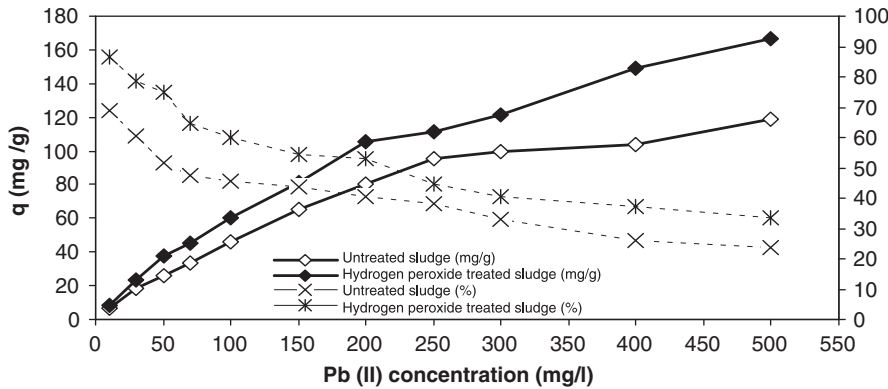


Figure 2 | Variations of biosorption rate and removal percentage of metal ions versus initial Pb(II) ion concentrations for two types of digested sludge, pH=4, mixing speed=150 rpm, biosorbent mass= 1 g l^{-1} , contact time= 2 h.

pH from 2 to 4. Maximum equilibrium biosorption capacities obtained at pH 4 for H_2O_2 treated and untreated sludge were 36.31 and 24.13 mg g^{-1} , respectively. At lower pH values, the biosorption capacity of Pb(II) is low, because large quantities of H^+ compete with metal cations for functional groups on the biosorbent surface. With increasing the pH of solution, the surface charge of the dried digested sludge become negative and biosorption increases (Norton *et al.* 2004; Gulnaz *et al.* 2005; Xuejiang *et al.* 2006; Kumar Naiya *et al.* 2009).

Kinetic studies

Pseudo-first order, pseudo-second order and saturation (mixed-order) model were used to correlate the experimental data (Eqs. 5, 6 and 7). Experimental data were plotted in form of $\log(q_e - q)$ against *time* in Figure 4 to test the validity of the pseudo-first order model and were plotted in form of t/q versus *time* to test the validity of the pseudo-second order kinetic model in Figure 5. Also in Figure 6 experimental data were plotted in form of $1/t \ln(C_0/C_t)$ against $(C_0 - C_t)/t$ to test the validity of the mixed-order model.

Correlation coefficients of the pseudo-first, pseudo-second and saturation (mixed-order) order models were shown

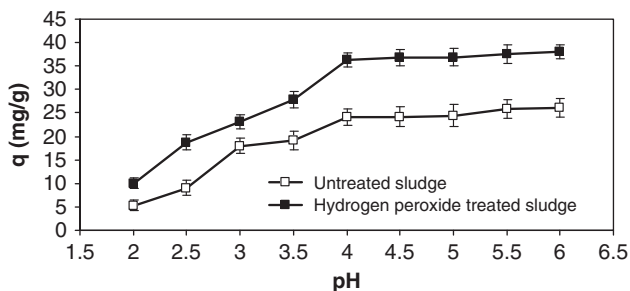


Figure 3 | Variations of biosorbed Pb(II) ion concentrations versus pH of solution for two types of digested sludge, mixing speed=150 rpm, biosorbent mass= 1 g l^{-1} , contact time= 2 h.

in Table 1. According to Table 1 the pseudo-second order model was found to be slightly suitable than pseudo-first order model for Pb(II) biosorption onto both of biosorbents

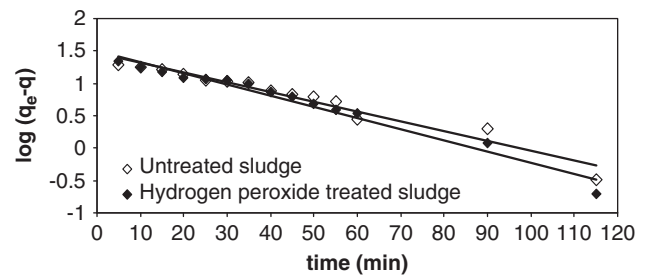


Figure 4 | Pseudo-first order kinetic of Pb(II) biosorption onto two types of digested sludge, pH=4, mixing speed=150 rpm, biosorbent mass= 1 g l^{-1} .

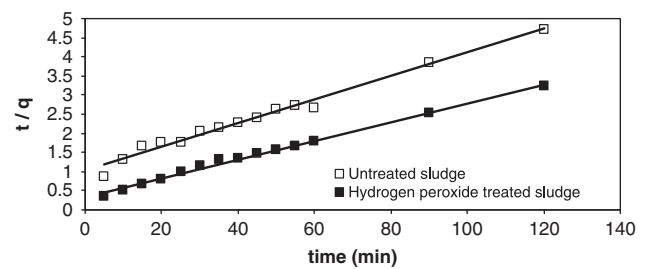


Figure 5 | Pseudo-second order kinetic model of Pb(II) biosorption onto both of digested sludge, pH=4, mixing speed=150 rpm, biosorbent mass= 1 g l^{-1} .

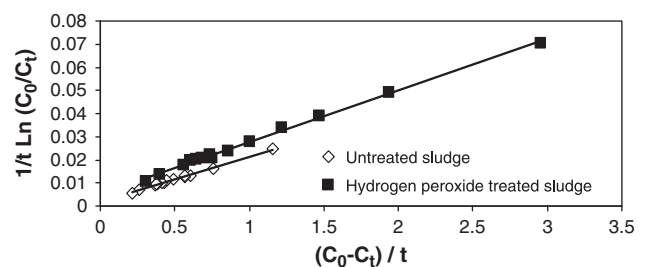


Figure 6 | Saturation (mixed-order) kinetic model of Pb(II) biosorption onto two types of digested sludge, pH=4, mixing speed=150 rpm, biosorbent mass= 1 g l^{-1} .

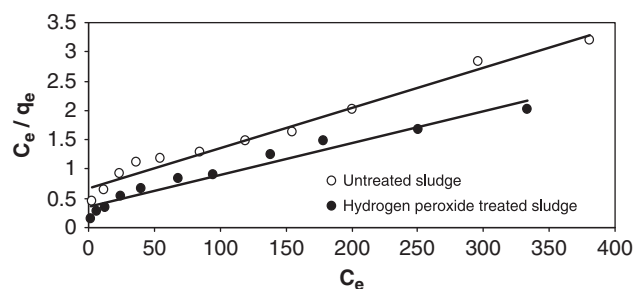
Table 1 | Kinetic parameters for biosorption of Pb (II) ion onto two types of digested sludge

Type of kinetic model	Type of aerobic digested sludge	
	Untreated sludge	H ₂ O ₂ treated sludge
Pseudo-first order model		
R ²	0.954	0.969
k _{1,ad} (min ⁻¹)	0.0348	0.0398
q _e (mg g ⁻¹)	29.067	32.122
Pseudo-second order model		
R ²	0.983	0.994
K _{2,ad} (g mg ⁻¹ min ⁻¹)	0.000946	0.001828
q _e (mg g ⁻¹)	32.258	40.650
Mixed-order model		
R ²	0.996	0.997

because of larger correlation coefficient. If metal biosorption is controlled by diffusion through a boundary layer, the kinetics fits to the pseudo-first order model. The variation in adsorption rate must be equivalent to the first capability of metal ion concentration for complete surface biosorption. However, the relationship between initial metal ion concentrations and biosorption rate will not be linear when pore diffusion limits the biosorption process. Biosorption involves various mechanisms: electrostatic and chemical interaction between functional groups and metal ions; Therefore, it is more suitable to apply the pseudo-second order model that fits most biosorption processes (El Nembr *et al.* 2009; Mata *et al.* 2009). In chemical sorption, the pseudo-second order model is superior to pseudo-first order model because it considers the interaction of adsorbent-adsorbate by way of their valency forces (Febrianto *et al.* 2009). Also, similar results were reported by Xuejiang *et al.* (2006) and Kumar Naiya *et al.* (2009) for biosorption of Pb(II) ions.

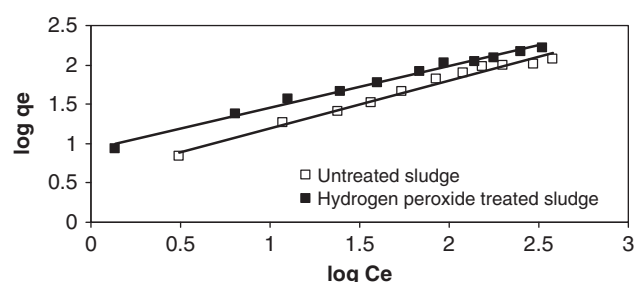
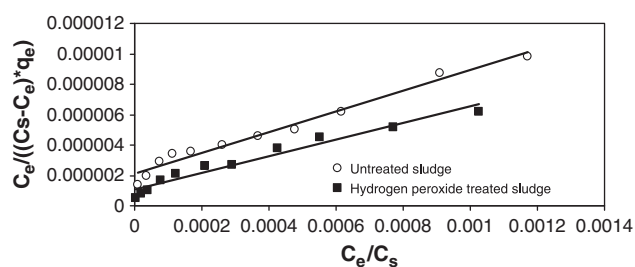
Adsorption isotherm studies

The parameters obtained from the different isotherm equations provide important information on the adsorption mechanisms and the surface properties and affinity of the adsorbent (El Nembr *et al.* 2009). For evaluation of isotherm models, concentration of Pb(II) was varied between 10–500 mg l⁻¹. The Langmuir, Freundlich, Freundlich-langmuir and BET equations (Eqs.1, 2, 3 and 4) were used

**Figure 7** | Langmuir isotherm plot of the Pb(II) biosorption onto two types of digested sludge, pH=4, mixing speed = 150 rpm, biosorbent mass = 1 g l⁻¹, contact time = 2 h.

to model adsorbed metal ions on the biosorbents and residual metal ions in solution (Aksu *et al.* 2002). The adsorption isotherms were studied for two types of digested sludge. In Figure 7, Figure 8, Figure 9 and Figure 10 were presented a plot of linear Langmuir equation as C_e/q_e versus C_e , linear Freundlich equation as $\log q_e$ versus $\log C_e$, linear BET equation as $C_e/((C_s - C_e) \cdot q_e)$ versus C_e/C_s and linear Freundlich-langmuir equation as $\log(1/q_e - 1/q_m)$ versus $\log(1/C_e)$, respectively. The Langmuir isotherm model was chosen for assessment of the maximum adsorption capacity (q_m) matching to complete monolayer coverage on the adsorbent surface.

The values of isotherm constants and maximum biosorption capacity (q_{max}) were given in Table 2. The maximum

**Figure 8** | Freundlich isotherm plot of the Pb(II) biosorption onto two types of digested sludge, pH=4, mixing speed = 150 rpm, biosorbent mass = 1 g l⁻¹, contact time = 2 h.**Figure 9** | BET isotherm plot of the Pb(II) biosorption onto two types of digested sludge, pH=4, mixing speed = 150 rpm, biosorbent mass = 1 g l⁻¹, contact time = 2 h.

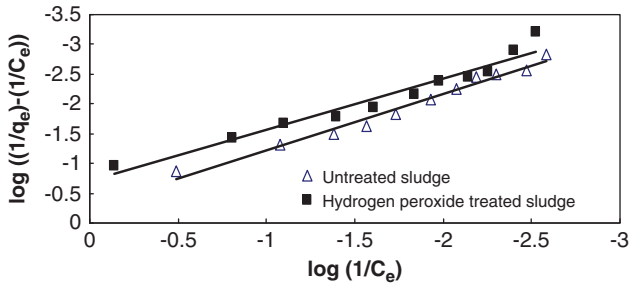


Figure 10 | Freundlich-Langmuir isotherm plot of the Pb(II) biosorption onto two types of digested sludge, pH=4, mixing speed=150 rpm, biosorbent mass=1 g⁻¹, contact time=2 h.

biosorption capacity, q_{max} , were determined as 185.19 and 144.93 mg g⁻¹ for Pb(II) removal with H₂O₂ treated and untreated digested sludge, respectively. Therefore, it can be concluded that pretreatment of dried digested sludge by H₂O₂ enhances Pb(II) biosorption capacity. On the other hand, suitable chemical pretreatment of the biomass demonstrated positive effects on capacity of biosorbent for metal ion biosorption (Liu *et al.* 2004). The H₂O₂ treated digested

sludge was found to be superior to the other waste biomass such as dried activated sludge, tea waste, rose waste, distillery sludge and pre-treated arca shell biomass yielding higher biosorption capacity as q_{max} for Pb(II) biosorption (Xuejiang *et al.* 2006; Febrianto *et al.* 2009; Kumar Naiya *et al.* 2009). Specially, high biosorption capacity of digested sludge contrasted to waste sludge and dried activated sludge can be explained by concentrated cell wall containing functional groups for Pb(II) uptake in aerobic digested sludge (Metcalf & Eddy 2003). In Table 2 were shown that the Freundlich equation provides slightly suitable than the other models for Pb(II) biosorption onto both of digested sludge, because of high values of the correlation coefficients. The Freundlich isotherm model provides a more realistic description of adsorption by organic materials because it gives an interpretation for different binding sites (Aksu *et al.* 2002). In agreement to this study, Jalali *et al.* (2002) demonstrated that Pb(II) biosorption onto marine algal biomass was fitted by Freundlich model. Also, same result for Pb(II) biosorption onto rice husk ash was reported by Kumar Naiya *et al.* (2009). Although, Xuejiang *et al.* (2006) showed the suitability of both Langmuir and Freundlich models for Pb(II) biosorption onto dried activated sludge. Essential characteristic of Langmuir isotherm can be expressed in term of equilibrium parameter, R_L , which is explained by below equation:

$$R_L = \frac{1}{1 + KC_e}$$

According to the value of R_L the isotherm model may be interpreted as follows (Gulnaz *et al.* 2005; Doğan *et al.* 2009):

Value of R_L	Type of adsorption
$R_L > 1$	Unfavorable
$R_L = 1$	Linear
$0 < R_L < 1$	Favorable
$R_L = 0$	Irreversible

The values of R_L given in Table 2 show that the biosorption of Pb(II) ions onto both of digested sludge is favorable. Also, according to BET isotherm model, the constant of energy (B) between the Pb(II) ions and the adsorbent surface obtained 5401 and 3401 for H₂O₂ treated and untreated digested sludge, respectively. This result demonstrated that the H₂O₂ treated digested sludge is more effective than untreated digested sludge for Pb(II) biosorption.

Table 2 | Isotherm parameters for biosorption of Pd (II) ion onto two types of digested sludge

Type of isotherm model	Type of aerobic digested sludge	
	Untreated sludge	H ₂ O ₂ treated sludge
Langmuir isotherm		
R^2	0.977	0.958
q_{max}	144.93	185.19
K	0.01	0.015
R_L	0.21–0.97	0.17–0.98
Freundlich isotherm		
R^2	0.983	0.990
K_f	3.86	8.48
n	1.65	1.9
Freundlich-Langmuir isotherm		
R^2	0.981	0.951
BET isotherm		
R^2	0.977	0.959
Q	147.016	185.151
B	3401	5401

CONCLUSIONS

The capability of using H₂O₂ treated and untreated digested sludge for biosorption of Pb(II) was examined, including pH variations, effect of initial Pb(II) ion concentrations, kinetic and isotherm studies. The equilibrium time for biosorption of Pb(II) onto two types of digested sludge was achieved within 2 h of contact time. The equilibrium adsorption capacity increased with increasing of initial metal ion concentrations and pH for both of digested sludge. Pseudo-second order kinetic model correlated the data better than the Pseudo-first order model for biosorption of Pb(II) ions onto both of digested sludge. Also, among isotherm models the Freundlich isotherm was found to fit the experimental data better than the other models. Hydrogen peroxide treated digested sludge was found to be more suitable than untreated digested sludge for Pb(II) biosorption that yielding higher biosorption capacity. This study indicated the suitability of H₂O₂ treated digested sludge for removing and recovery of Pb(II) from industrial wastewater effluent.

ACKNOWLEDGEMENTS

The authors acknowledge the support of Iran National Committee (National Water and Wastewater Engineering Co.).

REFERENCES

- Aksu, Z. 2001 Biosorption of reactive dyes by dried activated sludge: equilibrium and kinetic modeling. *Biochem. Eng. J.* **7**(1), 79–84.
- Aksu, Z., Acikel, U., Kabasakal, E. & Tezer, S. 2002 Equilibrium modeling of individual and simultaneous biosorption of chromium(VI) and nickel(II) onto dried activated sludge. *Wat. Res.* **36**(12), 3063–3073.
- Al-Qodah, Z. 2006 Biosorption of heavy metal ions from aqueous solutions by activated sludge. *Desalination* **196**(1–3), 164–176.
- APHA, AWWA, WEF. 1998 *Standard Methods for the Examination of Water and Wastewater*, 20th ed, United Book Press, Baltimore, Maryland.
- Doğan, M., Türkyılmaz, A., Alkan, M. & Demirbaş, Özkan. 2009 Adsorption of copper (II) ions onto sepiolite and electrokinetic properties. *Desalination* **238**(1–3), 257–270.
- El Nemr, A., Abdelwahab, O., El-Sikaily, A. & Khaled, A. 2009 Removal of direct blue-86 from aqueous solution by new activated carbon developed from orange peel. *J. Hazard. Mater.* **161**(1), 102–110.
- Febrianto, J., Natasia Kosasih, A., Sunarso, J., Ju, Y. H. Indraswati, N. & Ismadji, S. 2009 Equilibrium and kinetic studies in adsorption of heavy metals using biosorbent: A summary of recent studies. *J. Hazard. Mater.* **162**(2–3), 616–645.
- Gulnaz, O., Saygideger, S. & Kusvuran, E. 2005 Study of Cu(II) biosorption by dried activated sludge: effect of physico-chemical environment and kinetics study. *J. Hazard. Mater.* **B120**(1–3), 193–200.
- Jalali, H. R., Ghafourian, Y., Asef, S., Davarpanah, J. & Sepehr, S. 2002 Removal and recovery of lead using nonliving biomass of marine algae. *J. Hazard. Mater.* **B92**(3), 253–262.
- Kargi, F. & Cikla, S. 2006 Biosorption of zinc(II) ions onto powdered waste sludge (PWS): Kinetics and isotherms. *Enzym. Microb. Tech.* **38**(5), 705–710.
- Kumar Naiya, T., Kumar Bhattacharya, A., Mandal, S. & Kumar Das, S. 2009 The sorption of lead (II) ions on rice husk ash. *J. Hazard. Mater.* **163**(2–3), 1254–1264.
- Liu, H. L., Chen, B. Y., Lan, Y. W. & Chen, Y. C. 2004 Biosorption of Zn(II) and Cu(II) by the indigenous *Thiobacillus thiooxidans*. *Chem. Eng. J.* **97**(2–3), 95–201.
- Loukidou, M. X., Zouboulis, A. I., Karapantsios, T. D. & Matis, K. A. 2004 Equilibrium and kinetic modeling of chromium(VI) biosorption by *Aeromonas caviae*. *Colloid Surface, A: Physicochem. Eng. Aspects* **242**(1–3), 93–104.
- Mata, Y. N., Blázquez, M. L., Ballester, A., González, F. & Muñoz, J. A. 2009 Biosorption of cadmium, lead and copper with calcium alginate xerogels and immobilized *Fucus vesiculosus*. *J. Hazard. Mater.* **163**(2–3), 555–562.
- Metcalfe & Eddy. 2003 *Wastewater Engineering: Treatment and Reuse*, 4th ed. Tata McGraw-Hill Publishing Company Limited, New Delhi, India.
- Norton, L., Baskaran, K. & McKenzie, T. 2004 Biosorption of zinc from aqueous solutions using biosolids. *Adv. Environ. Res.* **8**(3–4), 629–635.
- Tokcaer, E. & Yetis, U. 2006 Pb(II) biosorption using anaerobically digested sludge. *J. Hazard. Mater.* **B137**(3), 1674–1680.
- Utigikara, V., Chena, B., Tabaka, H. H., Bishopa, D. F. & Govind R. 2000 Treatment of acid mine drainage: I. Equilibrium biosorption of zinc and copper on non-viable activated sludge. *International Biodeterioration & Biodegradation* **46**(1), 19–28.
- Wang, Y., Mu, Y., Zhao, Q. & Yu, H. 2006 Kinetics and thermodynamics of dye biosorption by anaerobic sludge. *Separ. Purif. Tech.* **50**(1), 1–7.
- Xuejiang, W., Ling, C., Siqing, X., Jianfu, Z., Chovelon, J. M. & Renault, N. J. 2006 Biosorption of Cu(II) and Pb(II) from aqueous solutions by dried activated sludge. *Miner. Eng.* **19**(9), 968–971.
- Yuncu, B., Dilek Sanin, F. & Yetis, U. 2006 An investigation of heavy metal biosorption in relation to C/N ratio of activated sludge. *J. Hazard. Mater.* **B137**(2), 990–997.
- Yunus Pamukoglu, M. & Kargi, F. 2006 Removal of copper(II) ions from aqueous medium by biosorption onto powdered waste sludge. *Process Biochem.* **41**(5), 1047–1054.