Removal of lead from aqueous solutions by low cost and waste biosorbents (lemon, bean and artichoke shells)

Feyza Ergüvenerler, Şerif Targan and Vedia Nüket Tirtom

ABSTRACT

Simple, fast, effective, low cost and waste biosorbents, lemon, bean and artichoke shells, were used to remove lead (II) ions from aqueous solution. The influence of pH, contact time, temperature and lead (II) concentration of the removal process was investigated. The sufficient contact time was deemed 10 minutes for bean and artichoke shells and 60 minutes for lemon shells for Pb(II) ions. The thermodynamic parameters, such as standard free energy (ΔG), standard enthalpy (ΔH), and standard entropy (ΔS) of the adsorption process were calculated as −5.6786, −5.5758, −3.1488 kJmol^{-1} for ΔG, −7.2791, −20.285, −9.5561 kJ mol^{-1} for ΔH, −0.00545, −0.05017, −0.02185 kJ mol^{-1} K^{-1} for ΔS, respectively, for lemon, artichoke and bean shells. Maximum adsorption capacities of lead (II) were observed as 61.30 mg g^{-1}, 88.5 mg g^{-1} and 62.81 mg g^{-1}, respectively, for lemon, bean and artichoke shells according to the Freundlich isotherm model at 20 °C. Scanning electron microscope (SEM) and energy-dispersive X-ray detector (EDX) were used to characterize the surface morphology of the adsorbents. Consequently, Pb(II) removal using lemon, bean and artichoke shells would be an effective method for the economic treatment of wastewater.

Key words | adsorption, artichoke shell, bean shell, lead, lemon shell, low cost adsorbents

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INTRODUCTION

Water contamination that is caused by heavy metal leads to serious environmental problems and it has lethal effects on living organisms. Even if lead (II) in particular is found in low amounts in the environment, it has negative effects on living organisms and, if it is above a certain degree, it shows a toxic effect. Heavy metal ions such as Pb(II) are toxic and carcinogenic at relatively low concentrations (Tirtom *et al.* 2012). Chronic exposure to high amounts of lead can result in various and considerable damages to systems of the body, damage to the kidneys, liver and reproductive system, basic cellular processes and brain functions. Moreover, high blood pressure, anemia, insomnia, headache, dizziness, irritability, weakness of muscles, hallucination and renal damage, lead poisoning, coma and death can be considered among the most substantial consequences (Malakootian *et al.* 2006; Fenglian & Wang 2011). Before being released as waste to the environment, the removal of the metal ions is significant. Among the many methods available to remove heavy metals from wastewater, the most common ones are chemical precipitation, ion-exchange, filtration, electrochemical treatment, adsorption and reverse osmosis. Adsorption is recognized as an effective and economic method for heavy metal wastewater treatment. In addition, the adsorption is sometimes reversible, the adsorbents can be regenerated by proper desorption, and they do not result in the formation of harmful substances (Dabrowski 2001; Crini 2006; Doyurum and Çelik, 2006; Gülbaş *et al.* 2012). According to recent studies, the usage of low cost and easily available biosorbents with high removal capacity for heavy metal ions is seen as more convenient in terms of providing a contribution to the environment (Crini 2005; Malakootian *et al.* 2009). In light of the above, waste biosorbents have emerged as an economic and eco-friendly option. Agricultural wastes, natural substances, industrial byproducts and wastes have been studied as adsorbents for heavy metal wastewater treatment

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(Ansari *et al.* 1999; Mohan & Singh 2002; Yoshihiro *et al.* 2005). Various different adsorbents and biosorbents can be employed for the treatment of wastewater laden with heavy metal (Bhattacharyya & Gupta 2008; Fenglian & Wang 2011). In the literature the adsorption efficiency of rice husk, maize cobs and sawdust for the removal of Pb(II) from aqueous systems is examined (Abdel-Ghani *et al.* 2007). Different forms of inexpensive, non-living plant material such as potato peels (Aman *et al.* 2008; Kaczala *et al.* 2009), eggshell (Jai *et al.* 2007), coffee husks (Oliveira *et al.* 2008), seed shells (Amudaa *et al.* 2009), black gram husk (Saeed *et al.* 2005) and sugar-beet pectin gels (Mata *et al.* 2009), sugarcane bagasse (Kausar *et al.* 2016), fungal dead biomass composite with bentonite (Rashid *et al.* 2016), vigna radiata biomass (Naeema *et al.* 2017), peanut husk (Kausar *et al.* 2018), and so on, have been widely investigated as potential biosorbents for heavy metals. In accordance with many natural adsorbents made up to now, the adsorption capacity of our adsorbents is quite high. In addition, our adsorbents form too much waste. It is very economical to use the materials found in nature so that they can remove heavy metals from water.

In this study, bean, lemon and artichoke shells were used as natural biosorbents in order to removal Pb(II) from aqueous solution. In the first process of the studies, the effect of optimum contact time on the capacity of metal adsorption was determined for the natural biosorbents.

Next, the effects of the concentration of Pb ions, pH, and temperature on the capacity of metal adsorption of natural biosorbents were determined. Characterization of the surface morphology of the biosorbents was performed on both adsorbents before and after lead adsorption.

MATERIALS AND METHODS

Materials

Three different biosorbents, lemon, bean and artichoke shells, were used in order to examine the removal of lead (II) from aqueous solutions. All reagents used throughout this study were analytical-reagent grade. De-ionized water was used for all reagent solutions. $Pb(NO_3)_2$ (99.5–100.2%), HCl, Tris, CH_3COOH, $NaCH_3COO{\cdot}3H_2O$, NH_3, and NH_4Cl were purchased from Merck.

Instruments

Lead concentration measurements were carried out using a Varian 220 FS atomic absorption spectrophotometer (AAS). An atomic absorption spectrophotometer equipped with a lead hollow cathode lamp at the wavelength of 193.7 nm was used for the determination of lead in sample solutions. The pH of the solution was measured with a Hanna P211 microprocessor pH-meter using a combined glass electrode. The shaking experiments were carried out in a Labart SH-5 thermostated electronic shaker and drying was carried out in a Nüve EN 400 drying oven. Surface morphology of samples was determined by Philips (FEI) XL30-SFEG Scanning Electron Microscope.

Method

Stock solution (1000 mg L^{-1}) of Pb(II) was prepared by using ultrapure grade (99.5–100.2)%) $Pb(NO_3)_2\ 4H_2O$. The stock solution was then diluted to give standard solutions of appropriate concentration.

Preparation of lemon, bean and artichoke shells

Lemon, bean and artichoke shells were sieved with a grinding mill to obtain 63 μm particle size and used in the adsorption studies. The biosorbents were used without any chemical pre-treatment. The samples were washed and air-dried and then kept in desiccators.

Adsorption experiments

Adsorption experiments were carried out by batch technique. 0.50 ± 0.0004 g of each biosorbent was put in a beaker containing 25 mL of 20 mg L^{-1} lead (II) solutions. The shaking was carried out in a thermostated electronic shaker under constant stirring at 160 rpm. After decantation, the concentration of lead (II) was analyzed by AAS at 193.7 nm by acetylene/air flame method. The effect of contact time was studied between 5 and 240 minutes and the initial metal concentration was fixed at 20 mgL^{-1}.

The effect of pH on the adsorption of lead (II) ions was studied in a pH range of 3.0–11.0. The pH of the initial 25 mL solution of 20 mg L^{-1} was adjusted to the required pH value using appropriate buffers. For this purpose, the following buffer solutions were used: 0.1 M acetic acid/sodium acetate (pH 4.0–6.0), 0.1 M Tris–HCl solution (pH 7.0–9.0) and 0.2 M ammonia/ammonium solution (pH 10.0–11.0). The study of influence of different temperatures was conducted over a range of 293–313 K under the optimum agitation period. Different concentrations of lead solution over the range of 5–6000 mg L^{-1} were studied under the optimum pH, temperature and agitation period as had been determined from the previous step. In order to obtain the sorption capacity, the amount of ions adsorbed per unit mass of adsorbent (qe in milligrams of metal ions per gram of biosorbent) was evaluated using the following expression (1):

$$q_e = \frac{((C_o - C_e) \times \mathrm{V})}{\mathrm{m}} \quad (1)$$

where q_e is the amount (mg g^{-1}) of metal ions adsorbed by the biosorbent, and C_o and C_e are the lead (II) concentrations (mg L^{-1}) in the solution initially and after adsorption. V is the volume (L) of the solution and m is the mass (g) of biosorbent used.

Percentage of adsorption was calculated according to Equation (2):

$$\mathrm{A\%} = \frac{\text{Amount of adsorbed metal ions}}{\text{Amount of initial metal ions}} \times 100 \quad (2)$$

Thermodynamics experiments

The effect of thermodynamics was studied between 293–313 K and using the initial 25 mL lead (II) solution of 20 mg L^{-1}. To investigate the controlling mechanism of the adsorption processes, the temperature-dependent distribution coefficient was computed as follows:

$$K_d = C_{ad}/C_e \quad (3)$$

where K_d is the equilibrium constant, and C_{Ad} and C_e are equilibrium concentrations (mg L^{-1}) of lead (II) on the beads and in the solution. The adsorption process was also assessed at different temperatures between 10 and 40 °C. Thus the lead (II) adsorption of lemon, artichoke and bean shells is exothermic in nature.

Thermodynamic parameters including the change in free energy (ΔG), enthalpy (ΔH), and entropy (ΔS) were calculated from the following equation:

$$\Delta G^\circ = -RT \ln Kd \quad (4)$$

where R is the universal gas constant (8.314 J/mol K), T is the temperature (K), and Kd (qe/Ce) is the distribution coefficient. The enthalpy (ΔH°) and entropy (ΔS°) parameters were estimated from the following van 't Hoff equation:

$$\ln Kd = \Delta S^\circ/R - \Delta H^\circ/RT \quad (5)$$

Desorption experiments

For desorption studies, 0.1 g of biosorbent was loaded with 25 mL of 100 mg L^{-1} lead (II) solution. Lead (II) loaded biosorbents were collected, and gently washed with distilled water to remove any unadsorbed lead (II) ions. The sorbents were contaminated with 25 mL of 0.01 M EDTA, 0.1 M HCl and 0.1 M HNO_3 solutions at 25 °C. The amount of desorbed lead (II) was determined as mentioned before.

The desorption ratio is calculated as follows:

$$\text{Desorption ratio} = \text{Amount of metal ions desorbed}/\text{Amount of metal ions adsorbed} \times 100 \quad (6)$$

RESULTS AND DISCUSSION

Effect of contact time on adsorption of lead (II)

The time-dependent behavior of lead (II) adsorption was measured by varying the contact time between the adsorbate and adsorbent in the range of 5–240 min. The percentage removal of lead (II) from aqueous solution as a function of contact time indicates that higher removal of lead (II) was observed in the case of lemon and artichoke shells. After 10 min, 90% lead (II) removal was obtained by artichoke shells and after 60 min, 90% lead (II) removal was obtained by lemon shells. After 10 min, 81% lead (II) removal was obtained by bean shells. The results for the effect of contact time on lead removal by lemon, artichoke and bean shells are presented in Figure 1. Figure 1 shows that uptake of lead (II) by bean and artichoke shells was rapid within the first 10 min of contact time. Equilibrium was reached at around 60 min, and beyond this time no change in adsorption occurred with lemon shells. Thus, the equilibrium time was maintained at 60 min in subsequent adsorption studies with lemon shells. In addition, optimum contact time was chosen as 10 min for bean and artichoke shells. Results of this study are entirely in accordance with the results of Inglezakis et al., which showed that 120 min is a sufficient time for Pb adsorption on bentonite and clinoptilolite (Inglezakis et al. 2007).

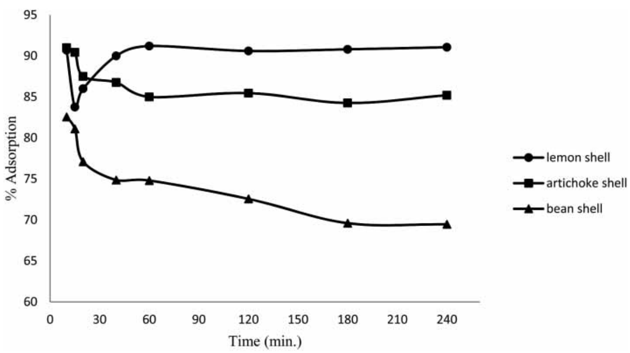

Figure 1 | Adsorption of metal ions by natural lemon, artichoke and bean shells as a function of contact time (m: 0.5 g of biosorbent; Pb(II) solution, 20 mg L^{-1}; V: 25 mL; T:20 °C; stirring speed: 160 rpm).

Effect of pH on adsorption of lead (II)

The pH of the aqueous solution is an important parameter in adsorption processes. The effect of pH is presented in Figure 2. The effect of pH on the adsorption of lead (II) ions was studied at different pH values (3.0 – 9.0) using lemon, artichoke and bean shells (500 mg) at a constant lead (II) ion concentration (20 mg L^{-1}). The effect of pH on adsorption of lead was studied at room temperature by using buffer solutions. As can be seen, lead (II) adsorption was observed due to the increasing positive ions on the adsorbent surface at low pH. At higher pH values, there should be competition between H^+ ions and lead (II) ions to occupy the adsorption sites. Also, as the solution pH value decreases, the adsorbent surface is more positively charged. Therefore, there would be a repulsion force between the surface and adsorbate species. At pH <6, the free ion Pb^{2+} is the predominating species. At pH < 6, positively charged metal ions are attracted to the surface of the biosorbent. The main species at pH 7–10 are $Pb(OH)^+$ and $Pb(OH)_2$ and thus the removal of Pb^{2+} is possibly accomplished by simultaneous precipitation of $Pb(OH)_2$ and sorption of $Pb(OH)^+$. By increasing the solution pH, there was an increase in ligands carrying negative charges, which resulted in higher binding of cations. Although high adsorption was observed at low and high pH, we carried out all studies at the natural water pH without using any buffer solution. Considering these results and the limitations concerning the discharge of acidic and alkaline effluents to the environment, neutral pH is logical and acceptable in the removal process.

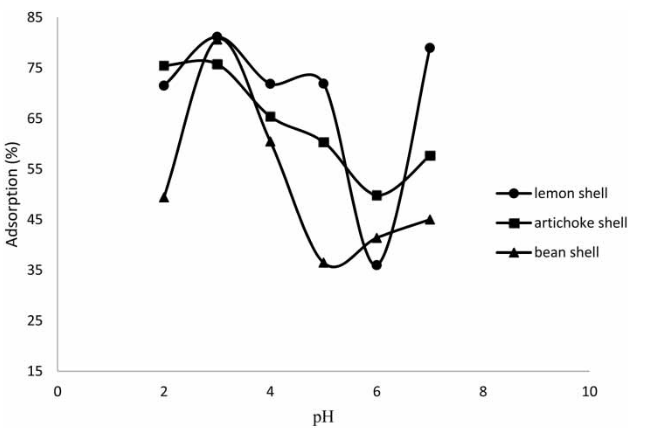

Figure 2 | Effect of pH on adsorption of lead (II) (m: 0.5 g of biosorbent; Pb(II) solution: 20 mg L^{-1}; V:25 mL; T:20 °C; stirring speed: 160 rpm; contact time:10 min for bean and artichoke shells, 60 min for lemon shells).

Effect of temperature on sorption of lead (II)

In this study, the adsorption process was assessed at different temperatures between 20 and 40 °C at an increment of 5 °C units. The contact time and pH were kept constant during the temperature experiments. Figure 3 shows that the temperature had no important effect on the adsorption of lead (II). Maximum adsorption was observed at 20 °C. It can be seen in Figure 3 that over 20 °C adsorption decreased a little. As seen in Figure 3, adsorption capacity decreased a little with an increase in temperature. With increasing temperature, the attractive forces between the lemon-metal ion, artichoke-metal ion and bean shells-metal ion are weakened, and then sorption decreases. The adsorption temperature was chosen as 20 °C.

Thermodynamics and adsorption isotherm models

Thermodynamic values are shown in Table 1. The negative values of ΔS (−0.00545, −0.05017, −0.02185 kJ/molK)

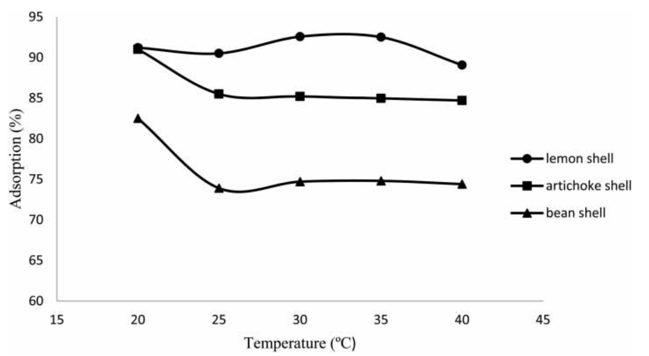

Figure 3 | Effect of temperature on adsorption of lead (II) (m: 0.5 g of biosorbent; Pb(II) solution: 20 mg L^{-1}; V: 25 mL; stirring speed: 160 rpm; contact time: 10 min for bean and artichoke shells, 60 min for lemon shells).

Table 1 | Values of Langmuir, Freundlich constants and thermodynamic parameters for lemon, artichoke and bean shells

	Langmuir model			Freundlich model			Thermodynamic parameters		
Adsorbent	R^2	b	qe	R^2	n	K_F (mg g^{-1})	ΔG (kj mol^{-1})	ΔH (kj mol^{-1})	ΔS (kjmol^{-1})
Lemon shell	0.8674	0.0578	20.618	0.9810	1.6764	0.8317	−5.6786	−7.2791	−0.00545
Artichoke shell	0.9418	0.0035	69.930	0.9094	1.392	0.7051	−5.5758	−20.285	−0.05017
Bean shell	0.7097	0.0032	51.813	0.8876	1.0456	0.1326	−3.1488	−9.5561	−0.02185

suggest decreased randomness during adsorption and reflect the affinity of the lemon, artichoke and bean shells for lead (II) ions. The negative value of ΔG (−5.6786, −5.5758, −3.1488 kJmol^{-1}) shows the adsorption process proceeds spontaneously. The negative value of ΔH indicated that the adsorption process was exothermic in nature.

Adsorption isotherms are used to express the surface properties and affinity of the adsorbent and can also be used to compare the adsorption capacities of the sorbents for pollutants in aqueous solutions. The adsorption isotherm is a functional expression that correlates the amount of solute adsorbed per unit weight of the adsorbent and the concentration of an adsorbate in the bulk solution at a given temperature under equilibrium conditions. The adsorption isotherms are one of the most useful data to understand the mechanism of the adsorption, and the characteristics of isotherms are needed before the interpretation of the kinetics of the adsorption process. Langmuir and Freundlich isotherms are most used to describe the equilibrium sorption of metal ions. The adsorption of lead ions onto lemon shell, artichoke shell and bean shell were studied at 20 °C by varying the lead concentration from 5 to 6000 mg L^{-1} (Figure 4). All other parameters were kept constant. The results in Figure 4 show the adsorption capacity of lemon shell, artichoke shell and bean shell used. The maximum adsorption capacities were found to be 61.3 and 88.5 and 62.81 mg g^{-1}of lemon, bean and artichoke shell, respectively.

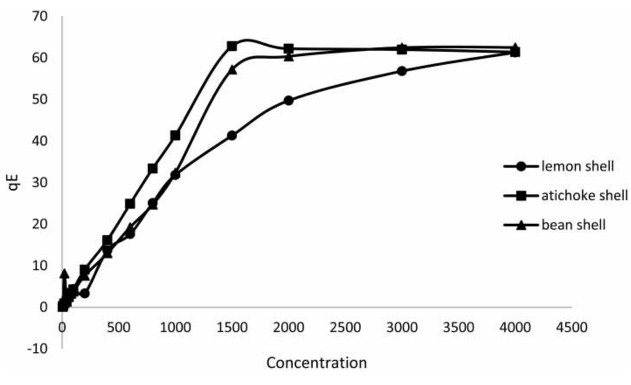

Figure 4 | Effect of lead (II) concentration (lemon shell: ●, artichoke shell: ■, bean shell: ▲) (m: 0.5 g of biosorbent; V: 25 mL; stirring speed: 160 rpm; contact time: 10 min for bean and artichoke shells, 60 min for lemon shells).

The study of equilibrium isotherms is fundamental in supplying the essential information required for the design of the adsorption process. In this investigation, Langmuir and Freundlich isotherm models were used to analyze the equilibrium data by means of biosorbents. The Langmuir adsorption isotherm is applied to equilibrium adsorption assuming monolayer adsorption onto a surface with a finite number of identical sites. It is represented in linear form, where C_e is the equilibrium concentration of the metal (mg L^{-1}) and q_e is the amount of the metal adsorbed (mg) per unit of the adsorbent:

$$C_e/q_e = 1/Q_b + C_e/Q. \tag{7}$$

When C_e/q_e is plotted against C_e, a straight line with a slope of 1/Q and intercept was obtained, which shows that the adsorption of lead (II) followed the Langmuir isotherm model.

According to the results, the Freundlich model was found to describe adsorption more successfully than the Langmuir isotherm in respect to linearity coefficients obtained for both models (lemon, artichoke, bean shell) ($R^2_{Freundlich}$ = 0.9810, 0.9094, 0.8876, $R^2_{Langmuir}$ = 0.8797, 0.0835 and 0.7097) (Figures 5–7).

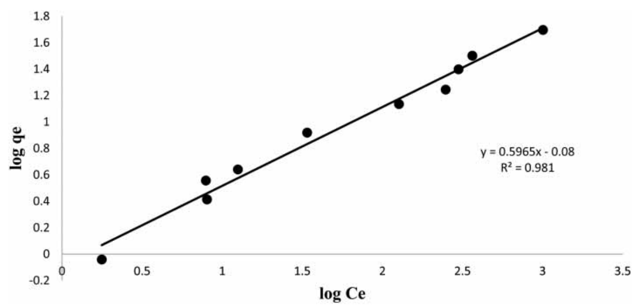

Figure 5 | Freundlich Isotherm of Pb(II) ions' concentration on the Qe (mg/g) by lemon shell.

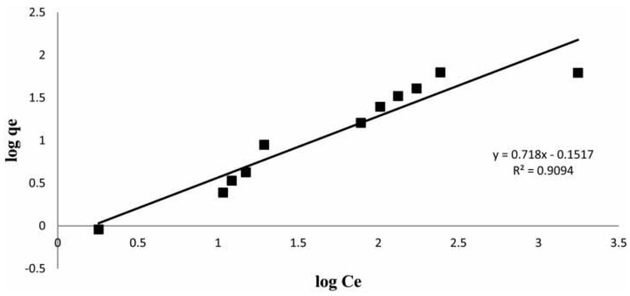

Figure 6 | Freundlich Isotherm of Pb(II) ions' concentration on the Qe (mg/g) by artichoke shell.

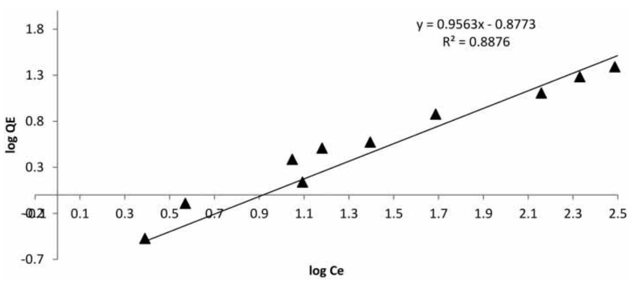

Figure 7 | Freundlich Isotherm of Pb(II) ions' concentration on the Qe (mg/g) by bean shell.

The biosorbents' adsorption behaviors can be described with the Freundlich model adsorption equation as:

$$q = K_F.C^{1/n} \quad \log q = \log K_F + \log C.1/n \tag{8}$$

The Freundlich parameters K_F (mg g^{-1}) and n were calculated from the slope and intercept and are given in Table 1.

As can be seen in Table 2, lemon, bean and artichoke shells even without any chemical pretreatments showed better adsorption capacities for lead compared with conventional adsorbents.

Adsorbent characterization

The scanning electron microscopy of lemon shell, artichoke shell, bean shell and Pb(II)-loaded lemon shell, artichoke shell, and bean shell are shown in Figures 8–10. The surface change in the scanning electron microscope (SEM) micrographs indicated the structural changes in the sorbent before and after Pb(II) treatment. The general morphology of the modified chestnut shell before adsorption could be characterized as rough and folded. It was found that the surface of the Pb(II) loaded chestnut shell was a shiny material.

Table 2 | Comparative adsorption of Pb(II) ions onto various types of natural adsorbents

Type of adsorbent	q_e Pb(II) (mg/g)	Reference
Peat	82.31	Bartczak *et al.* (2018)
Natural *Pinus halepensis* sawdust	13.4	Semerjian (2018)
Banana peel	227.27	Amin *et al.* (2018)
Plum	1.3	Pap *et al.* (2018)
Apricot kernel waste biomass	0.9	Shen *et al.* (2017)
Rice husk biochar	35.0	Shen *et al.* (2017)
Pine wood feedstock biochar	4.9	Wang *et al.* (2015)
Soft wood pellets biochar	8.1	Shen *et al.* (2017)
Bean shell	88.5	This study
Lemon shell	61.30	This study
Artichoke shell	62.81	This study

It was seen that the surface is more uneven after adsorption for Pb(II).

Energy-dispersive X-ray (EDX) results are shown in Figures 11 and 12 of artichoke shell and bean for Pb(II). Since the biosorbents are in the cellulosic structure, C and O are visible, and the adsorbed Pb ions are also found in EDX (Tables 3 and 4). The Ca, K and Mg ions seen in EDX are due to the mineral content of the adsorbents.

Fourier transform infrared (FTIR) spectra are shown in Figure 13 of bean, lemon and artichoke shell and bean, lemon and artichoke shell with Pb(II). The bands at 3539, cm^{-1} are assigned to the stretching vibration of the surface hydroxyl. The major bands for the bean, lemon and artichoke shell can be assigned as follows: 2921 cm^{-1} (CH stretching vibration in CH and CH_2), 1643 cm^{-1} (NH_2 bending vibration), and 1021 cm^{-1} (CO stretching vibration in CONH).

Desorption studies

The desorption process is very important as it allows the metals to be recovered and the adsorbent to be used for large-scale industrial application. (Rashid *et al.* 2016; Godiya *et al.* 2019). Studies have shown that the protons of mineral acids such as HCl, and HNO_3 can displace metals from the sorbents' binding sites (Bux *et al.*, 1995) and that the strong chelating agent EDTA is also an efficient desorbing agent (Njikam & Schiewer, 2012) causing metal desorption by reducing the concentration of metal ions in solution. Percentage desorptions (Equation (6)) of lead (II) ions from the biosorbent are shown in Table 5. Table 5

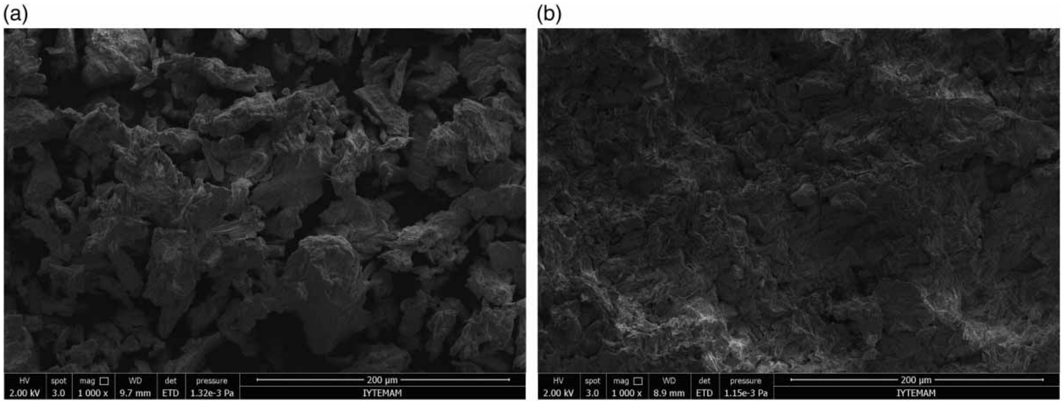

Figure 8 | The SEM analyses of lemon shell and lemon shell with Pb(II). (a) Lemon shell (before adsorption), (b) lemon shell (after Pb(II) adsorption).

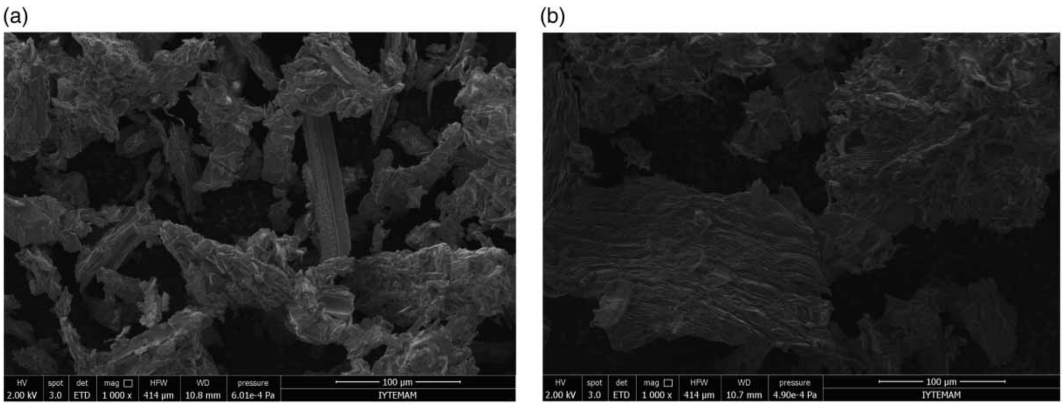

Figure 9 | The SEM analyses of artichoke shell and artichoke shell with Pb(II). (a) Artichoke shell (before adsorption), (b) artichoke shell (after Pb(II) adsorption).

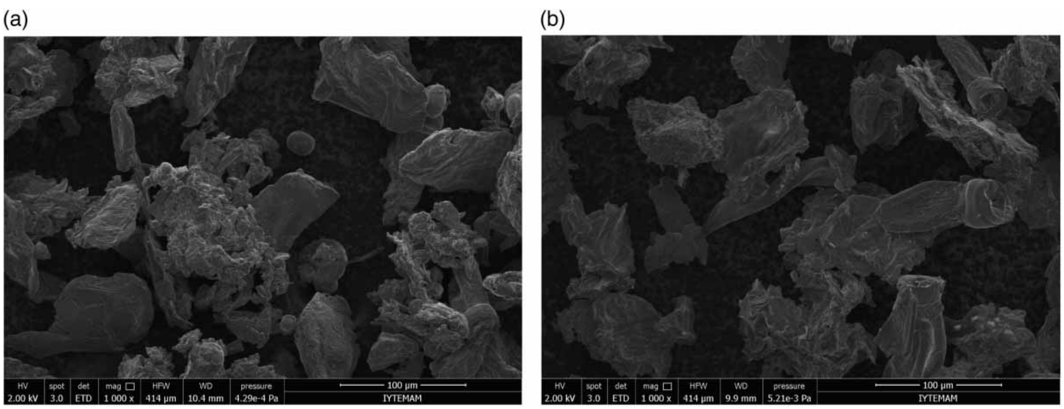

Figure 10 | The SEM analyses of bean shell and bean shell with Pb(II). (a) Bean shell (before adsorption), (b) bean shell (after Pb(II) adsorption).

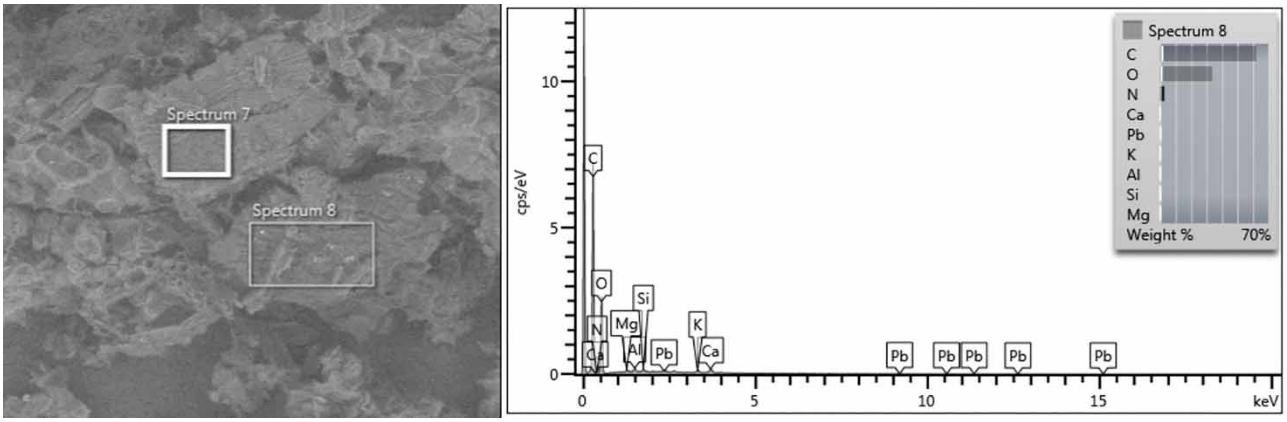

Figure 11 | EDX of artichoke shell for Pb(II).

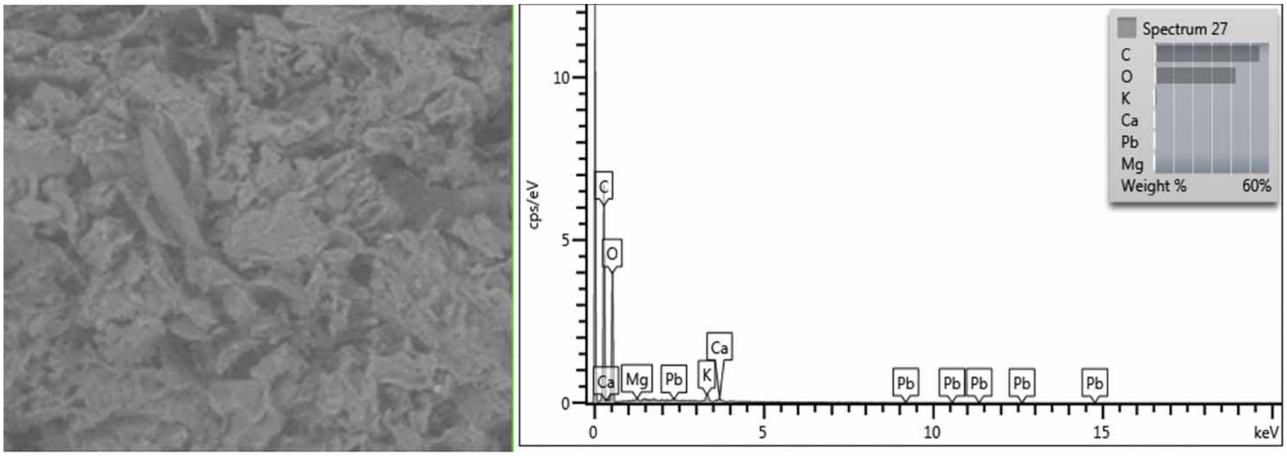

Figure 12 | EDX of bean shell for Pb(II).

Table 3 | EDX of artichoke shell for Pb(II)

Element	Wt%	Atomic %
C	62.12	69.57
N	1.29	1.23
O	33.58	28.24
Mg	0.21	0.11
Al	0.34	0.17
Si	0.25	0.12
K	0.51	0.18
Ca	0.98	0.33
Pb	0.73	0.05
Total:	100.00	100.00

Table 4 | EDX of bean shell for Pb(II)

Element	Wt%	Atomic %
C	54.98	62.74
O	42.56	36.46
Mg	0.23	0.13
K	1.27	0.45
Ca	0.57	0.19
Pb	0.39	0.03
Total:	100.00	100.00

shows the percentage of lead (II) released after treatment with desorbents such as EDTA, HCl and HNO_3. It was

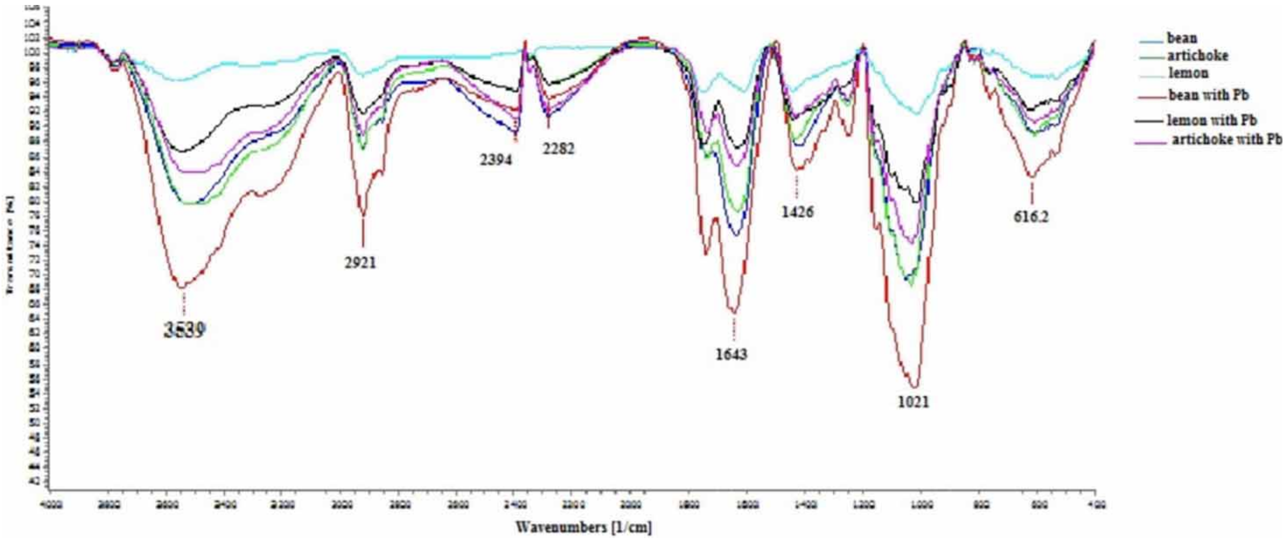

Figure 13 | FTIR spectra of lemon, artichoke and bean shells.

Table 5 | Percentage of desorption of lead (II) from the biosorbents

	Desorption (%)		
Biosorbents	**HCl**	**HNO_3**	**EDTA**
Lemon shell	59.03	37.8	74.02
Bean shell	73.9	54.6	85.3
Artichoke shell	71.7	55.7	93.8

observed that EDTA was a more efficient desorbing agent than HCl and HNO_3 for all three biosorbents. EDTA has a high level of complexing capacity with respect to heavy metals (Zhao *et al.* 2014). EDTA has been widely demonstrated as a chelating agent in washing treatment (Martinez *et al.* 2006). Desorption rates of 74.02% 85.3% and 93.8% obtained from desorption studies of lemon, artichoke and bean biosorbents with EDTA show us that lead ions from these biosorbents can be recovered very successfully and that the biosorbents can be used again.

CONCLUSION

Lead (II) removal using lemon, artichoke and bean shells would be effective methods for the economic treatment of wastewater. Bean shell was the most effective, for which the removal reached 88.5 mg g^{-1} of Pb at room temperature. 61.30 mg g^{-1} and 62.81 mg g^{-1} lead (II) ion capacities were found for lemon and artichoke shells, respectively. The optimum pH for lead removal was found to be 4.5. The adsorption process was exothermic (ΔH°ads <0) and proceeds spontaneously (ΔG° ads <0) for both adsorbents. The Freundlich models achieve good fittings for all biosorbents. This indicates that these materials have a greater capacity, and are most effective, low cost and environmentally friendly adsorbents for the removal of lead (II) from wastewater. The results prove that lead ions can easily be removed with these biosorbents in a very short time.

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