Pb(II) Removal from Aqueous Solution by Cucumissativus (Cucumber) Peel: Kinetic, Equilibrium & Thermodynamic Study

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Abstract *Cucumissativus* peel (CSP), was investigated as a new adsorbent for Pb(II) removal from aqueous solution under several varying conditions such as pH, adsorbent dosage, and contact time. Maximum metal sorption was found to occur at initial pH 5.0. The adsorption capacity of CSP was found to be 28.25 mg/g for initial Pb(II) concentration of 25 mg/l at 25° C. The equilibrium data best fitted to the Langmuir adsorption isotherm model. Batch adsorption models, based on the assumption of the pseudo first-order and pseudo second order mechanism were applied to examine the kinetics of the adsorption. The results showed that kinetic data were followed pseudo second-order model than the pseudo first-order equation. With no loss in the Pb(II) ion removal efficiency, CSP could be regenerated using 1M HNO₃ during repeated sorption–desorption cycles and showed recovery of 93.5% for 25mg/l of Pb(II) ion concentration. Comprehensive characterization parameters using FTIR, and SEM were recorded before and after adsorption to explore the number and position of the functional groups available for Pb(II) binding onto adsorbent and changes in surface morphology of the adsorbent.

Keywords: Cucumis sativus, adsorption, equilibrium, kinetic, sorption-desorption, recovery, FTIR, SEM

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1. Introduction

Heavy metal ions present in the environment especially from the transition series are of foremost concern due to their toxicity to several life forms. Amongst them Lead is a non-essential metal for human consumption and due to its widespread existence in natural systems and the propensity to accumulate as it moves up in the food chain, represent imperative environmental and occupational hazards. Concern over the problem of heavy metal pollution has led to develop alternative technologies for effective removal of pollutants from aqueous effluents explaining the use of several agro waste materials and byproducts of cellulosic origin for sorption of heavy metals [1]. It is evident that low-cost adsorbents have demonstrated outstanding removal capabilities for certain metal ions as compared to activated carbon [2]. On the other hand, conventional methods can be used such as ion exchange, chemical oxidation and chemical precipitation for eradicating heavy metal ions from aqueous solution. However, some disadvantages of these technologies, such as high cost, sensitive operating conditions and production of secondary sludge [3,4]. These methods use huge

amounts of chemicals and at low concentrations of metals, are incompetent [5].

This paper describes the use of a novel adsorbent, dried Cucumber peel (Cucumissativus peel, CSP) for the removal of Pb(II) ions from aqueous solution through batch experiments. Cucumber peel is generated as a residue of the food processing, and has no significant industrial and commercial use. CSP is Fibrous material, mostly composed of cellulose, hemi-cellulose, lignin, and chlorophyll pigments [6]. In our previous study [7], it is also found that it contain carboxyl and hydroxyl functional groups, thus making it a potential adsorbent material for several metals through ion-exchange and/or complexation mechanism. The main objective of this study was to investigate the effects of various parameters such as solution pH, adsorbent dosage, and contact time on the adsorption efficiency of Pb(II) ions on CSP.In most of the batch studies, effect of individual parameter of the adsorption process has been investigated maintaining other parameter constant at unspecified levels [8]. Equilibrium, kinetics and thermodynamic studies were performed to determine potential application of CSP for metal ion removal.

2. Methodology

2.1. Chemicals

All reagents used including Standard Pb(II) 1000mg/l solution were of analytical grade purchased from Merck, India. The experimental stock (1000mg/l) solution was prepared from Lead Nitrate Pb(NO₃)₂ and further dilutions were prepared from this stock solution with the use of deionized distilled water produced by a pure hyper filtration water system (Millipore, Water purification system, USA). For the pH study, pH of the solutions was maintained by using 0.1N HNO₃/0.1N NaOH. Standard lab ware and glassware cleaned with HNO₃ and rinsed with double distilled water (DDW) were used all over. All the solutions were analyzed for Lead on a flame atomic absorption spectrophotometer (AAS; Perkin-Elmer, Analyst 300, USA), using Electrodeless discharge lamp.

2.2. Adsorbent Preparation

CSP was collected in bulk from local market. It was thoroughly rinsed with DDW to remove dust and soluble material and allowed to dry at 100°C for 24 hours. The dried CSP were crushed, ground using a domestic mixer. The ground materials were then sieved to constant particle sizes of +60 to -85 mesh [9] stored in a desiccator for further use. Characterization of CSP including percent ash content, moisture content, particle density, bulk density, and porosity was summarized in Table 1.

Table 1. Physical Characteristics of CSP					
Parameters					
Particle density	0.235				
Bulk density (gml^{-1})	0.127				
Porosity (%)	0.15				
Moisture content (%)	13.5				
Ash content (%)	8.5				

2.3. Desorption and Regeneration

Desorption procedure was followed as described by [10]. A sample volume of 25mL, containing 25 mg/l of Pb(II) ions, was transferred into a beaker; 10mL of buffer solution was added. After a fast shaking, 1 g/l of CSP was added and the mixture was shaken again for 60 min at 160 rpm. The system was filtered with What man filter paper. The filter and constituents were washed with DDW. In order to elute the adsorbed analytes onto CSP, 8–10mL of 1M HNO₃ was used. The final volume was completed to 25 ml with 1M HNO₃. Pb(II) in the final solution were determined by flame atomic absorption spectrometry. The same procedure was applied to the blank solution. In order to reuse CSP for next set of experiment, it was washed with excess of 1M HNO₃ and distilled water, successively.

3. Results and Discussion

3.1. Batch Studies

3.1.1. Effect of pH and Adsorbent Dosage

pH plays a significant role on the sorption of adsorbates on adsorbents. The pH level affects the network of negative charge on the surface of the adsorbent cell walls, as well as the physic chemistry and hydrolysis of the metal ions. Preliminary experiments have been performed to determine the optimum pH value and for this, pH of the solution was varied from 3 ± 0.1 to 8 ± 0.1 . A trend of increasing metal ion binding with increasing pH from 3.0 to 5.0 could be observed that is similar to results of some researcher [11]. Under highly acidic conditions (pH \approx 3.0) the metal sorption efficiency was very small, and this lower efficiency is due to the presence of high concentration of H⁺ ions/hydronium ions (H₃O⁺) and also partly because of the chemical speciation of Pb(II) [12]. Besides, at higher pH value, fewer H⁺ ions exist, and consequently, Pb(II) ions have a better chance to bind free binding sites. Later, when the pH enters basic conditions beyond pH 8 (Eq.1&2), lead hydroxide formation takes place due to the dissolution of Pb(OH)₂ and as a result, the adsorption rate decreases.

$$Pb^{2+} + H_2 O \rightleftharpoons Pb (OH)^+ + H^+$$
(1)

$$Pb^{2+} + 2H_2O \rightleftharpoons Pb(OH)_2 + 2H^+$$
(2)

As shown in Figure 1, results revealed that the optimum biosorption pH value for Pb(II) removal is pH 5.0. After pH 5.0, a plateau was obtained with slight decrease in Pb(II) sorption.



Figure 1. Effect of pH on Pb(II) sorption by CSP at 25°C (Condition: 25mg/l Pb(II), 160 rpm, 1g/l Adsorbent dosage, 60 min)

3.1.2. Effect of Adsorbent Dosage



Figure 2. Effect of adsorbent dosage for Pb(II) sorption by CSP at 25°C (Condition: 25mg/l Pb(II), 160 rpm, 60 min)

The sorption of Pb(II) with different adsorbent dosage (0.5–10.0 g/l) was studied keeping other experimental condition constant,Pb(II) concentration(25 mg/l), stirring speed (160 rpm), pH (5.0) and contact time (60 min). The outcome indicates (Figure 2) that increases in adsorbent dosage resulted in a higher removal of Pb(II). This may be due to the increase in the number of adsorption sites on surface of CSP. Maximum removal of 87.12% was observed with an adsorbent dosage of 5.0 g/l and beyond this, the removal capacity was lesser, may be attributed to overlying or aggregation of available binding sites [13], ensuing in decrease in total available adsorbent surface area to metal ions and an increase in diffusion path length.

3.1.3. Effect of Contact time

The retention of heavy metals on adsorbent increased with increasing contact time for a fixed concentration of heavy metal and a fixed adsorbent mass [14]. The effect of contact time can be seen in Figure 3 for the adsorption of Pb(II) ions on CSP. The Pb(II) ions sorption increased hastily with time up to 90 min and thereafter shows steady adsorption rate. The uptake of Pb(II) ions was 85.92% at 90 min. This is apparent by the fact that a large number of sites are available for sorption during the initial stage, and few minutes later, the remaining vacant surface sites are hard to be occupied due to repulsive forces between the Pb(II) on the solid and the aqueous phases. According to the results, the equilibrium reached at 90 min and was taken as the optimal contact time for the succeeding experiments to make sure that equilibrium is properly attained.



Figure 3. Effect of contact time on Pb(II) sorption by CSP, at 25°C, (Condition: 25mg/l Pb(II), 160 rpm, 5g/l Adsorbent dosage:)

3.2. Equilibrium Studies

The analysis and design of the process entail the relevant equilibrium sorption, which is the most important informative parameter to understand the adsorption since they indicate how metal ions are partitioned between the adsorbent and liquid phases at equilibrium as a function of metal concentration. When an adsorbent comes into contact with a metal ion solution, the concentration of metal ions on the adsorbent surface will increase until a dynamic equilibrium is reached; at this point, there is a clearly defined distribution of metal ions between the solid and liquid phases [14]. For heavy metal ion concentrations ranged from 5 to 150 mg/l with a fixed adsorbent mass

and pH, the removal decreased from 75.4 to 65.1% while the adsorption density increased from 0.754- 19.622 mg/g (Figure 4). The apparent behavior can be accredited to the increase in the amount of Pb(II) ions to the static number of available active sites on the CSP. Hence, more metal ions were left in solution [15]. This also indicates that, there is some metal concentration that produces the maximum adsorption for a given adsorbent mass, and thereafter, adding more metal cannot increase adsorption because no more sites are available: all are occupied. A progressive decrease in the proportion of covalent interactions and an increase in the proportion of electrostatic interactions at sites with a lower affinity for heavy metals can also be attributed as another reason for decreased percentage removal.



Figure 4. Effect of Initial Pb(II) concentration on sorption process by CSP (Condition: 25°C, 160 rpm, 5g/l Adsorbent dosage, 60 min)

The heavy metal adsorption capacities were calculated by means of least-squares regression using linear expression of Freundlich Isotherm [16] Eq. (3) and Langmuir Isotherm [16] Eq. (4).

$$\log q_e = \log K_F + \frac{1}{n} \log C_e \tag{3}$$

where $C_{\rm e}$ (mg/l) the metal concentration in the aqueous phase; $K_{\rm F}$ and n are the Freundlich coefficients. $K_{\rm F}$ provides an indication of the adsorption capacity and n is related to the intensity of adsorption.

$$\frac{1}{q_{e}} = \frac{1}{q_{m}K_{L}C_{e}} + \frac{1}{q_{m}}$$
(4)

where q_e , q_m are equilibrium adsorption capacity and maximum adsorption capacity, C_o , C_e are initial and equilibrium concentration. The Langmuir constant K_L related to the energy of adsorption. One of the essential characteristics of the Langmuir isotherm is separation factor or dimensionless equilibrium parameter " R_L " as shown in Eq. 5 provides significant information about the nature of adsorption. The value of R_L indicates the type of the Langmuir isotherm [17] to be irreversible (R_L =0), favorable ($0 < R_L < 1$), linear (R_L =1) or unfavorable (R_L >1). The R_L values as shown in Table 2, at different temperatures (298, 308 and 318K) indicates the favorable biosorption.

$$R_{L} = \frac{1}{1 + (1 + K_{L}C_{o})}$$
(5)

The resulting adsorption isotherms parameters for heavy metals used in this study are summarized in Table 2, indicate that the data best fitted to Langmuir isotherm at all three temperatures, which implies the occurrence of monolayer adsorption onto homogeneous surface for the experimental conditions used. With respect to the coefficients of the Langmuir model, K_L increases with the temperature, indicating that the adsorption capacity increases with the temperature and the higher values of K_L confirm the stronger binding affinity [5] of dried CSP to Pb(II) ions. The q_m values compared to maximum

adsorption capacity obtained by some other researcher are quite higher [18-23]. The adsorption capacity is quite high with the finding of our previous studies for removal of Cd(II) ion using *Cucumissativus* (q_{max} , 3.597 mg/g) [7] and NaOH modified *Desmostachyabipinnata* Leaves(q_{max} , 19.84 mg/g) & *Bambusaarundinacea* Leaves (q_{max} , 19.71 mg/g) [24] at room temperature i.e. 298K.A little difference in adsorption capacity was observed i.e. at temp 298 K compared to 308K & 318K. This means that any temperature can be used for removing Pb(II) effectively from aqueous solutions.

Temp		Freundlich Isotherm			Langmuir Isotherm			
	\mathbf{R}^2	Ν	$K_F(mg^{1-1/n}g^{-1}l^{1/n})$	\mathbf{R}^2	$q_m(mgg^{-1})$	$K_L(l mg^{-1})$	\mathbf{R}_{L}	
298K	0.963	1.31	1.34	0.987	28.25	0.049	0.312	
308K	0.964	1.35	1.57	0.985	27.40	0.060	0.266	
318K	0.961	1.37	1.67	0.986	26.74	0.067	0.273	

Table 2. Equilibrium Parameters for the adsorption of Pb(II) on CSP at different temperatures

3.3. Thermodynamic Studies

Analysis of thermodynamics of equilibrium sorption data can give noteworthy information about sorption process. Thermodynamic parameter can be determined from following equations [25,26].

$$\Delta G^{\circ} = -RT \ln K_{c}$$
 (6)

$$\Delta G^{\circ} = \Delta H^{\circ} - T \Delta S^{\circ} \tag{7}$$

where K_c is the distribution constant, obtained by multiplying Langmuir constant K_L and maximum adsorption capacity $q_m(mg/g)$ [27]. R is the universal gas constant (8.314×10⁻³ kJ/mol/K) and T is the absolute temperature (K). The values of ΔH° and ΔS° were dogged from the slope and the intercept from the plot of ln K_c versus 1/T as shown in Figure 5.



Figure 5. Plot of ln K_c versus 1/T for Pb(II) sorption onto CSP

The enthalpy change (ΔH°) and the entropy change (ΔS°) recorded from the study were shown in Table 3. The negative values of Gibbs free energy (ΔG°) indicate feasibility and the spontaneous nature of Pb(II) sorption. The ΔG° value is more negative with increasing temperature, which suggests that higher temperature makes the adsorption easier. The negative value of ΔH° indicates the exothermic nature of the biosorption of Pb(II) onto CSP [28]. The positive ΔS° value shows increase in

randomness, irreversible process and the affinity of biosorbent at the solid aqueous interface during the adsorption process. In addition, the positive value of ΔS° suggests a few structural changes in the adsorbent, favored complexion and sorption constancy [29,30]. The thermodynamic parameters indicated favored biosorption for the removal of Pb(II) ions by CSP.

 Table 3. Thermodynamic parameters at different temperatures

	Thermodynamic Parameters						
Тетр	ΔG° (kJmol ⁻¹)	ΔH° (kJ mol ⁻¹)	ΔS ⁰ (J mol ⁻¹ K ⁻¹)				
298K	-0.774	-1255	4.54				
308K	-1.230						
318K	-1.427						

3.4. Biosorption Kinetics and Mechanism

A further kinetic investigation with pseudo-first order, pseudo-second-order and intra-particle diffusion kinetic models have been used to investigate the Pb(II) ion sorption mechanism onto CSP and the mechanism of rate-controlling steps. The integral form of the pseudo-first-order kinetic model [31] is generally expressed as follows:

$$\log(q_e - q_t) = \log q_e - K_{1ad}t$$
(8)

where, q_e and q_t are the adsorption capacities (mg/g) at equilibrium and time t (min), respectively. The pseudo-first-order rate constant K_{1ad} (min⁻¹) was determined experimentally by plotting log (q_e - q_t) versus t.

The pseudo-second-order kinetic model, proposed by Ho and McKay [32], is based on the assumption that the adsorption follows chemisorption. The linear form can be written as:

$$\frac{t}{q_{t}} = \frac{1}{K_{2ad}q_{e}^{2}} + \frac{1}{q_{e}}t$$
(9)

where, q_e (mg/g), q_t (mg/g) are the adsorption capacity at equilibrium and time t(min), whereas, K_{2ad} (g/mg/min) is the rate constant of adsorption. By plotting a curve of t/q_t against t, q_e and K_{2ad} can be evaluated. The pseudo first

and second order kinetic parameters were summarized in the Table 4.

The evaluation of rate controlling steps such as chemical reaction and mass transport is very advantageous to understand the mechanism involve in the adsorption phenomenon. The overall adsorption process can be divided into four steps [33]:

Ist **Step:** The transport of metal ion from the bulk to the boundary layer takes place.

IInd Step: The film diffusion, i.e. transport of metal ions from the boundary layer to the external surface of the adsorbent.

IIIrd Step: Transfer of ions from the surface to the intra-particular spaces present in adsorbent as active sites and this step is known as particle diffusion.

IVth & Final Step: Metal ions interaction at the available adsorption sites on the internal surfaces of the adsorbent.

The second and third steps are slow, therefore, due to their slow rate, the rate controlling steps mainly depend on either film diffusion or particle diffusion.

Therefore, to provide insightful description of mechanism involved in biosorption process, the intraparticle diffusion model [34], is of major consideration. The Eq.10 is a common representation of intra-particle diffusion model, where the intercept is associated with the mass transfer across the boundary layer and the expected value of the exponent is 0.5.

$$q_{t} = K_{i}t^{0.5} + I \tag{10}$$

where $q_t (mg/g)$ is the adsorbed metal amount and K_i is the intra- particle diffusion rate constant $(mg/g/min^{1/2})$. According to this model, the plot of uptake (q) versus the square root of time should be linear if intra-particle diffusion is involved in the adsorption process and if these lines pass through the origin then intra-particle diffusion is the sole rate-controlling step. As shown in the Figure 6, the first sharp section signifies the external surface

adsorption and shows that, in the beginning higher rate of metal removal is due to the immediate availability of large surface area and active adsorption sites. The second portion represents the gradual adsorption, where ratecontrolling step is the intra-particle diffusion. The intraparticle diffusion is not the only rate controlling step for the adsorption of Pb(II) ions onto CSP, which is confirmed by the deviation of plot from the origin.

All three kinetic models applied at different temperatures, confirms the applicability of the Pseudo second-order kinetic model, with a straight line obtained through a plot of t/q_t against t with a higher correlation coefficient (Table 4) compared to Pseudo first order and intra particle diffusion model. This suggests that the rate-limiting step may be the chemisorption instead of mass transport promoted through sharing of electrons between the sorbate and biosorbent, or covalent bond formation, through the interchange of electrons between the parties involved [32]. Figure6 present multi-linear plots, that predicts, two or more steps influence the adsorption process such as external diffusion, intra-particle diffusion etc [35].



Figure 6. Intra particle diffusion model of Pb(II) sorption by CSP

Table 4. Kinetic Farameters for the adsorption of PD(11) on CSF at university temperatures									
Τ	Pseudo First Order			Pseudo Second Order			Intra Particle Diffusion		
Iemp	R ²	qe (mgg ⁻¹)	$k_1(min^{\text{-}1})$	\mathbf{R}^2	q _e (mgg ⁻¹)	$\begin{array}{c} k_2 \\ (g mg^{-1}min^{-1}) \end{array}$	R ²	$\frac{K_{id}}{(mgg^{-1}min^{1/2})}$	I
298K	0.854	1.58	0.018	0.999	4.44	0.028	0.758	0.125	2.64
308K	0.856	3.90	0.463	0.999	4.52	0.030	0.735	0.126	2.76
318K	0.844	1.40	0.018	0.999	4.56	0.032	0.706	0.125	2.76

Table 4. Kinetic Parameters for the adsorption of Pb(II) on CSP at different temperatures

3.5. Desorption of the Adsorbed Pb(II) ions

Desorption of adsorbed Pb(II) ions onto CSP also studied by using HNO₃. For this studies, 10mL of HNO₃ was used. The effects of volume of 1M HNO₃ as eluent were also investigated in the range of 5.0-10.0 ml The recovery for Pb(II) ions was found to be 93.5% even using only 6.0mL of 1M HNO₃. Subsequent elution with high amount of HNO₃ readily strips the Pb(II) ions from CSP. In addition, as it can be seen from Figure 7, the high stability of permitted five times of adsorption–desorption process along the studies without a decrease about 5% in recovery of Pb(II) ions was observed.



Figure 7. Desorption efficiency of CSP with cycle number

3.6. FTIR and SEM Analysis

To identify the type of possible Pb(II) binding sites of CSP, FTIR spectra and to observe changes in surface morphology SEM images were recorded before and after the adsorption (Figure8&9). The FTIR spectrum of CSP was complex due to the existence of various functional groups on the surface of the biomass. When CSP got to interact with Pb(II) of aqueous phase, the bond energy of C=O, -COO⁻ and C-O-C functional groups present at the surface of adsorbent were impacted by chemical action generated in adsorption process, consequently, resulting in the shift on the characteristic peaks. There are several distinct peaks that were observed from the spectrum as shown in Table 5. A broad and strong band stretch was observed from 3000 to 3600 cm⁻¹, indicating the presence of free or hydrogen bonded -OH groups present on the adsorbent surface [36] (alcohols and carboxylic acids). The peak present at 3451.9 cm⁻¹ before adsorption

broaden and shifted towards 3464.9 cm⁻¹ after adsorption may be due to replacement of OH bonded H ion with Pb(II) ion. The peaks located at 2270.3 cm⁻¹, 1723.7 cm⁻¹ may be of isocyanate and -C=O present on cyclic ring respectively shifted to 2148.1cm⁻¹ and 1729.9cm⁻¹ shows their contact with the Pb(II). The band at 1659 cm⁻¹ correspond to stretching of C=O of primary amide. Shifting of 1102.6cm⁻¹ towards 1218.6cm⁻¹ shows the participation of C-O-C group of cellulose in metal binding. The peak at 1593 cm^{-1} of C=C may be of the aromatic ring of CSP shifted to 1627.1 cm⁻¹ after metal interaction. Below 1000 cm⁻¹the region which exist known as "fingerprint region" and the adsorption cannot be clearly assigned to any particular vibration because they correspond to complex interacting vibration systems [37]. Although according to Jahn et al. [38] peaks in range of 950-700cm⁻¹ shows side group deformation region for COH, CCH and OCH of cellulose and hemicelluloses.



Figure 8. FTIR spectra of CSP before and after Pb(II) adsorption

 Table 5. Functional groups and mode of vibration from the FTIR

 spectrum of CSP

FTIR Peaks (cm ⁻¹)	Assignment of bonds	Mode of Vibration
3879.9	Unknown	
3777.8	-	
3692.2, 3655.1, 3629.9 and 3451.9	Free O-H and H-bonded OH on Surface respectively	Stretching
2369.2 & 2270.3	- NCO group	Stretching
1813.5	Carbonyl C=O	Strong stretching
1723.7	6-membered cyclic ketone	Strong stretching
1659.1	C=O of amide	Strong stretching
1593.7	C=C present in aromatic rings	Stretching
1102.6	C-O-C of phenol, cellulose	Symmetrical stretching

In addition, the surface structure of the CSP was analyzed by scanning electron microscopy (SEM Zeiss, Germany). The scanning electron micrographs enable the direct observation of the surface microstructures of the adsorbent. Figure 9a illustrates the SEM of native adsorbent at 800X that shows irregular grooves and porous structure that might favor accessibility of Pb(II) to the adsorbent surface [8]. Figure 9b shows SEM of exhausted adsorbent clearly indicates the presence of new shiny bulky particles and layer over the surface of metal loaded adsorbent those are absent from the native adsorbent before metal loading, and thus observed significant visible changes in the morphology of CSP before and after Pb(II) sorption.



Figure 9. Scanning Electron Micrograph showing morphology of virgin CSP (a) and (b) Pb(II) loaded CSP

4. Conclusion

Pb(II) ion sorption on CSP were found to be dependent on experimental conditions, particularly on pH and initial concentration of Pb(II) ions in solution. Adsorption capacity was affected at low pH but increased with increase in concentration, adsorbent dosage and contact time. The equilibrium data presented a better fit to the Langmuir isotherm model indicating monolayer sorption while following kinetics of pseudo-second order. The FTIR analysis revealed -OH, -C=O, -C-O-C-, -COOH, and -COO- as the major functional groups that act as adsorption sites for Pb(II). Chemical adsorption was the main adsorption mechanism involved as indicated by Langmuir isotherm, pseudo second order kinetics and FTIR. As CSP has no commercial value and is a good, inexpensive source of readily available biomaterial so from the reported observations it can be concluded that this can be successfully used as a low-cost environmentfriendly adsorbent for the removal of heavy metals from aqueous solution.

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