Chitosan-based Magnetic Composites - Efficient Adsorbents for Removal of Pb(II) and Cu(II) from Aqueous Mono and Bicomponent Solutions

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A series of three chitosan-based magnetic composites was prepared through a simple coprecipitation method. It was investigated the influence of mass ratio between chitosan and magnetite on the physical and chemical properties of the composites in order to establish the optimum conditions for obtaining a composite with good adsorption capacity for Pb(II) and Cu(II) from mono and bicomponent aqueous solutions. It was found that the microspheres prepared using mass ratio chitosan / magnetite 1.25/1, having a saturation magnetization of 15 emu g⁻¹, are the best to be used as adsorbent for the metal ions. The influence of different parameters such as initial pH values, contact time, initial concentration of metal ions, on the adsorption of Pb(II) and Cu(II) onto the chitosan-based magnetic adsorbent was investigated in details. The adsorption process fits the pseudo-second-order kinetic model in both mono and bicomponent systems, and the maximum adsorption capacities calculated on the basis of the Langmuir model were 79.4 mg g⁻¹ for Pb(II) and 48.5 mg g⁻¹ for Cu(II) in monocomponent systems, while in bicomponent systems were 88.3 and 49.5 mg g⁻¹, respectively. The results revealed that the as prepared chitosan-based magnetic adsorbent can be an effective and promising adsorbent for Pb(II) and Cu(II) from mono and bicomponent aqueous solutions.

Keywords: Lead; copper; magnetic adsorbents; chitosan

Environmental pollution with toxic heavy metals from the fuel, power, mining, automotive, tanning, textile, fertilizer industry, agricultural processes and waste disposal, is a very serious problem throughout the world. Heavy metal ions are not biodegradable and persist in natural ecosystems for long periods of time, accumulating in the trophic chains and tissues of living organisms. Exposure to high concentrations of heavy metal ions over long periods of time can cause important diseases and dysfunctions in living organisms [1]. Lead and copper are one of the most hazardous heavy metals. Among poisoning effects of lead can be mentioned: hematological damage, anemia, kidney malfunctioning, brain damage, severe lesions in kidney, liver, lungs and spleen [2]. Although in trace amounts copper is an essential metal for human organism, in excess it can cause severe health disorders, including liver and lung damage, gastrointestinal disturbances, congestion of the nasal mucosa, gastritis, diarrhea [2,3]

Heavy metal ions can be removed and recovered from contaminated waters using both conventional and nonconventional methods. From the category of conventional methods can be mentioned chemical precipitation, ion exchange, coagulation / flocculation, membrane filtration, electrochemical treatment, reverse osmosis, flotation, chemical oxidation and reduction [4]. The main disadvantage of the conventional methods is the production of large volumes of toxic chemical sludges whose separation / deposition / treatment involves additional non eco-friendly processes and, implicitly, higher costs. Among all these methods, adsorption is considered one of the best because of convenience, high removal efficiency, low cost, easy operation, simplicity, possibility to apply a large number of natural and synthetic materials, and even waste as adsorbents. In addition, the adsorbents can be regenerated and reused in new adsorptiondesorption cycles.

Magnetic nanomaterials like spinel ferrites (magnetite, cobalt ferrite, etc.) have been intensively studied as adsorbent materials for organic and inorganic pollutants removal due to their superior characteristics in comparison with the traditional adsorbents (i.e. large surface area, high number of active surface sites, tunable magnetic properties and high adsorption capacities) [5-10]. In spite of many advantages, the use of the bare magnetic nanoparticles for water / wastewater remediation processes, also have a number of disadvantages such as aggregation, oxidation, low stability in suspension medium, affecting their longterm performance and applicability of the separation process [11]. To overcome this limitation, the best strategy is to coat their surface with different capping agents or to include them in different kinds of composites materials. In recent years, special attention has been paid to the use of natural organic biomolecules, such as cellulose, cyclodextrin, starch, dextran, arabic gum, chitosan, alginate, etc. to obtain magnetic adsorbents for heavy metal ions from wastewater, due to the presence of different functional groups in their structure which provides them high capacity and selectivity. A particularly important aspect to be considered is the mass ratio between the magnetic and non-magnetic part which must be controlled in order to preserve the magnetic properties of the composite material which is essential for the magnetic recovery of the adsorbent [11].

A number of recent studies have recently focused on the use of chitosan and its derivatives to obtain magnetic composite materials for heavy metal ions removal from contaminated waters [12-15]. Chitosan is a hydrophilic, nontoxic and biocompatible biopolymer obtained by deacetylation of chitin, an inexpensive biopolymer

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extracted from the shells of shrimp or crabs, which are waste products of the seafood processing industry [16-19]. Its adsorption capacity is due to the presence of numerous reactive functional hydroxyl and amino groups.

Herein, we report the synthesis of chitosan magnetic composites by a simple and inexpensive precipitation method, followed by a hydrothermal treatment. The asprepared materials were characterized in detail by various physicochemical techniques. It was investigated the influence of mass ratios chitosan / magnetite on the properties of the final materials. The adsorption properties of the optimized chitosan magnetic composite for the removal of Pb(II) and Cu(II) from mono and bicomponent aqueous solutions were studied by varying different parameters such as initial pH values, contact time, initial concentration of metal ions.

Experimental part

Materials

Ferric chloride hexahydrate (FeCl₃×6H₂O), ferrous chloride tetrahydrate (FeCl₂×4H₂O), chitosan (high molecular weight) were purchased from Fluka. Lead nitrate (Pb(NO₃)₂), copper nitrate trihydrate (Cu(NO₃)₂×3H₂O) and sodium hydroxide (NaOH) were purchased from Merck KGaA Germany. All chemicals were of analytical grade and used as received. Deionized water was used in experiments.

Synthesis of Fe₃O₄-chitosan composites

The Fe₃O₄-chiťosan composites were prepared by chemical coprecipitation of Fe(II) and Fe(III) salts in the presence of chitosan. Briefly, 0.5 g chitosan was disolved in 50 mL acetic acid (10%) to form a clear gel, followed by the addition of 20 mL solution containing the Fe(III) and Fe(II) chlorides in molar ratio 2:1. After stirring for an hour, the obtained reddish gel was dropped using a syringe into 500 mL NaOH solution (30%). The black magnetite-chitosan microspheres instantly formed were aged in the NaOH solution at room temperature for ~ 20 h, then washed several times with copious amounts of water (till the *p*H of the runoff became neutral) and dried in oven at 60 °C for 5 h. The following mass ratios chitosan / magnetite have been used: 1.25/1 (MC-1); 2.5/1(MC-2) and 5/1 (MC-3).

Characterization

FTIR spectra were recorded using a Fourier transform infrared spectrophotometer (Jasco FTIR 4100) by the KBr pellets method. The content of chitosan in the samples was analyzed by a thermogravimetric analyzer (Mettler Toledo Star System TGA/SDTA) with a heating rate of 10 °C min⁻¹, in air. Powder X-ray diffraction patterns (XRD) were recorded on a Rigaku Ultima IV apparatus, with $CuK_{\alpha} \lambda =$ 1.5406 Å radiation, in the $2\theta = 10-80^\circ$ range, with a speed of 5° min⁻¹ and a 0.02 steps size, at 40 kV and 30 mÅ. The magnetic properties of the samples were measured on a Lake Shore's fully integrated Vibrating Sample Magnetometer system 7404 (VSM), at room temperature. An atomic adsorption spectrophotometer (AAS 1N Carl Zeiss Jena) was used for determining the concentration of metal ions in solutions before and after adsorption. Specific surface area (S_{RET}) were measured by N_2 adsorption-desorption at -196 °C using an automatic adsorption system (Micromeritics ASAP 2020) using the Brunauer Emmett Teller method based on adsorption data in the partial pressure (P/Po) range of 0.05 - 0.3. Before analysis, the samples were degassed for 8 h at 100°C under vacuum. Surface analysis performed by XPS was carried out on PHI Quantera equipment with a base pressure in the analysis

chamber of 10^{-9} Torr. The X-ray source was monochromatized Al K α radiation (1486.6 eV) and the overall energy resolution is estimated at 0.65 eV by the full width at half-maximum (FWHM) of the Au4f7/2 photoelectron line (84 eV). Although the charging effect was minimized by using a dual beam (electrons and Ar ions) as neutralizer, the spectra were calibrated using the C1s-sp2 line (BE = 284.4 eV)

Sorption studies

For the adsorption experiments batch procedures were used. Stock metals solutions (1000 mg L⁻¹) were prepared from the corresponding nitrate salts, then the desired concentrations were prepared by dilution. 0.025 g of sorbent and 25 mL of metal (Pb(II) or Cu(II)) solution were shaken on a rotary GFL shaker 3015 (150 rpm) at room temperature (25 °Č), for desired time intervals. At the end of adsorption experiment, the sorbent was magnetically separated from solution (using a hand-held magnet) and the residual metal ions concentrations were determined by atomic absorption spectroscopy (AAS). The same procedure was also used for studying the effect of pH of metal solution. The kinetic adsorption experiments were performed at room temperature, in the range of 5 - 600 min for monocomponent solutions, at *p*H 6 for Pb(II) and 4.5 for Cu(II), while for bicomponent solutions the pH was 4.3. The concentrations of Pb(II) and Cu(II) in monocomponent solutions were 112.84 and 122 mg L⁻¹, while for bicomponent solutions were 128.84 and 133.6 mg L⁻¹. The adsorbent dose was 25 mg/25 mL solution in all experiments.

The adsorption capacity was calculated using the equation (1):

$$Q = \frac{(C_i - C_f) \cdot V}{m} \tag{1}$$

where Q - adsorption capacity (mg g⁻¹), C_i - the initial concentration of metal solution (mg L⁻¹), C_i - the equilibrium concentration of metal solution (mg L⁻¹), V - total volume of metal solution (L) and m - the mass of the sorbent used (g).

Results and discussions

Characterization of the chitosan magnetic composites

The XRD patterns of the three samples are shown in figure 1. All curves show typical diffraction peaks of Fe₃O₄, indexed to (220), (311), (400), (422), (511) and (440). However, it must be mentioned that the background is quite noisy, this fact being attributed to the amorphous dried chitosan present in samples in relatively big amount. Similar findings were reported by Silva and colab. for Fe₃O₄ nanoparticles coated with fucan polysaccharides [20].

Figure 2 shows FTIR spectra of the magnetite- chitosan composites and free chitosan in the range 4000- 390 cm⁻¹.



REV.CHIM.(Bucharest) \diamond 69 \diamond No. 9 \diamond 2018



The band located at 584 cm⁻¹ in the spectra of all three magnetic composites is associated with the Fe-O stretching vibrations [21]. The other strong bands at the same wavelengths as in free chitosan confirms its presence in magnetic composites. The main bands of chitosan can be assigned as follows: 3424 cm⁻¹ to OH stretching vibrations, 2875, 1425, 1319 and 1263 cm⁻¹ to CH₂ bending, 1380 cm⁻¹ to CH₂ wagging, and 1658 cm⁻¹ to amide I, 1594 cm⁻¹ to amide II [22,23]. As can be seen in figure 3, the magnetic composites are

As can be seen in figure 3, the magnetic composites are quasi-sherical in shape in both wet and dry form. It is worth mentioning that by increasing of the molar ratio between chitosan and magnetite, the microspheres have a more compact surface, with lesser porosity. The S_{BET} values were found to be 16.8 m² g⁻¹ for MC-1, 3.6 m² g⁻¹ for MC-2 and < 1 m² g⁻¹ for MC-3.

To quantify the amount of chitosan in the synthesized samples, thermogravimetric analysis was performed. The TG curves presented in figure 4 show mass losses of 55.54% for MC-1, 70.34% for MC-2 and 83.03% for MC-3, until 900 °C. The thermal decomposition profiles are similar for all three samples.

The magnetic properties of the composites microspheres were measured on VSM at room temperature by registering the magnetization versus applied field curves (fig. 5) in order to establish if they could





Temperature / °C



Fig. 5 Magnetic hysteresis curves of the composites at room temperature

be used as magnetic adsorbents. As can be seen in figure 5 there is no remanence and coercivity indicating that all three composites are superparamagnetic. The saturation magnetization (M_s) values were found to decrease as the mass ratio between chitosan and magnetite increases (15 emu g⁻¹ for MC-1, 7.41 emu g⁻¹ for MC-2 and 4.53 emu g⁻¹ for MC-3). For this reason, only the sample with the highest saturation magnetization (MC-1) was involved in subsequent adsorption studies, 15 emu g⁻¹ being enough for magnetic separation from the suspension by application of a permanent magnet.

Adsorption studies

Effect of the solution *p*H

The *p*H of solution is one of the most important factor influencing metal ions adsorption on different adsorbents. In our experiments, the effect of *p*H on adsorption of chitosan magnetic composites was investigated by varying the initial *p*H range between 4 and 6.5 for Pb(II) and 3.5 to 6 for Cu(II). As shown in figure 6a,b, the adsorption of Pb(II) increases by raising the *p*H from 4 to 6, then decreases at *p*H > 6. At *p*H values higher than 6 the adsorption competes with lead removal by precipitation. In the case of Cu(II) the adsorption increases as the pH raises in the range 3.5 to 4.5. Beyond this *p*H level (between 4.5 and 6) the



adsorption of copper ions dramatically decreases. Therefore the uptake of Pb(II) and Cu(II) at low *p*H values was not favored, mainly due to the repulsive forces between the divalent metal ions and the positively charged adsorbent surface and also to the excess hydrogen ions competing with metal ions in the solution. Based on the adsorption data, the solution *p*H of 6 was selected as the optimum *p*H for the adsorption of Pb(II) while for Cu(II) the optimum *p*H was considered to be 4.5.

Adsorption isotherms

To understand the mechanism of adsorption and to evaluate the adsorption capacity of the adsorbent for Pb(II) and Cu(II), two commonly used models Langmuir and Freundlich were applied [24]. According to Langmuir model, adsorption takes place on localized sites with no interaction between the adsorbed molecules. Maximum adsorption occurs when the surface is completely covered by a monolayer of adsorbate molecules [25]. The expression of the Langmuir model is given by the following equation:

$$Q = \frac{K_L Q_m C_e}{1 + K_L C_e} \tag{2}$$

where Q is the amount of metal ions adsorbed at equilibrium (mg g⁻¹); C is the equilibrium concentration of metal ions (mg L⁻¹); \mathring{Q}_m and K_L are Langmuir constants related to the maximum adsorption capacity and affinity;

The Freundlich model which corresponds to heterogeneous adsorbent surfaces, is depicted by the equation (3) :

$$Q = K_F \cdot C_e^{\frac{1}{n}} \tag{3}$$

 K_F and n are Freundlich constants representing sorption capacity and sorption intensity, respectively.

Figure 7 shows the equilibrium adsorption isotherms of Pb(II) and Cu(II) on magnetic chitosan composite MC-1 in mono and bicomponent solutions. To obtain the equilibrium adsorption isotherms, all the experiments in monocomponent solutions were performed at ambient temperature (298 K), at *p*H 6 and concentration range 5 to 113 mg L⁻¹ for Pb(II), while for Cu(II) the *p*H was 4.5 and the concentration range 4 to 122 mg L⁻¹. For bicomponent solutions, the experiments were performed at *p*H 4.3, in the concentration range 10 to 129 mg L⁻¹ for Pb(II), and 10 to 134mg L⁻¹ for Cu(II). The calculated values for the Langmuir and Freundlich constants are listed in table 1.

Based on the regression coefficient values, it can be suggested that Langmuir describes the sorption process better than Freundlich model in both monocomponent and bicomponent systems. This indicates that the adsorption of heavy metals on the chitosan magnetic microspheres takes place by a monolayer coverage, the surface of the adsorbent being homogenous. Analyzing the maximum adsorption capacity it can be noticed that for Cu(II) this



Fig.7. Equilibrium adsorption isotherms of Pb(II) and Cu(II) on the chitosan magnetic composit MC-1 using mono and bicomponent solutions (solid black line -Langmuir isotherm; dash black line-Freundlich isotherm).

parameter is almost similar in mono and bicomponent systems, while for Pb(II) a slightly higher value has been determined in bicomponent comparing with that in monocomponent system. This behavior suggest that Pb(II) is more competitive than Cu(II) in bicomponent system.

The essential features of Langmuir isotherm can be expressed in terms of a dimensionless separation factor, $R_{_L}$, defined by the eq. 4, that indicates the nature of the adsorption process (unfavorable if $R_{_L} > 1$, linear if $R_{_L} = 1$, favorable if $0 < R_{_L} < 1$, or irreversible if $R_{_L} = 0$ [22].

$$R_L = \frac{1}{1 + K_L C_0} \tag{4}$$

where C_0 (mg L⁻¹) is the initial M(II) concentration, and K_L is the Langmuir equilibrium constant.

Figure 8 shows the variation of R_{μ} with initial metal ion concentration. The R_{μ} values ranging between 0 and 1



Fig. 8 Variation of R_L as function of initial metal ion concentration

Table 1
LANGMUIR AND FREUNDLICH ISOTHERM PARAMETERS OBTAINED BY NONLINEAR REGRESSION.

Metal ion	Langmuir parameters			Freundlich parameters		
	Qm (mg g ⁻¹)	K _L (L mg ⁻¹)	R ²	K _F (mg g ⁻¹)	n	R ²
Pb(II) in monocomponent solution	79.4 ± 2.36	0.073 ± 0.005	0.997	9.80 ± 1.69	2.04 ± 0.198	0.973
Pb(II) in bicomponent solution	88.3 ± 2.75	0.026 ± 0.001	0.998	5.22 ± 0.715	1.74 ± 0.281	0.989
Cu(II) in monocomponent solution	48.5 ± 2.56	0.175 ± 0.040	0.976	10.79 ± 1.99	2.79 ± 0.202	0.954
Cu(II) in bicomponent solution	49.5 ± 0.57	0.043 ± 0.001	0.999	5.74 ± 1.25	2.27 ± 0.183	0.955



Fig. 9 The C1s, O1s and N1s high-resolution deconvoluted spectra for the samples MC-1and Pb-MC-1.

indicate that the adsorption of Pb(II) and Cu(II) on chitosan magnetic composite is favorable regardless if the system is mono or bicomponent. The tendency of R_L to approach zero with the increase of initial concentration of the adsorbate (C_0) suggests that the adsorption of both Pb(II) and Cu(II) ions on the studied composite is less favorable at high initial concentrations.

In order to evidence the chemical states of the surface elements of the adsorbent before and after adsorption and to get more informations on the adsorption mechanism. XPS analysis was performed. Further on it will be presented the XPS analysis for adsorbent (MC-1) before and after Pb(II) adsorption. After collecting the wide scan spectrum which allows us to detect the elements present on the surface, the high resolution spectra (C1s, Ô1s, N1s, Fe2p, and Pb4f) were recorded in order to get insight on their associated chemical states (figs. 9, 10). The relative concentrations of the elements, calculated based on the peak areas, are listed in table 2. As shown in figure 9b, the high-resolution spectrum of Pb 4f after Pb(II) adsorption onto MC-1 exhibits two peaks at around 138.5 eV and 143.4 eV which can be assigned to Pb 4f 7/2 and Pb 4f 5/2. In spite of a very low relative concentration (0.2%), we can attribute the oxidation state as Pb²⁺ according to reliable databases [27, 28]. The presence of a lower oxidation state

Fig. 10 The superimposed Fe2p highresolution spectra for MC-1 and Pb-MC-1 (a) and Pb4f high-resolution spectrum for the sample Pb-MC-1 (b).

could be attributed to the interaction with the amino groups of chitosan which is a well-known anti-oxidizing agent for metals [29,30]. For the same sample one can notice the iron diffusion tendency from the surface to the subsurface (bulk region) accompanied by carbon segregation to the outermost surface layer, as compared to the MC-1 sample. This finding is in agreement with the O1s feature (O-Fe, BE = 530.3eV, fig. 9d and table 2) indicating a higher percentage for the sample MC-1.

Adsorption kinetics

The effect of contact time on the adsorption of Pb(II) and Cu(II) in mono and bicomponent solutions on chitosan magnetic composite MC-1 is shown in figure 11. It can be noticed that the adsorption process is fast for both ions in mono and bicomponent solutions, the biggest amount of ions being retained in the first 30 min. This behaviour was expected due to the availability of the adsorption sites on the adsorbent surface at the begining of the process. The adsorption rate gradually increases until the reaction reached equilibrium, after 7 h in monocomponent systems and 4 h in bicomponent system, respectively.

Pseudo-first order and pseudo second order were used to establish the rate limiting step and to elucidate the Table 2

ELEMENTS ON THE SURFACE (< 5nm) AND THEIR ASSOCIATED CHEMICAL STATES, BINDING ENERGIES (BEs, eV), ELEMENT RELATIVE CONCENTRATIONS (ATOM %), CHEMICAL STATE RELATIVE CONCENTRATIONS (%) FOR THE SAMPLES MC-1 AND Pb-MC-1



Fig. 11 Effect of contact time on adsorption of Pb(II) and Cu(II) onto MC-1 adsorbent

mechanism of the adsorption process. The first two kinetic models are expressed by the following equations:

$$Q_t = Q_e (1 - e^{-\kappa_t t}) \tag{5}$$

$$Q_{t} = \frac{Q_{s}^{2}k_{2}t}{1 + Q_{s}k_{2}t}$$
(6)

where Q_e , Q_1 are the adsorption capacities at equilibrium and time t (mg g⁻¹), k_1 and k_2 are the rate constants of pseudo-first order (min⁻¹) and pseudo second-order kinetics (g mg⁻¹ min⁻¹). The parameters calculated by these two models were determined by nonlinear regression analysis using GraphPad Prism 7.02 and listed in table 3.

Comparing the results, it can be seen that the regression coefficients (R²) are higher while AIC and RMSE values are smaller for pseudo second-order model than for pseudo first-order model regardless of the metal ion in mono or bicomponent solution. Also the experimental and calculated Q_e values are in better agreement for pseudo second-order model. These results suggest that the adsorption of both metal ions in mono and bicomponent solutions follows the pseudo second-order model, chemical adsorption by chelation being the rate-liminting step of the process. It can be observed in table 3 that the rate constant (k_2) of the pseudo-second-order equation is higher in bicomponent systems, indicating that the adsorption of Pb(II) and Cu(II) onto MC-1 adsorbent might be favorable in these conditions. The graphical representation of the pseudo second-order kinetic is given in figure 12.

The maximum adsorption capacity is comparable or even higher than that of other similar chitosan magnetic adsorbents reported in literature (table 4).

Sample	Cu²⁺	Pb ²⁺	Cu2+	Pb2+
	monocomponent	monocomponent	bicomponent	bicomponent
	solution	solution	solution	solution
Qe exp (mg g ⁻¹)	43.2	61.9	40.1	58.5
Pseudo-first-order model			/ / /	/ / / /
k1 (min ⁻¹)	0.007	0.031	0.102	0.088
Qe cal (mg g ⁻¹)	40.9	57.5	36.6	55.5
R ²	0.877	0.905	0.891	0.970
AIC	56.3	62.5	43.6	38.9
RMSE	4.53	5.57	3.90	3.16
Pseudo-second-order model				
k2(10 ⁻³ g mg ⁻¹ min ⁻¹)	1.47	1.28	4.43	2.371
Qe cal (mg g ⁻¹)	42.9	59.9	38.4	58.8
R ²	0.903	0.953	0.953	0.996
AIC	48.9	48.0	29.1	10.6
RMSE*	4.02	3.90	2.56	1.10

Table 3KINETIC PARAMETERS FORMETAL IONS ADSORPTIONONTO MC-1 ADSORBENT INMONO AND BICOMPONENTSOLUTIONS

'RMSE is Root Mean Square Error

Adsorbent	Adsorption ca	Ref.	
	Pb(II)	Cu(II)	
Magnetic chitosan/graphene oxide	79	-	[31]
imprinted Pb ²⁺			
Xanthate-modified magnetic chitosan	76.9	34.5	[32]
Magnetic chitosan nanoparticles	-	35.5	[33]
EDTA-modified chitosan/SiO ₂ /Fe ₃ O ₄	123	44.4	[34]
Epichlorohydrin cross-linked xanthate		43.47	[35]
chitosan			
Chitosan/magnetite composite beads	63.3	-	[36]
Tetraethylenepentamine modified	72.99	58.85	[22]
chitosan/CoFe2O4 particles			
MC-1	79.4	48.5	This work

Table 4COMPARISON OF MC-1ADSORPTION CAPACITY WITHOTHER PREVIOUSLY REPORTEDMAGNETIC ADSORBENTS FORPb(II) AND Cu(II) REMOVAL FROMAQUEOUS SOLUTIONS

Conclusions

In this study a series of three chitosan-based magnetic composites was prepared by varying the mass ratio between chitosan and magnetite in order to establish the optimum conditions for obtaining a composite with good adsorption capacity of Pb(II) and Cu(II) from mono and bicomponent aqueous solutions. The mass ratio chitosan / magnetite of 1.25/1 was found to lead to the best magnetic adsorbent, with a saturation magnetization of 15 emu g⁻¹. Adsorption of Pb(II) and Cu(II) onto the as prepared magnetic adsorbent followed the Langmuir adsorption isotherm model. The maximum adsorption capacity was confirmed as 79.4 and 48.5 mg g⁻¹ for Pb(II) and Ču(II), respectively, in monocomponent systems, while in bicomponent systems were 88.3 and 49.5 mg g⁻¹. Kinetic study indicated that the adsorption process is fast and can be better described by the pseudo-second-order kinetic model in both mono and bicomponent systems. The convenient magnetic separability and the adsorption characteristics recommend this magnetic adsorbent for practical application in the removal of Pb(II) and Cu(II) from mono and bicomponent aqueous solutions.

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