

NiFe₂O₄ coated sand as a nano-adsorbent for removal of Pb (II) from aqueous solutions

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Abstract

In this study, NiFe₂O₄ magnetic nanoparticles as an adsorbent for lead (Pb) removal were coated on sand particles. Adsorption studies were conducted to investigate the efficacy of contact time, pH, adsorbent dosage and initial lead ion concentration on the removal efficiency. To choose the most fitting kinetic model, the pseudo-first order and pseudo-second order models were compared and the most suitable kinetic model was selected by the pseudo-second order. Langmuir and Freundlich isotherms were evaluated and the most suitable isotherm was observed as the Freundlich model. In addition, the NiFe₂O₄ coated sand can simply be removed by an ordinary filtration process.

Keywords: Pb(II) removal; sand; magnetic nanoparticles; adsorption; NiFe₂O₄.

Introduction

In recent years, environmental pollution by heavy metals, especially some toxic metals, has been a fascinating issue for scientists due to the increased leakage, toxicity, inconsistency in nature and other fatal effects [1]. One of the main trace elements is lead (Pb), because of its high toxicity even at very low values [2,3]. Lead contains many important industrial applications such as the manufacture of car batteries, color printing, ceramics, photographic materials, explosives and pipe materials. [4]. Lead has been reported to cause hypertension, intense stomach-ache, damaged blood synthesis and kidney injury [5]. Based on the United States

Environmental Protection Agency, the allowable level for Pb(II) in water is 0.05mg L⁻¹. So, an extremely low concentration of Pb(II) in water is highly toxic and noxious [6]. Various methods have been used to treat and remove heavy metals from water and wastewater sources; including, ion exchange, reverse osmosis, chemical precipitation, electro-dialysis, electrolysis and membrane filtration [7-10]. The used methods have disadvantages, for instance, time consuming, high cost, and secondary waste [11]. Nanotechnology can be utilized to resolve the deficiencies of above-mentioned methods [10]. Magnetic nanoparticles (NPs) have a great surface area, significant adsorption

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capacity, and fast sorption rate. In recent years, these new materials have been considered for their unique properties [12-14]. Magnetic nano-materials have attracted more and more attention due to the good stability, large surface-to-volume ratio, and efficient recovery procedure by magnetic attraction, which lead to versatile applications in biotechnology, biomedicine, environmental [15-18]. One of its features is that most of the atoms are on the surface of the NPs. Since surface atoms are not saturated, it may be linked to another atom with high chemical reactivity. As a result, NPs can absorb metal ions at high absorption rate [19]. Iron oxide-based adsorption is most desirable for the adsorption of Pb(II). If these adsorbents are made on a nanoscale, they will increase the absorption efficiency due to a larger surface area than bulk counterpart [20, 21]. Anyway, in spite of the benefits, iron-based nanoscale absorbers have limitations, for example, they need an external magnetic field to separate from the solution after use. One solution to overcome the limitation of requiring the external magnetic field is that they can be filtered by the cartridge, but this can be expensive because a lot of material is needed in the cartridge. A better way to achieve an invaluable technology is to fade the nano iron oxide powder into a cheap material such as sand and sand [22]. Between different magnetic NPs, magnetic NiFe_2O_4 shows extensive uptake capacity and affinity to the Pb.

In this study, we report a method to expand an economical adsorbent by coating NiFe_2O_4 nanoparticles on sand surface through co-precipitation procedure. The sand is used as a substrate for NiFe_2O_4 to provide an inexpensive practical way in order to remove the poisonous Pb from aqueous solutions. NiFe_2O_4 -coated nano-adsorbent does not

need any external magnetic field for the breakaway of the adsorbent. For this purpose, nano-sorbent was synthesized and characterized by various techniques. In the next step, the adsorption properties of lead were investigated. Finally, the effect of contact time, adsorption dose, pH and concentration of lead solution on adsorption were investigated. Here, using a NiFe_2O_4 nanoscale adsorbent coating on the surface of sand particles, a sand filtering feature is used to avoid the use of a magnetic field and also to disassociate NiFe_2O_4 nanoparticles.

Materials and Methods

Materials

Ferric nitrate 9-hydrate and nickel nitrate hexahydrate were obtained from Sigma-Aldrich. Hydrochloric acid and nitric acid were purchased from BDH. Analytical-grade salt $\text{Pb}(\text{NO}_3)_2$ was obtained from Merck, Germany. A $1,000 \text{ mgL}^{-1}$ stock solution of the salt was prepared in deionized water. All working solutions were made by diluting the concentrate solution with deionized water.

Analytical measurements

An XRD analysis was performed using a PAN analytical X'Pert Pro X-ray diffractometer. Surface and particle size morphology was studied by SEM-Hitachi S-4800. The FT-IR spectrum was determined on a Bruker 470 spectrophotometer. The concentration of metal ions was measured by an atomic absorption spectrometer with AA 240 FS variance.

Preparation of NiFe_2O_4 nanoparticles on sand surface

Sand was initially sieved between 0.6 and 0.9 mm in geometric dimensions, soaked in acidic solution (1.0 M HCl) for 24 hours, then washed several times with deionised water and dried at 100°C . Then the sand was etched with HNO_3/HCl in a 1: 3 ratios for 5 minutes

and then washed out to remove the etchant solution.

60 mL of egg white was mixed with 40 mL of deionized water and mixed until a homogeneous solution was obtained at room temperature. Subsequently, 2.9081 g of Ni(NO₃)₂·6H₂O and 8.0800 g of Fe(NO₃)₃·9H₂O (a mole ratio corresponding to the nominal composition of Ni:Fe ratio of 1:2) and 3.000 g pre-prepared sand were added slowly to the egg white solution with powerful stirring at room temperature for 2 h to obtain a well-dissolved solution. In the described process, no PH setup was performed. The mixture was then evaporated with warming at 80 °C and dried over several minutes. To ensure coating the NiFe₂O₄ nanoparticles on the surface of sand particles, the coated sand was washed with deionized water up to a clear supernatant was obtained. After filtration, the sand was dried at 85 °C for 3 h. The dried precursor was crushed into powder using a mortar.

pH_{PZC} determination of NiFe₂O₄ coated sand The pH_{PZC} (point of zero charge) of NiFe₂O₄ coated sand was defined as the pH value at which the surface carries no net charge. The pH_{PZC} was obtained by the acid and base titrations. 4 grams of NiFe₂O₄ coated sand was taken in 500 mL of purified water and titrated with standard 0.1 mol.L⁻¹ of HNO₃ or NaOH solutions, and the corresponding pH values were recorded using a pH meter. The obtained pH data versus the standard addition of acid or base was then utilized to evaluate the pH_{PZC} of the NiFe₂O₄ coated sand.

Lead adsorption by coating NiFe₂O₄ nanoparticles on sand surface Adsorption of lead from aqueous solution by NiFe₂O₄ coated sand adsorbent was investigated in batch experiments. The effect of some important parameters i.e. contact time, pH, adsorbent dosage and lead

concentration were studied. In these experiments all the containers were homogenized at 200 rpm, and all experiments were carried out at the laboratory temperature (25±1 °C). The temperatures were set using water bath equipped with circulator and thermostat. The pHs were set with suitable concentrations of HCl and NaOH using a pH meter. Kinetic experiments were conducted with constant adsorbent dose (0.1 g) at certain time intervals (1.0, 3.0, 5.0, 10, 15, 20, 30, 50 and 60 min.) and pH = 6. The adsorption isotherm experiments were done by mixing 0.3 g of NiFe₂O₄ coated sand in a jar containing 20 mL of Pb(II) solutions with varying concentrations (5, 10, 30, 50, 100, 200, 400, 600 and 800 mg/L) at pH = 6 for 30 min to reach equilibrium condition. Kinetic experiments indicate that the absorption time of 30 min was appropriate for achieving equilibrium. Therefore, 30 min mixing was selected for all batch isotherms. After the test, solids were separated from solutions and then the residual lead concentration was determined by an atomic absorption spectrophotometer. Then, removal efficiency percent (% R), was calculated using equation (1) [23]:

$$\% R = \frac{C_0 - C_e}{C_0} \times 100 \quad (1)$$

where C₀ and C_e are the initial and equilibrium lead concentrations (mg/L) in solution, respectively.

Equilibrium experiments

The most commonly used method for examining equilibrium absorption data is absorption isotherm, which describes the concentration of adsorbate in the solid phase q as a function of adsorbate concentration in liquid phase C at constant temperature [24]. Two most popular equations, Langmuir and Freundlich isotherm equations, were used for this purpose to fit the equilibrium data, and consequently

predict the sorption capacities of the materials used, and identify the mechanism of adsorption. Equation 2 shows the linear form of the Langmuir equation[25]:

$$\frac{1}{q_e} = \frac{1}{K_L q_m C_e} + \frac{1}{q_m} \quad (2)$$

where q_e is the content of Pb(II) adsorbed per unit mass of adsorbent at equilibrium (mg/g), q_m denotes the maximum amount of adsorbent that can be adsorbed per unit mass of adsorbent (mg/g), C_e is the concentration of adsorbent at equilibrium (mg/L) and K_L (L/mg) represents the Langmuir isotherm constant. A linear plot of $1/q_e$ against $1/C_e$, gives a straight forward line with a slope of $1/K_L q_m$ and an intercept of $1/q_m$ [25]. The main features of Langmuir isotherm can be represented according to a dimensionless constant separation factor R_L defined as [26]:

$$R_L = \frac{1}{1 + K_L C_0} \quad (3)$$

where C_0 is the initial concentration of Pb(II) ions (mg/L), and K_L (L/mg) is the Langmuir constant. The value of R_L shows the feature of the isotherm to be either unfavorable ($R_L > 1$), favorable ($0 < R_L < 1$), linear ($R_L = 1$) or irreversible adsorption ($R_L < 0$).

Freundlich isotherm is used to absorb heterogeneous sites with different surface energy levels, and assumes the change of absorption through the exponential distribution of adsorption sites and energies. The Freundlich model is expressed by[27]:

$$\log q_e = \log K_F + \frac{1}{n} \log C_e \quad (4)$$

where q_e is the amount of adsorbent adsorbed per unit mass of adsorbent (mg g^{-1}), C_e denotes the equilibrium concentration of adsorbent in the solution (mg L^{-1}), K_F (mg $^{1-(1/n)}$ L $^{1/n}$ g $^{-1}$) and n represent Freundlich constants

indicating the sorption capacity for the adsorbent and adsorption intensity, respectively. Freundlich parameters K_F and n can be estimated from the intercept and slope of a linear plot with $\log q_e$ versus $\log C_e$.

The values of n ranging from 1 to 10 show the chemisorption. Isotherms with $n > 1$ are noticed as L-type isotherms showing a high attraction between the adsorbate and the adsorbent and assigned to the chemisorption. To differentiate between chemical and physical adsorption, the uptake data were analyzed using the Dubinin–Radushkevich (D–R) equation defined as:

$$\ln q_e = \ln q_m - \beta \varepsilon^2 \quad (5)$$

where q_m is the maximum uptake capacity of metal ions (mg/g), β is a constant related to the average uptake energy (mol 2 kJ $^{-2}$), and ε is the Polanyi potential given as follows:

$$\varepsilon = RT \ln \left(1 + \frac{1}{C_e} \right) \quad (6)$$

where T is the temperature (K), R is the real gas constant (8.314 J K $^{-1}$ mol $^{-1}$). A linear plot of $\ln q_e$ against ε^2 gives a straight line with a slope of β and an intercept of $\ln q_m$. Using the below equation and the β value, the mean energy E which is the free energy transfer of one mole of solvent from infinity to absorbing surface is evaluated as:

$$E = \frac{1}{\sqrt{2\beta}} \quad (7)$$

If $E < 8$ kJ mol $^{-1}$, then the adsorption process may be physically conducted, but if $E > 8$ kJ mol $^{-1}$ chemical adsorption may occur.

Adsorption kinetics

Different kinetic models have been used to accurately design the absorption process [28]. In this study, the equations

of Lagergren's pseudo-first-order kinetic model and Ho's pseudo-second-order kinetic model were used. The Pseudo-first order by Lagergren is given as [29]:

$$\ln(q_e - q_t) = \ln q_e - k_1 t \quad (8)$$

where q_e and q_t (mg g^{-1}) are the uptake capacities at equilibrium and at time t (min) respectively. k_1 ($1/\text{min}$) is the rate constant for the pseudo-first-order model.

The Pseudo-second order equation is defined as [30]:

$$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{t}{q_e} \quad (9)$$

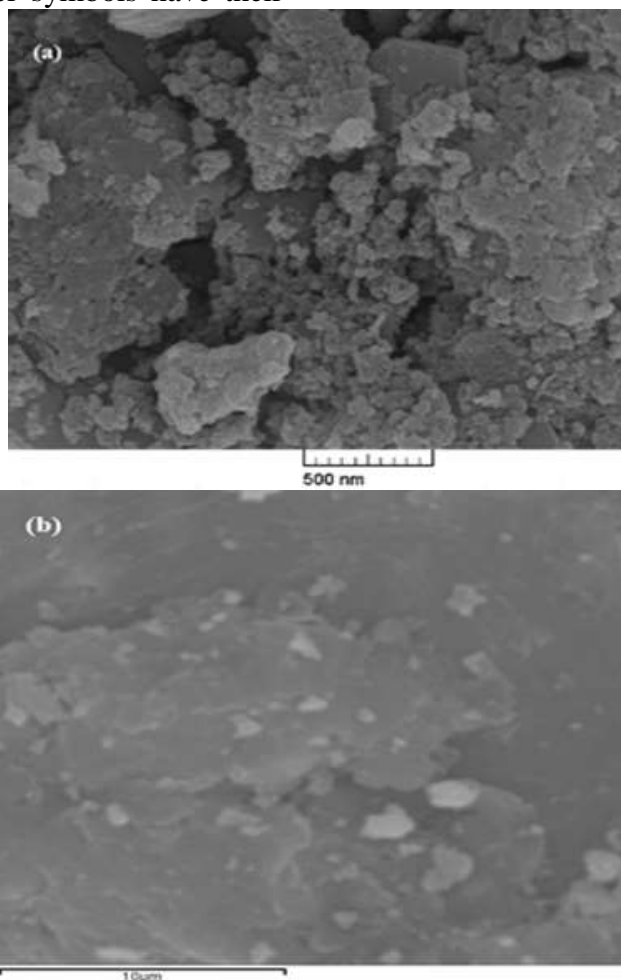
where k_2 ($\text{g mg}^{-1} \text{min}^{-1}$) is the rate constant for the pseudo-second order rate equation, and other symbols have their

common definitions. The amounts of q_e and k_2 can be obtained from the slope and intercept of the plot of t/q_t versus t .

Results and discussion

Characterization of NiFe₂O₄ nano particles coated sand adsorbent

Figure 1 indicates SEM images of NiFe₂O₄ nanoparticles, uncoated sand, and coated sand with NiFe₂O₄ nanoparticles. The nanoparticles have sizes less than 100 nm (Figure 1a). Figure 1b indicates uncoated sand particles; this indicates that the surface of the sand is nearly clear before coating, and after coating is covered with NiFe₂O₄ nanoparticles of size less than 100 nm as shown in Figure 1c.



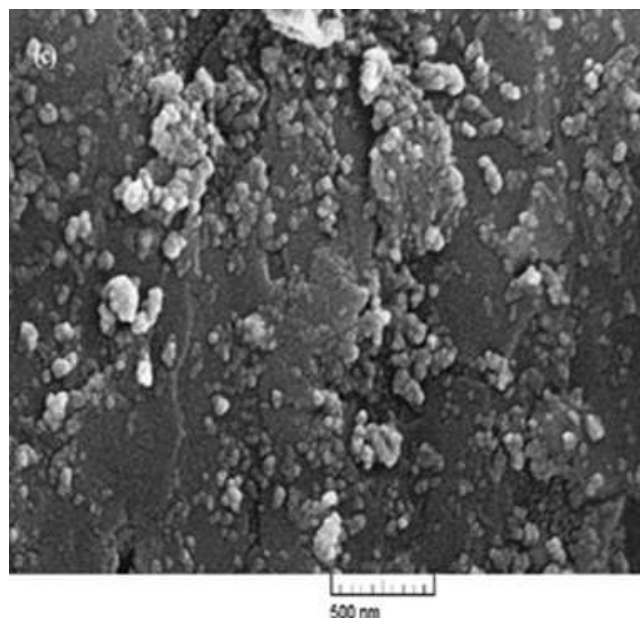
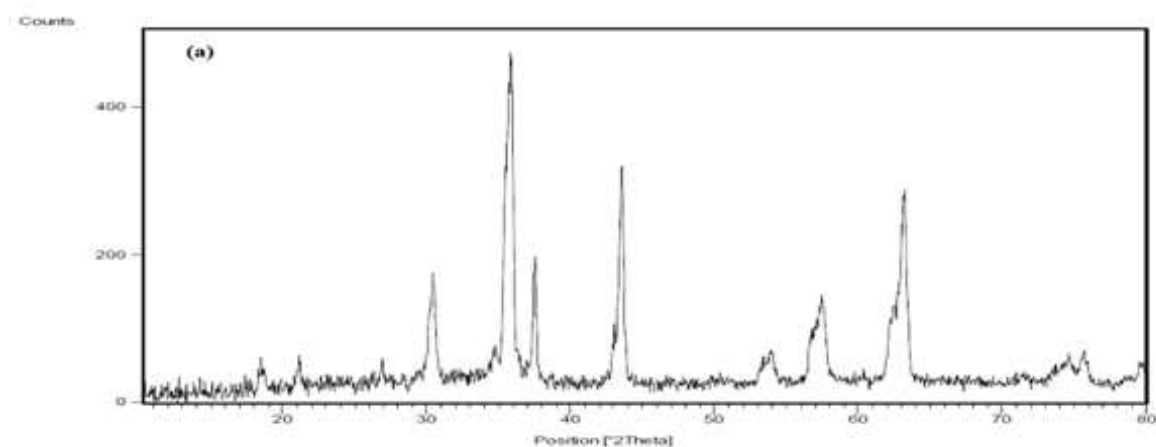


Figure 1. SEM Image of NiFe₂O₄ Nanoparticles (a), Uncoated Sand (b) and NiFe₂O₄

Figure 2 indicates XRD analysis of NiFe₂O₄ nanoparticles, uncoated sand, and NiFe₂O₄ nanoparticles coated sand, respectively. Figure 2a shows that these nanoparticles have a spinel structure and all of the principal peaks are in accordance with the standard pattern of bulk NiFe₂O₄ (JCPDS 08-0234). In the XRD pattern of coated sand (Figure 2c), most of the peaks are compatible with

that of the pure NiFe₂O₄ nanoparticles in Figure 2a, indicating the formation of NiFe₂O₄ nanoparticles on the surface of sand. As shown in Figure 2b, in the case of uncoated sand, sharp and narrow peaks are appeared in different positions that fit to different faces in the sand. Some of the peaks in the XRD pattern of sand fit to the uncovered sand peaks.



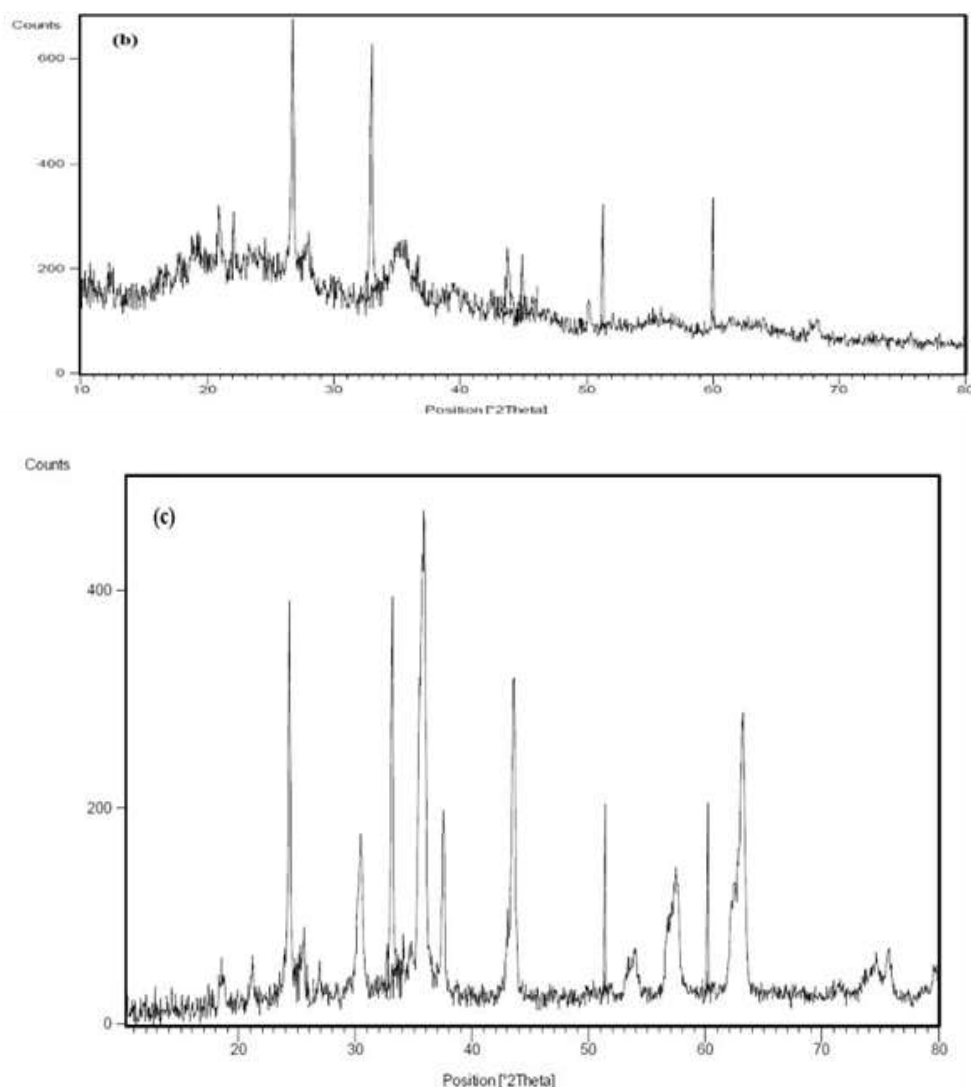


Figure 2. XRD Pattern of NiFe₂O₄ Nanoparticles (a), Uncoated Sand (b) and NiFe₂O₄ Nanoparticles Coated Sand (c)

Effects of different experimental conditions

Whereas adsorption is affected by physical and chemical variables, the influence of contact time, pH, initial Pb(II) concentration and adsorbent dosage is studied.

Effects of contact time

The impact of contact time on the Pb(II) adsorption value by NiFe₂O₄ coated sand was studied at 5.0 mg L⁻¹, to optimize the adsorption time and to investigate the kinetics of the uptake process. As contact

time enhances, the concentration of Pb(II) in the solution reduces quickly at first and later decelerates until remains constant at around 30 minutes, that was taken as the equilibrium time (Figure 3). This indicates that the Pb(II) removal of by NiFe₂O₄ coated sand was very rapid at the beginning. In the first minute, the absorption rate of Pb(II) is rapid, which can be the result of a large number of unoccupied sites that are accessible at the start of absorption process [31]. The optimum time value was considered to be 30 minutes.

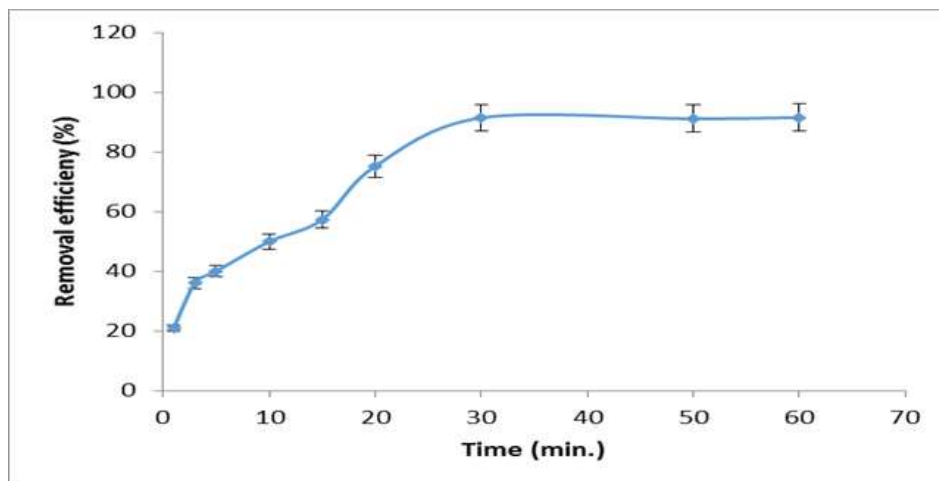


Figure 3. Effect of contact time on % Pb(II) removal efficiency

Effect of pH

One of the most important factors in the adsorption process (especially adsorption capacity) is the acidity of aqueous solution [32]. In order to assess the effect of pH on the uptake capacity of adsorbents, the experiments were performed with the pH range of 2 – 9 (Figure 4). The pH-dependent data obtained for Pb(II) ions using NiFe₂O₄ coated sand were explained by the surface properties of NiFe₂O₄ coated sand as well the nature of adsorbing species in the presence of the solution. The pHPZC of NiFe₂O₄ coated sand sample was found to be 6.31. Thus, The surface of NiFe₂O₄ coated sand was carried with positive charge below pH 6.31 and became negatively charged beyond this. On the other hand up to the pH 5.8 Pb(II) ions were dominantly existed as positively charged species. At extreme low pH region i.e. pH between 2 and 4 both solid surface of NiFe₂O₄ coated sand and adsorbing species were

possessed with enhanced positive charge which ultimately caused the strong electrostatic repulsion. Therefore, seemingly, it caused the significantly low adsorption of Pb(II) ions. However, the further increase in pH i.e. beyond 4 the partial acidic dissociation of solid NiFe₂O₄ coated sand surface may cause some electrostatic attraction of Pb(II) ions which showed an increase in Pb(II) adsorption. The similar results were obtained for different metal cations by the manganese coated sand [33,34]. However, the only electrostatic attraction could not be ascribed to explain the sorption of Pb(II) ions since surface carries a net negative charge beyond pH 6.31 (pHPZC of NiFe₂O₄ coated sand). Therefore, in addition to partial electrostatic attraction, the surface complexation through ion–exchange process was also postulated for enhanced uptake of Pb(II) ions within the range 4 – 6.

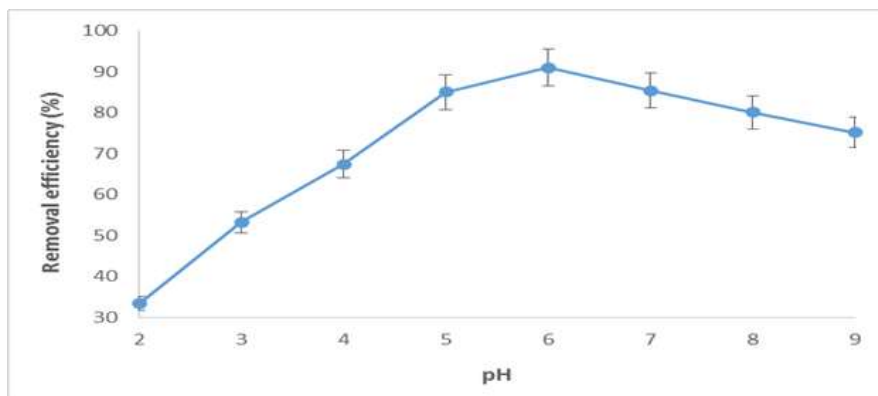


Figure 4. Effect of pH on % Pb(II) removal efficiency

The quantity of Pb(II) adsorbed raised with increasing the pH value of solution from 2.0 to 6.0 (approximately) and then with raising the pH value of solution from 6.0 to 9.0 the extent of Pb(II) adsorbed decreased. In these pH values (> 6) the Pb(II) ions start to hydrolyze and then form a little amount of Pb(OH)₂ or Pb(OH)₃⁻ diversities [35]. Compared with Pb (II) ions, these species are not suitable for absorption,

which reduces the absorption capacity, thus, the maximum adsorption occurs at pH values close to pH 6.0 and therefore for all absorption experiments in this study it's been chosen.

Effect of adsorbent dosage

The dependency of Pb(II) uptake on adsorbent dosage was examined by changing the amount of the adsorbent doses in the range of 0.01–0.5 g (Figure 5).

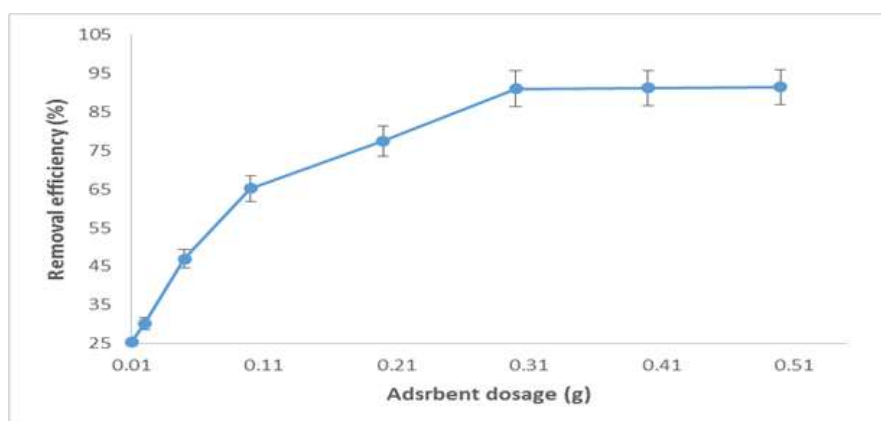


Figure 5. Effect of adsorbent dosage on % Pb(II) removal efficiency

The outcomes indicate that as the adsorbent dosage rises, the removal percentage of lead increased, until it approximates to a saturation point where the enhancement in NiFe₂O₄ coated sand dosage does not change the removal percentage. This can be ascribed to increased surface area and accessibility of more adsorption sites with increasing

quantity of adsorbent. The adsorption reached maximum percentage using 0.3 g of adsorbent.

Effect of initial Pb(II) concentration

Batch adsorption experiments were carried out at different initial concentrations of Pb(II) (5, 10, 30, 50, 100, 200, 400 and 600 mg L⁻¹), at pH 6.

An amount of 0.3 g L^{-1} of NiFe_2O_4 coated sand was used for each adsorption experiment, in 30 min. Figure 6 illustrates that with rising the initial lead concentration from 0.0 to 600 mg L^{-1} , the amount of lead adsorption decreases. Removal efficiency percentage (% R) was greater for low initial Pb(II)

concentration due to accessibility of unoccupied binding sites on the adsorbent. Since the binding sites were approximately entirely covered at high Pb(II) concentrations, removal efficiency decreased with increasing Pb(II) concentration.

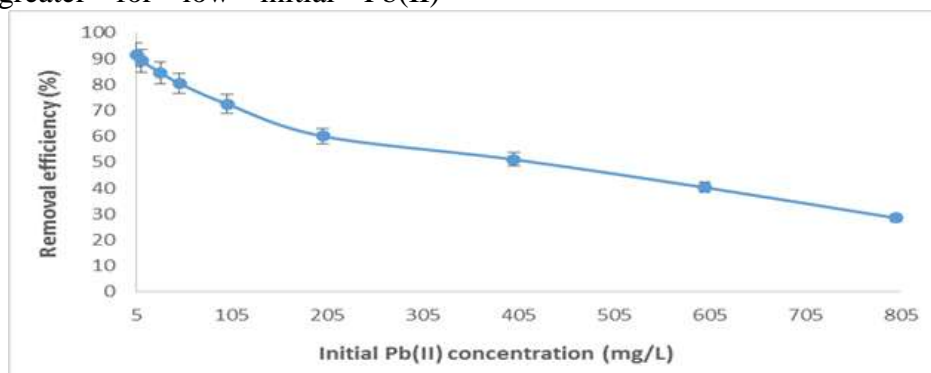


Figure 6. Effect of initial Pb(II) concentration on % Pb(II) removal efficiency

Effect of ionic strength

In order to study the influence of ionic strength on the Pb(II) ions removal efficiency by NiFe_2O_4 coated sand, experiments were carried out in optimum conditions and five different time durations (5, 10, 20, 30, and 60 min) with three different ionic strengths (0.1 , 0.3 , and 3 mol L^{-1}) solution. The ionic strength in each experiment was set using sodium sulfate. The results of each experiment were calculated and indicated in Figure 7. The ionic strength of the solution in the adsorption process of Pb(II) ions is very important. Because solutions with high ionic strength are similar and comparable to wastewaters. Such solutions result in more absorption through electromagnetic interactions between Pb(II) ions and adsorbent surface. In accordance to the surface chemistry theory, when NiFe_2O_4 coated sand is in contact with Pb(II) ions in solution, it is encircled by an electrical diffused double layer, the thickness of which is remarkably extended by the existence of electrolyte [36]. In this

study, for examining the effect of ionic strength on adsorption process by NiFe_2O_4 coated sand, the capability of three different ionic strengths (0.1 , 0.3 , and 3 mol L^{-1}) were chosen. As Figure 7 displays, with rising of ionic strength from 0.1 to 3 mol L^{-1} , Pb(II) ions removal efficiency reduces. This phenomenon occurs because increasing the concentration of sodium ions in the solution increases the ionic strength of the solution too. The sodium ions are located near to the surface of NiFe_2O_4 coated sand. The aggregation of these positive ions throughout the adsorbent leads to a reduction in the exposure between Pb(II) ions and NiFe_2O_4 coated sand and finally, Pb(II) ions adsorption capability by the adsorbent reduces. From the other point of view, the high concentration of sodium ions contends with Pb^{2+} ions and place on the active sites present on the surface of NiFe_2O_4 coated sand. Therefore, the active sites on the surface of the NiFe_2O_4 coated sand fill completely and cause a reduction in Pb(II) ions removal efficiency.

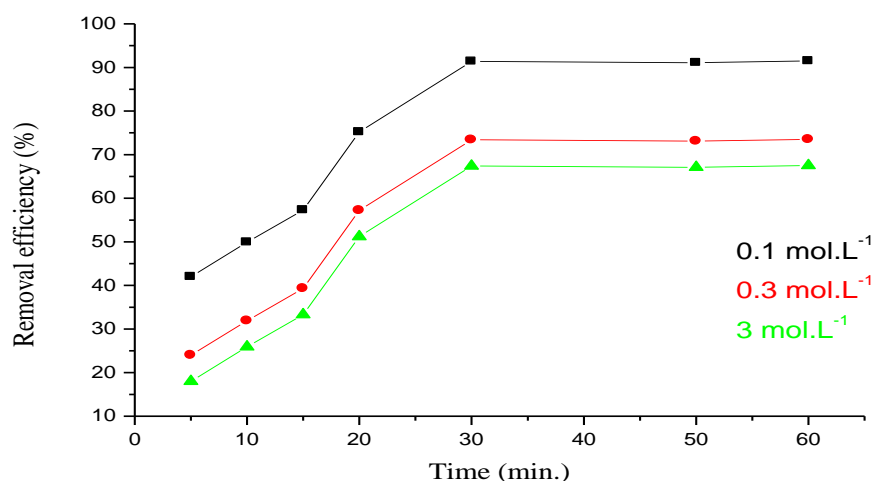


Figure 7. Effect of the ionic strength on % Pb(II) ions removal efficiency

Adsorption isotherms

The result outcomes of this study were investigated by Langmuir, Freundlich

and Dubinin–Radushkevich (D–R) models, as indicated in Table 1.

Table 1. Langmuir, Freundlich and D–R isotherm constants for the adsorption of Pb(II) ions onto NiFe₂O₄ coated sand

Langmuir			
q_m (mg g ⁻¹)	K_L	R_L	R^2
70.92	1.119	0.002 - 0.205	0.907
Freundlich			
n	K_F	R^2	
2.439	19.240	0.980	
Dubinin–Radushkevich (D–R)			
q_m (mg g ⁻¹)	β (mol ² kJ ⁻²)	R^2	E (kJ mol ⁻¹)
126.723	8×10^{-8}	0.503	2.500

As the results show, the highest value of R^2 for Freundlich isotherm (0.980) describes that the Pb(II) adsorption on NiFe₂O₄ coated sand is best represented by this model. According to this model, the maximum absorption capacity, K_F and n values are calculated to be 19.240 and 2.439, respectively, which indicate the suitability of the absorption process. The value of n was more than one, indicating that the uptake of Pb(II) on NiFe₂O₄ coated sand adsorbent was favorable. The maximum absorption capacity (q_m) and Langmuir constant, K_L for the adsorption process were 70.92 mg g⁻¹

and 1.119 L g⁻¹, respectively, based on the Langmuir model.

According to the results of isotherm studies, lead adsorption on NiFe₂O₄ coated sand shows multi-layer adsorption. From Table 1, it is denoted that the predicted q_m value from D-R isotherm is not in agreement with the formerly determined Langmuir isotherm q_m value. The correlation coefficient for the D-R isotherm is the lowest in comparison to those values of other two isotherm models (Table 1) indicating that the Pb(II) uptake on NiFe₂O₄ coated sand is not a physical process [37].

Adsorption kinetics

The kinetics parameters of the pseudo-first and pseudo-second order models are given in Table 2 in which the correlation coefficient value (R^2) for pseudo-second order model was found to be 0.983 for Pb(II) adsorption by NiFe₂O₄ coated

sand. In addition, as seen in Table 2, the theoretical q_e value from pseudo-second order model is closer to the experimental q_{exp} value. Therefore, the adsorption of Pb(II) on NiFe₂O₄ coated sand can be well described by the pseudo-second order kinetic model.

Table 2. Kinetic models parameters for the Pb(II) adsorption on NiFe₂O₄ coated sand

Kinetic models						
Pseudo first-order			Pseudo second-order			
R^2	$q_{e,cal}$ (mg g ⁻¹)	k_1 (min ⁻¹)	R^2	$q_{e,exp}$ (mg g ⁻¹)	$q_{e,cal}$ (mg g ⁻¹)	k_2 (g/(mg.min))
0.922	1.215	0.067	0.983	1.490	1.682	0.810

The absorption capacity is a significant parameter that determines the behavior of an adsorbent. Table 3 compares the maximum uptake capacity

of NiFe₂O₄ coated sand for Pb(II) adsorption with that of other adsorbents in the literature.

Table 3. Maximum adsorption capacity of different adsorbents for Pb(II) removal

Adsorbents	Langmuir adsorption capacity q_m (mg g ⁻¹)	References
Activated sludge biomass	44.75	[37]
β - Manganese oxide	13.57	[38]
Aluminum oxide nanoparticles	34.10	[39]
Multi-walled carbon nanotubes/polyacrylamide	29.71	[40]
Magnetic halloysite nanotubes/manganese oxide	59.90	[41]
Magnetic alginate beads	50.00	[30]
NiFe ₂ O ₄ coated sand	70.92	Present study

Conclusion

The kinetic study indicates that the equilibrium contact time is 30 min and was well-arranged with pseudo-second-order kinetics model rather than pseudo-first-order kinetics model. Adsorption isotherm data is well-fitted in Freundlich adsorption isotherm with greater correlation coefficient ($R^2 = 0.980$). Thus, the nano-adsorbent NiFe₂O₄ coated sand provides an economical and favorable method for the removal of Pb(II) from aqueous solutions.

Acknowledgements

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