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Functionalized core-shell nanoparticles as an effective and recyclable magnetic nanoadsorbent for the removal of Pb^{2+} ions from aqueous solutions

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1. ABSTRACT

In the present study, glucosamine-modified $Fe_3O_4@SiO_2$ -TCT-GA nanosorbents were synthesized and their ability to separate lead ions from aqueous solutions was investigated. The effects of parameters affecting the adsorption efficiency, including adsorption isotherms, adsorbent dose, adsorbent contact time, selective removal, and solution pH, on the adsorption behavior were evaluated and discussed. Kinetic adsorption tests showed a better fit with the pseudo-second-order model, and the equilibrium data were in good agreement with the Langmuir model, which estimated the maximum $Pb(II)$ adsorption to be 131.58 mg/g using this model. The desorption of heavy metal ions using HCl solution was effectively performed, and the results showed that the nanosorbent could be magnetically separated, regenerated, and effectively reused for seven consecutive cycles without significant loss of adsorption capacity. The effective heavy metal removal performance of this adsorbent demonstrated the feasibility of the adsorbent for industrial applications.

Keywords: $Fe_3O_4@SiO_2$ -TCT-GA nanosorbent; surface modification; adsorption/desorption; lead heavy metal; magnetic adsorbent; adsorption capacity.

2. INTRODUCTION

The use of metals and chemicals and the rapid development of various industries have led to an increase in metal pollution in water. Heavy metal pollution is a major environmental problem due to its non-biodegradability, potential for accumulation, and high toxicity in the environment. Heavy metals such as lead are considered as toxic elements for humans, animals, and the environment [1].

In recent years, various conventional methods (filtration, adsorption, membrane processes, ion exchange, chemical complexation, chemical precipitation, electro dialysis and flocculation) have been reported for the separation of heavy metal ions from wastewater. Most of these methods have disadvantages such as inefficiency, high cost, technical complexity and economic unprofitability. Adsorption is known as one of the best methods due to its simple operation, effectiveness and flexible selection of adsorbents, higher preconcentration factors, low cost and renderability. Therefore, the development of adsorption methods and the fabrication of new adsorbent materials for the removal of heavy metal ions are in demand [2].

Nanomaterials play a significant role in the separation of metal ions as a promising alternative adsorbent due to their unique properties such as increased active sites, size and surface effects, low diffusion resistance and high surface area. Among the available adsorbents, magnetic nanoparticles such as Fe_3O_4 nanoparticles are of interest due to their magnetic

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properties, advantages of high sensitivity and efficiency, and rapid separation from aqueous solution using a magnetic field, which provides ease of operation for applications [3].

Nowadays, functionalization of $\text{Fe}_3\text{O}_4@/\text{SiO}_2$ nanoparticles has attracted special attention, mainly due to the potential applications of these materials, especially in catalysts, drug delivery and adsorption. Therefore, the present work focuses on the synthesis of trichloro triazine (TCT) and glucosamine (GA) immobilized on superparamagnetic $\text{Fe}_3\text{O}_4@/\text{SiO}_2$ nanoparticles for the removal of heavy metal ions from aqueous media [4].

3. MATERIALS AND METHODS

3.1. Materials and Equipment

All reagents and solvents were purchased from Merck & Aldrich and used without any pretreatment. Metal concentrations were estimated using an inductively coupled plasma spectrometer (ICP, Varian, Vista-pro).

3.2. Methodology

The Fe_3O_4 nanoparticles were prepared using chemical co-precipitation method. Afterwards, Fe_3O_4 nanoparticles were encapsulated by SiO_2 according to the modified Stöber method and $\text{Fe}_3\text{O}_4@/\text{SiO}_2$ nanoparticles were produced. $\text{Fe}_3\text{O}_4@/\text{SiO}_2$ nanoparticles were mixed with 3-chloromethoxypropylsilane and the obtained products were named $\text{Fe}_3\text{O}_4@/\text{SiO}_2\text{-Cl}$ samples (with 81% yield). $\text{Fe}_3\text{O}_4@/\text{SiO}_2\text{-Cl}$ nanoparticles were added to a mixture of 3-(3-hydroxypropylamino)-propan-1-ol (and triethylamine) to complete the reaction. Finally, the resulting $\text{Fe}_3\text{O}_4@/\text{SiO}_2\text{-N(OH)}_2$ was synthesized (with a yield of 87%). Cyanuric chloride compound was added to the $\text{Fe}_3\text{O}_4@/\text{SiO}_2\text{-N(OH)}_2$ nanoparticles, and $\text{Fe}_3\text{O}_4@/\text{SiO}_2\text{-TCT}$ nanoparticles (with a yield of 83%) were prepared by magnetic separation. Then, glucosamine compound was added to the $\text{Fe}_3\text{O}_4@/\text{SiO}_2\text{-TCT}$ nanoparticles, and the final product (with a yield of 82%) was synthesized as magnetic nanoparticles $\text{Fe}_3\text{O}_4@/\text{SiO}_2\text{-TCT-GA}$ [5].

4. RESULTS AND DISCUSSION

4.1. Optimization of effective parameters in the adsorption process

The effect of the magnetic nanoadsorbent on the amount of lead adsorption (80 mg/L) at 25°C and pH 7 is investigated. According to the experimental data, the q values increased and after 25 mg q slightly decreased with increasing the adsorbent dose (from 2.5 to 25 mg). With increasing the adsorbent dose, more surface area is available for adsorption and as a result, more adsorption sites are available for effective adsorption.

The pH of the solution plays an important role in the interaction between the adsorbent and the pollutant. The results show that with increasing pH from 3 to 7, the q value increased and after pH 7, the q value decreased. With increasing pH, the amount of H^+ ions on the active sites of the adsorbent surface decreases and accordingly, the amount of positive charge on the adsorbent surface should decrease. This reduces the electrostatic repulsion between the heavy metals and the adsorbent surface and, as a result, the adsorption rate increases. At solution pH above 7, lead hydroxyl moieties predominate, which prevent the binding between the heavy metals and the adsorbent, and a decrease in adsorption capacity occurred.

At an initial concentration (C_0) of less than 80 mg/L, the adsorption capacity (q) increases with increasing C_0 values. This phenomenon proves that with increasing heavy metal concentration, higher ions are available and increase the adsorption driving force. Meanwhile, the steric barrier increases and prevents ions from penetrating the active surface of the adsorbent at a higher initial contaminant concentration. On the other hand, the electrostatic repulsion of ions causes particles to move away from the adsorbent surface and the adsorption capacity remains almost constant after a certain initial concentration.

As the temperature increases from 25 to 35°C, the adsorption capacity of lead increases. However, as the temperature increases to 45°C, the adsorption capacity decreases. With increasing temperature, the irregular movements of the pollutant and the adsorbent in the solution increase and the probability of pollutant adsorption increases. The decrease in adsorption capacity at 45°C may be due to the breaking of weak Vander Waals bonds between the heavy metal and the adsorbent.

4.2. Isotherm and adsorption kinetics

The results showed that the R^2 values of the Langmuir isotherm model are higher than those of the Freundlich model which indicates a better fit of the data with the Langmuir model and indicates that the adsorption of lead pollutants on the surface of the $\text{Fe}_3\text{O}_4@/\text{SiO}_2\text{-TCT-GA}$ adsorbent is more homogeneous and monolayer. The maximum adsorption capacity estimated by the Langmuir model for the $\text{Fe}_3\text{O}_4@/\text{SiO}_2\text{-TCT-GA}$ adsorbent for the removal of lead ions is 131.58 mg/g. The data of kinetics experiments proved that the pseudo-first and second order kinetic parameters for the $\text{Fe}_3\text{O}_4@/\text{SiO}_2\text{-TCT-GA}$ adsorbent for the removal of lead ions. According to the R^2 values, the pseudo-second order kinetic model were shown a better fit with the data. This indicates that the controlling mechanism can be chemical adsorption and electrostatic adsorption.

5. CONCLUSION

This nanoadsorbent exhibits fast adsorption kinetics for the target ion. The proposed method was well fitted to the second-order kinetic model which indicates that the rate-limiting step is chemisorption. The adsorption data were analyzed according to the Langmuir isotherm model, and the maximum adsorption of lead ion by the $\text{Fe}_3\text{O}_4@/\text{SiO}_2\text{-TCT-GA}$ nanoadsorbent was calculated to be 131.58 mg/g by applying the Langmuir equation. Moreover, after 7 times of adsorption/desorption operations, only 8% decrease in the removal efficiency of lead metal by the nanoadsorbent



occurred. The simple preparation method, high adsorption capacity, fast adsorption rate, and good reusability make this nanoadsorbent an environmentally friendly and economically viable adsorbent for the rapid removal of heavy metal ions from contaminated water.

6. REFERENCES

- [1] Esmailpour, M. and Ghahraman Afshar, M., Magnetic Nanoadsorbent: Preparation, characterization, and Adsorption Properties for Removal of Copper (II) from Aqueous Solutions, *App Chem. Today*, 18, pp. 11-20, 2023.
- [2] Asgharinezhad, A. A., Esmailpour, M., Ghahraman Afshar, M., Synthesis of magnetic $\text{Fe}_3\text{O}_4@ \text{SiO}_2$ nanoparticles decorated with polyvinyl alcohol for Cu (II) and Cd (II) ions removal from aqueous solution, *Chem. Papers*, 78, pp. 3799-3814, 2024.
- [3] Esmailpour, M., Ghahraman Afshar, M., Noroozi Tisseh, Z., Ghahremanzadeh, R., Removal of copper and chromium ions from aqueous solutions with magnetic nanoparticles functionalized with N-phosphonomethyl amino diacetic acid, *J. Appl. Res. Chem.-Pol. Eng.*, 7, pp. 33-46, 2023.
- [4] Esmailpour M., Ghahraman Afshar, M., Kazemnejadi, M., Preparation, characterization, and adsorption properties of bis-salophen schiff base ligand immobilized on $\text{Fe}_3\text{O}_4@ \text{SiO}_2$ nanoparticles for removal of lead (II) from aqueous solutions, *App. Chem. Today*, 18, pp. 125-146, 2023.
- [5] Zarabadipour, M., Soleimani, M., and Ghahraman Afshar, M., Application of functionalized $\text{Fe}_3\text{O}_4@ \text{SiO}_2$ nanoparticles as an adsorbent for heavy metal removal, *Res. Chem.*, 17, p. 102514-102527, 2025.