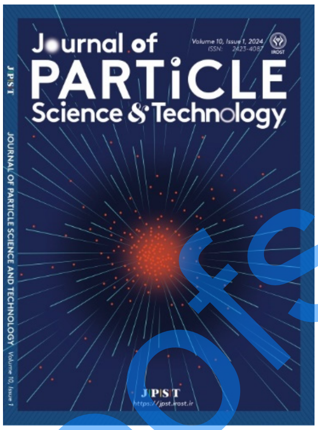

Application of modified bentonite for efficient water purification: A case of Cr(VI) adsorption

Zahra Jelodari, Maryam Khajenoori, Pouya Mottahedin

DOI: https://doi.org/10.22104/jpst.2025.7462.1273
Manuscript number: JPST-2503-1273

To appear in: *Journal of Particle Science and Technology (JPST)*

Received Date: 16 March 2025

Received Date in revised form: 20 April 2025

Accepted Date: 8 May 2025

Please cite this article as: Jelodari Z., Khajenoori M., Mottahedin P Application of modified bentonite for efficient water purification: A case of Cr(VI) adsorption, *Journal of Particle Science and Technology* (2024), doi: https://doi.org/10.22104/jpst.2025.7462.1273

Application of Modified Bentonite for Efficient Water Purification: A Case of Cr(VI) Adsorption

Zahra Jelodari[a], Maryam Khajenoori[a,*] , Pouya Mottahedin[b]

[a] Faculty of Chemical Petroleum and Gas Engineering, Semnan University, Semnan, Iran
[b] Department of Chemical Engineering, Faculty of Engineering, University of Garmsar, Garmsar, Iran

Abstract

This study explores the use of acid-activated bentonite as an efficient adsorbent for removing hexavalent chromium (Cr(VI)) from water. Acid activation enhances the surface area and adsorption capacity of bentonite, improving its water treatment efficiency. Various techniques, including BET, FT-IR, XRD, XRF, and SEM, were used to analyze structural and compositional changes after activation. Adsorption experiments showed that under optimal conditions—room temperature, 0.1 ppm Cr(VI), and 1 g of acid-activated bentonite—100% removal was achieved. The adsorption followed the Langmuir isotherm with a maximum capacity of 0.122 mg/g. Kinetic studies confirmed a pseudo-second-order reaction model ($R^2 = 0.99$), indicating a chemisorption mechanism. Thermodynamic analysis showed the process is spontaneous and exothermic, requiring no external energy input. Groundwater tests from the Foroomad region (Semnan Province) compared raw and acid-modified bentonite, revealing a 92% Cr(VI) removal efficiency with the modified form, reducing contamination to safe levels. These results highlight acid-activated bentonite as a cost-effective and eco-friendly adsorbent for water purification, demonstrating its real-world potential for ensuring safer drinking water.

Keywords: Adsorption, Bentonite, Acid-activated bentonite, Hexavalent chromium, Thermodynamic and kinetic study

1. Introduction

This study addresses the significant environmental issue of hexavalent chromium (Cr(VI)) contamination in water. Cr(VI) is a highly toxic heavy metal associated with serious health risks such as kidney damage, digestive disorders, and cancer. It primarily originates from industrial discharges, making its removal from water essential to protect human health and the food chain. Traditional methods for heavy metal removal, such as ion exchange and filtration, are costly and often produce secondary pollutants, making them less suitable for large-scale or low-concentration treatment [1]. As an alternative, bentonite, a natural clay mineral, has been explored due to its low cost, high surface area, and ability to adsorb cationic contaminants. However, to enhance its ability to adsorb anionic pollutants like Cr(VI), bentonite is modified through acid activation, which increases its surface area and acidity. Sulfuric acid is particularly effective for this purpose, improving the bentonite's adsorptive capacity for Cr(VI) compared to hydrochloric acid. The acid activation process creates additional active sites on the clay, boosting its efficiency in adsorbing harmful ions [2,3]. Using advanced characterization techniques, such as X-ray diffraction (XRD) and scanning electron microscopy (SEM), the study investigates the effects of sulfuric acid activation on bentonite's structure and adsorption properties. The results indicate that acid-activated bentonite is highly effective in removing Cr(VI) from contaminated water, with the process being spontaneous and thermodynamically favorable [4,5].

Researches support the use of acid-modified bentonite as a cost-effective and environmentally friendly solution for heavy metal contamination in water. They offer a sustainable alternative to traditional water treatment methods and has potential for large-scale application in industrial and municipal water treatment [6,7]. Bentonite's properties, especially after acid activation, significantly enhance its effectiveness as an adsorbent, proving its potential for widespread use in the purification of water contaminated by heavy metals [8,9].

In recent years, pollution of water resources by heavy metal ions, particularly hexavalent chromium, has become a serious environmental issue. Conventional methods for removing these pollutants, such as ion exchange and membrane processes, have limitations due to high costs and the generation of secondary waste. In this context, bentonite has attracted attention as an effective adsorbent due to its wide availability, low cost, and high ion exchange capacity. However, raw bentonite has limited efficiency in adsorbing anionic pollutants, and improving its structural properties requires physical or chemical modification processes.

This study focuses on the preparation of acid-activated bentonite and its use in the removal of hexavalent chromium from polluted water. The objective is to examine the efficiency of evaluating the modified bentonite's effectiveness as an adsorbent and to investigate the underlying adsorption mechanisms through various characterization techniques and thermodynamic analyses. Structural and chemical investigations showed that the modification process led to a significant increase in chromium removal from aqueous solutions. Unlike many previous studies that focused solely on laboratory experiments, this research evaluated the adsorbent's performance under real conditions using groundwater samples from the Faromad region (Semnan province), demonstrating the industrial applicability of this method. Moreover, optimization of adsorption conditions through Response Surface Methodology (RSM) and Box-Behnken Design (BBD) enabled the identification of ideal operational parameters. The results of this study indicate that acid modification of bentonite not only significantly increases chromium removal but also facilitates the reuse of this adsorbent in the treatment of polluted waters. By using advanced characterization techniques and thermodynamic analyses, the research aims to evaluate the structural and chemical properties of the modified bentonite and contribute to the development of effective and sustainable methods for treating Cr(VI)-contaminated water. This research offers a novel, effective, cost-efficient, and environmentally friendly approach for removing metal pollutants from water resources.

2. Materials and Methods

2.1. Materials

Raw bentonite was procured from Niakan Company in Semnan, Iran. The chromium testing tablets were sourced from Wagtech, UK, while potassium dichromate ($K_2Cr_2O_7$) powder and sulfuric acid (H_2SO_4, 98%) were acquired from Merck, Germany, and subsequently utilized in the experimental procedures.

2.2. Chromium (VI) standard solution preparation

To prepare a 1000 ppm standard solution of hexavalent chromium, dissolve 0.1 grams of potassium dichromate ($K_2Cr_2O_7$) powder in a 100 mL beaker containing purified water. From this solution, take 10 mg/L and Dilute the solution to a final volume of 100 mL to attain the target concentration of 100 ppm. Standard solutions with chromium concentration values of (0.1 - 0.5 - 1) mg/L are then prepared using distilled water. The initial concentration of each standard is determined using a spectrophotometer at a wavelength of 540 nm [1,2].

2.3. Raw bentonite adsorbent preparation method

Initially, 100 grams of raw bentonite is mixed with distilled water (double distilled) and allowed to soak for 6 hours. After soaking, the wet bentonite is passed through filter paper to partially dry it, and then, it is placed in an oven at 120°C and heated for 6 hours to ensure complete drying. Once dry, the bentonite is ground and sieved for uniform particle size [12,13].

2.4. Acid activation procedure for bentonite adsorbent

To activate bentonite, mix 50 grams of raw bentonite with 500 mL of 3 M sulfuric acid solution in a 1000 mL beaker. Heat the mixture to 110 °C under continuous stirring (220 rpm) for 4 hours. Quickly stop the reaction by adding 500 mL of ice-cold water and discontinue heating. Filter the suspension and wash the residue with distilled water to remove residual acid. Finally, dry the acid-treated bentonite at

120 °C for 6 hours, then grind and sieve it to ensure uniform particle size, making it ready for adsorption [11].

Figure 1. Process of modifying natural bentonite with sulfuric acid, application of modified clay for chromium(VI) removal from aqueous solutions, and Extraction of hexavalent chromium from potable water using acidic bentonite.

2.5. Removal of hexavalent chromium

To assess the removal of hexavalent chromium, a specific amount of raw and acid-activated bentonite is mixed with a chromium(VI) solution in a jar test apparatus at 300 rpm (as shown in Figure. 1). After a designated contact time, the solution is separated from the adsorbent using centrifugation, yielding a clear supernatant. Finally, the hexavalent chromium concentration in the supernatant is measured using a spectrophotometer at a wavelength of 540 nm.

The laboratory equipment used in this study includes a WTW Inolab7110 pH meter, a Wagtech 7100 spectrophotometer, a Sartorius laboratory balance with an accuracy of five decimal places, a JTR90 six-position jar test apparatus, a DEMERD oven, and a DHS 700 hot plate magnet.

2.6. Removal of hexavalent chromium in batch mode

Batch adsorption studies were performed in 100 mL conical flasks, mixed using a shaker at a constant speed. Optimal conditions for factors like adsorbent dosage, temperature, and initial chromium(VI) concentration were analyzed using Design Expert software. After the experiments, suspensions were centrifuged, and the final chromium(VI) concentration was measured using a spectrophotometer [14,15].

The percentage of chromium (VI) removed can be determined using the following formula:

$$R\% = \frac{C_o - C_f}{C_o} \times 100 \tag{1}$$

To calculate the adsorption capacity (q) of the adsorbent, the following formula can be used:

$$q_e = \left(C_o - C_f\right) \times \frac{V}{m} \tag{2}$$

In the above equations, C_0 and C_f represent the starting and ending concentrations regarding hexavalent chromium solution, respectively, while V denotes the volume of the solution, and mmm represents the mass of the adsorbent.

2.7. Investigation of the point of zero charge (pHpzc) in raw bentonite

The point of zero charge pH_{pzc} for raw bentonite was assessed by mixing 0.55 grams of bentonite with a hexavalent chromium solution, with the initial pH adjusted between 2 and 10 using nitric acid and sodium hydroxide. The mixture was diluted to reach a total volume of 100 ml/g. Subsequently, 0.55 mL of the adjusted solution was placed in a jar test apparatus and blended at 300 rpm over a 24-hour period. The final pH, referred to as pH_f , was measured after the mixing period. By plotting pH_f against the initial pH values, the pH_{pzc} was derived from the intersection of the plotted curve [16,17].

3. Results and Discussions

The XRD patterns of raw bentonite (Figures 2A and 2B) reveal distinct peaks for montmorillonite (M) at 6°, 19.8°, 34.9°, and 60.3°, confirming its layered structure, characterized by high cation exchange capacity and significant water absorption. Peaks for clinoptilolite (C) appear at 9°, 11.2°, and 22.3°, along with heulandite (H) peaks at 9° and 23.3°, both exhibiting notable adsorption and ion exchange properties. Quartz (Q) peaks at 26.6° and 50.1° indicate its presence as a stable impurity. In acid-activated bentonite, montmorillonite peaks (5.5°, 19.8°, 34.9°, and 60.3°) persist, demonstrating structural resilience to acid treatment, while the peaks for clinoptilolite and heulandite decrease, suggesting potential structural degradation. Quartz peaks remain unchanged, indicating its stability. Both bentonites exhibit similar crystallinity with varying peak intensities, and new peaks appear in the acid-activated sample, with an expansion in interlayer spacing from 14.72 Å to 16.04 Å post-acid treatment, indicating structural alterations potentially due to acid infiltration or enhanced water absorption.

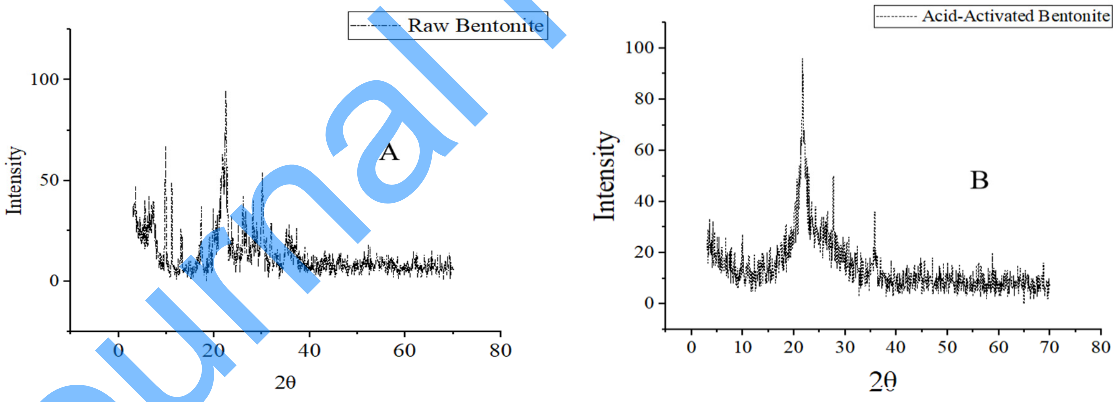

Figure 2. XRD patterns of A) unmodified bentonite and B) treated bentonite.

The layered structure of raw bentonite (Figures 3A and 3B) indicates its natural and intact state, characterized by well-ordered, fibrous layers that provide exceptional properties, including high cation exchange capacity and superior water absorption. In contrast, the irregular and fragmented morphology of acid-activated bentonite reveals that the acid treatment has caused degradation and disintegration of the clay layers, resulting in increased specific surface area and porosity, significantly enhancing its adsorption capacity for contaminants and metal ions.

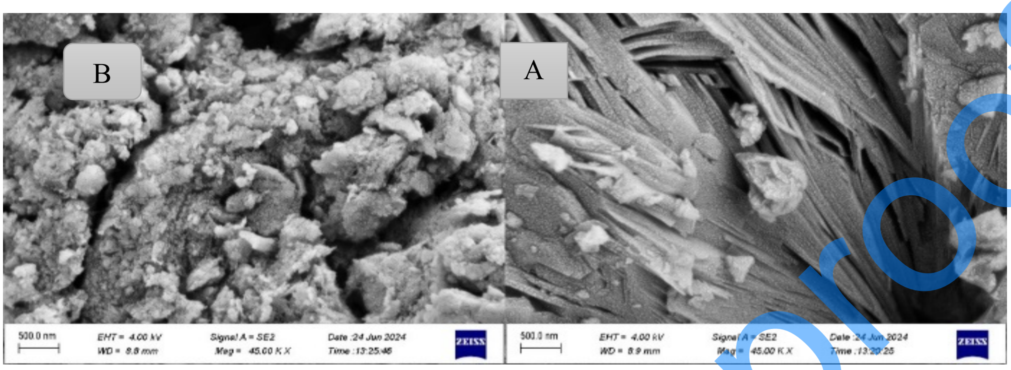

Figure 3. SEM image: A) Raw bentonite, B) Acid-modified bentonite.

The FT-IR spectrum analysis of both raw and acid-activated bentonite (Figures 4A and 4B) reveals their intricate mineral structures and provides crucial insights into their chemical compositions and functional groups. Key peaks at 3487.06, 3452.34, and 3433.06 cm^{-1} indicate the presence of molecular water and hydroxyl (OH) groups that enhance adsorption capacity, while the peak at 3627.85 cm^{-1} reflects free OH groups. The peak at 1635.52 cm^{-1} shows vibrations of adsorbed water, and the peaks at 1047.27 and 1068.49 cm^{-1} are associated with Si-O-Si stretching vibrations that contribute to structural integrity. The peak at 792.69 cm^{-1} indicates bending modes of Si-O-Si or Si-O-Al, and the peaks at 1609.46, 520.74, and 468.67 cm^{-1} relate to deformational vibrations of Si-O and Al-O bonds, essential for cation exchange capacity. These observations highlight the significant roles of hydroxyl groups, silicate and aluminosilicate structures, and the presence of water in enhancing the adsorption properties of both types of bentonite.

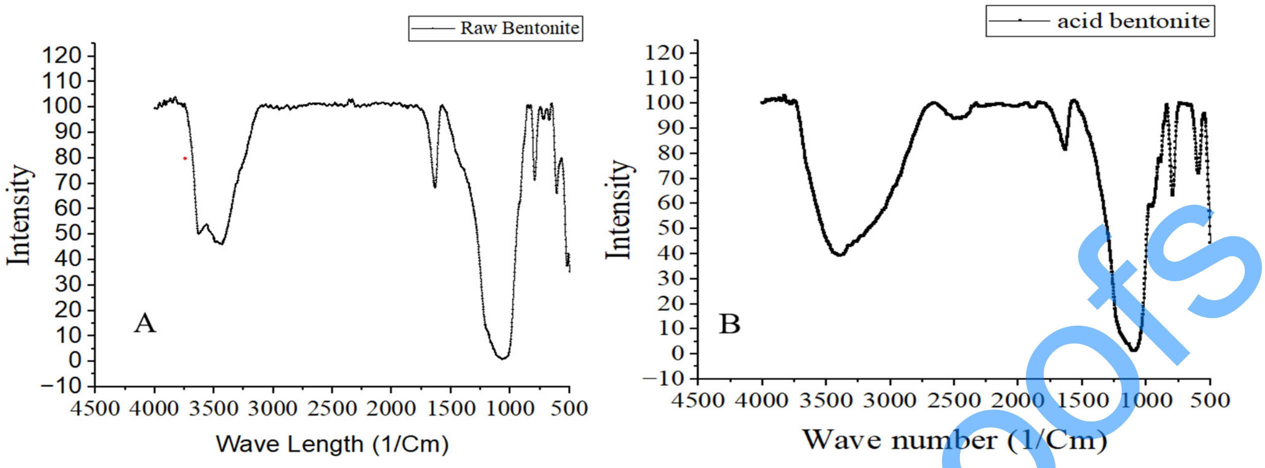

Figure 4. FTIR spectra of raw and acid-modified bentonite: A) Raw bentonite, B) Acid-modified bentonite.

The textural properties of raw and acid-activated bentonite, as shown by the N_2 adsorption/desorption isotherms in Figures 5A and 5B, indicate that both samples follow type IV isotherms with H3 hysteresis loops, which are characteristic of layered clays with slit-like mesopores. As shown in Table 1, acid activation significantly increased the specific surface area from 18.33 m²/g to 53.42 m²/g, while the total pore volume increased from 0.056 cm³/g to 0.069 cm³/g, likely due to particle breakdown and the edge-opening of clay sheets[18].

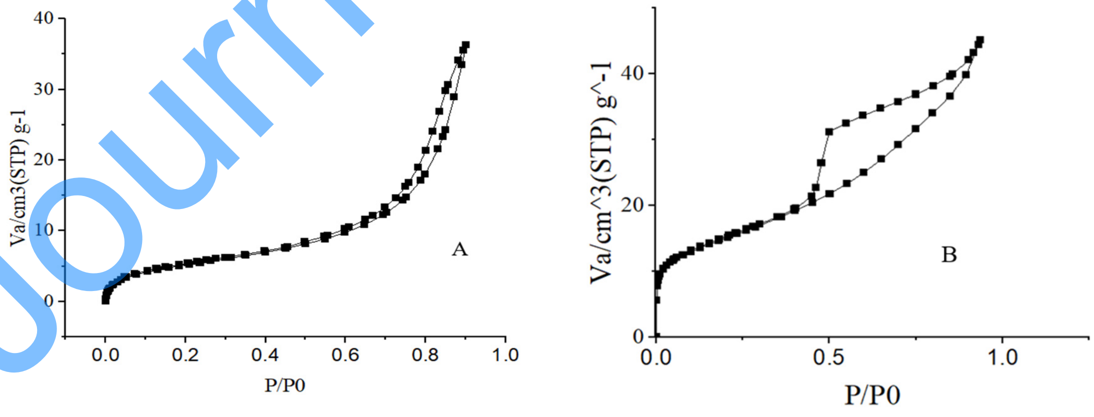

Figure 5. N_2 Adsorption-Desorption isotherm curves: A) Raw bentonite, B) Acid-modified bentonite.

Table 1. Structural pore parameters for natural and acid-activated samples.

Sample	**Parameters**	**Unit**	**Value**
Raw bentonite	V_m	[cm^3(STP)/g]	4.2125
	as, BET	[m^2/g]	18.335
	Total Pore Volume ($p/p_0 = 0.901$)	[cm^3/g]	0.056
	Mean Pore Diameter	[nm]	12.244
Acid-activated bentonite	Vm	[cm^3(STP)/g]	12.275
	as, BET	[m^2/g]	53.426
	Total Pore Volume ($p/p_0 = 0.937$)	[cm^3/g]	0.069
	Mean Pore Diameter	[nm]	5.234

3.1. Interaction of parameters and optimization using RSM-BBD

Response Surface Methodology (RSM) was employed to develop a mathematical model relating independent variables to chromium removal efficiency. The analysis considered temperature (20–40°C) and acid adsorbent concentration (0.1–1 g/L), with results summarized in Table 2, detailing removal efficiency and adsorption capacity. Table 3 presents the ANOVA results for the second-order response surface model, showing a total sum of squares of 9290.29, a mean square of 1327.18, an F-value of 73.95, and a p-value of <0.0001, confirming the model's significance. The Lack of Fit test yielded a p-value of 0.1472, indicating an insignificant lack of fit and confirming the model's adequacy. Table 4 reports the coefficient of determination ($R^2 = 0.9829$) and adjusted R^2 (0.9696), demonstrating that the model explains 98.29% of the total variability.

The Eq.(3) represents the model provided by the software for the response percentage of hexavalent chromium removal:

$$R\% = 76.96 - 15.98 \times A + 26.85 \times B - 5.19 \times C + 7668 \times AB + 4.85 \times AC - 8.87 \times B^2 - 11.44 \times C^2 \quad (3)$$

Table 2. Experimental design matrix generated by RSM-BBD utilization of acid-activated bentonite as an adsorbent for chromium (VI) ion removal.

Run	Concentration(mg/l)	Dose(g)	Temperature(℃)	R%
1	0.550	0.100	20	30.909
2	0.100	0.100	30	62.500
3	0.550	0.550	30	78.182
4	0.550	1.000	20	90.909
5	0.100	1.000	30	100.000
6	1.000	0.550	40	43.925
7	0.550	0.100	40	30.909
8	0.100	0.550	20	93.750
9	1.000	0.100	30	17.757
10	0.550	0.550	30	76.364
11	0.550	1.000	40	80.000
12	0.550	0.550	30	74.546
13	1.000	0.550	40	68.750
14	0.550	0.550	30	80.000
15	0.550	0.550	30	81.818
16	1.000	0.550	20	49.533
17	1.000	1.000	30	85.981

The response surface plot (Figure 6A) indicates that increasing the adsorbent dose improves the removal efficiency of chromium (VI) held at room temperature (30°C) throughout the process, but excessive dosing may lead to particle aggregation, reducing the effective adsorption surface area; additionally, the response surface plot (Figure 6B) shows that maximum removal efficiency using acid-activated bentonite occurs at specific temperatures (between 35 to 40°C) and varying initial chromium concentrations, with higher temperatures enhancing adsorption until potential degradation of the adsorbent occurs.

Table 3. ANOVA results for the second-order response surface model for chromium removal percentage using acid-activated bentonite.

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	9290.29	7	1327.18	73.95	< 0.0001	significant
A-concentration	2041.72	1	2041.72	113.76	< 0.0001	
B-dose	5768.20	1	5768.20	321.39	< 0.0001	
C-temperature	215.45	1	215.45	12.00	0.0071	
AB	236.00	1	236.00	13.15	0.0055	
AC	94.02	1	94.02	5.24	0.0479	
B^2	332.04	1	332.04	18.50	0.0020	
C^2	552.39	1	552.39	30.78	0.0004	
Residual	161.53	9	17.95			
Lack of Fit	128.47	5	25.69	3.11	0.1472	not significant
Pure Error	33.06	4	8.26			
Cor Total	9451.82	16				

Table 4. Statistical data for evaluating the reduced model for the response of hexavalent chromium removal percentage by acid-activated bentonite.

Std. Dev.	4.24	**R^2**	0.9829
Mean	67.40	**Adjusted R^2**	0.9696
C.V. %	6.29	**Predicted R^2**	0.9124
		Adeq Precision	29.4731

In Figure 7, Cr(VI) removal efficiency with acid-activated bentonite rises rapidly, reaching 74% at 20 minutes and peaking at 89% at 40 minutes, indicating abundant active sites. It then slightly decreases to 85% at 60 minutes, 82% at 90 minutes, and stabilizes around 80% at 110 minutes, suggesting adsorption equilibrium. This trend aligns with Moradi et al., where adsorption increased sharply before stabilizing. The initial rise is due to available active sites, while the decline occurs as Cr(VI) ions at these sites decrease [11].

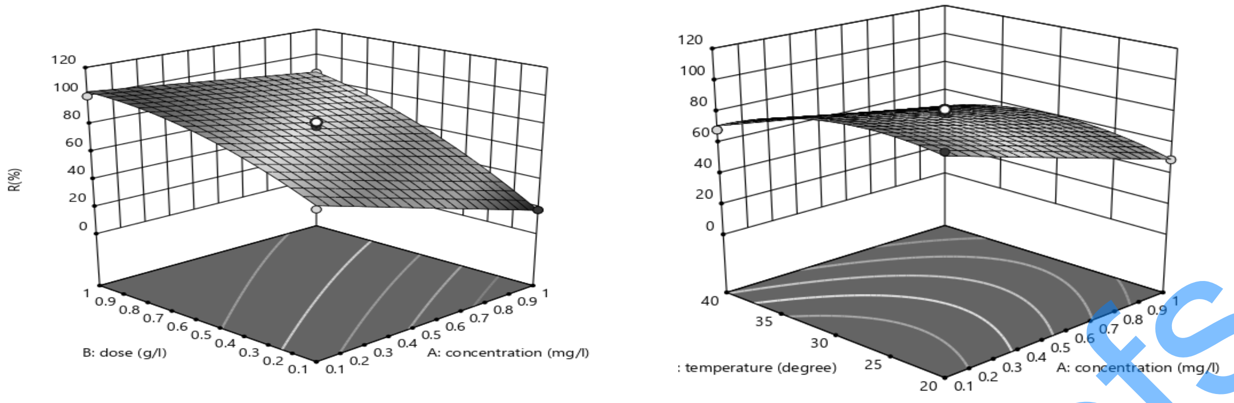

Figure 6. Response surface plots for Cr(VI) removal, illustrating the interaction effects of (A) adsorbent dose and initial Cr(VI) concentration under an adsorption time of 40 minutes and ambient temperature, and (B) solution temperature and initial Cr(VI).

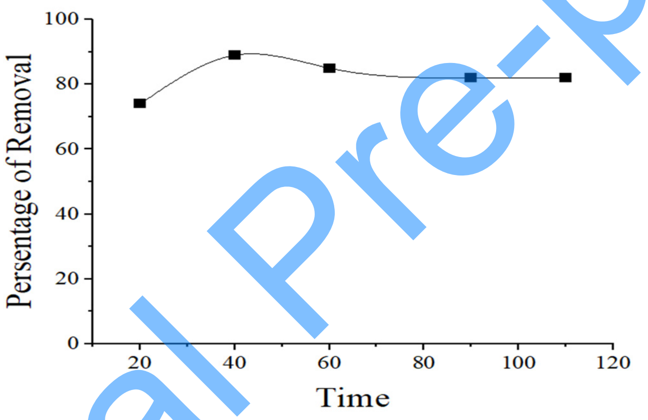

Figure 7. Time-dependent removal of hexavalent chromium (Cr(VI)) using 0.55 grams of both acid-activated and raw adsorbents, with chromium at an initial concentration of 0.55 mg/L at temperatures ranging from 25 to 30 ºC.

3.2. Adsorption isotherm

In Figures 8A and 8B, the adsorption of hexavalent chromium on acid-activated bentonite is best described by the Langmuir model. The Langmuir coefficient of determination is close to 1, indicating a good fit between the data and the model. This suggests that adsorption occurs in a monolayer with uniform energy sites on the surface of the acid-activated bentonite. Table 5 shows that the maximum adsorption capacity (qm) is 0.122 mg/g, and the Langmuir constant (Kl) is 0.047 L/mg. The Freundlich model also fits the data to some extent, but it is less accurate as it describes multilayer adsorption on heterogeneous surfaces. In this model, the parameter n is 1.750, and the Freundlich constant (Kf) is 0.047. A similar conclusion was reported by Najafpoor et al., who found that the Langmuir isotherm better described chromium adsorption onto carbon nanotubes compared to the Freundlich model [20].

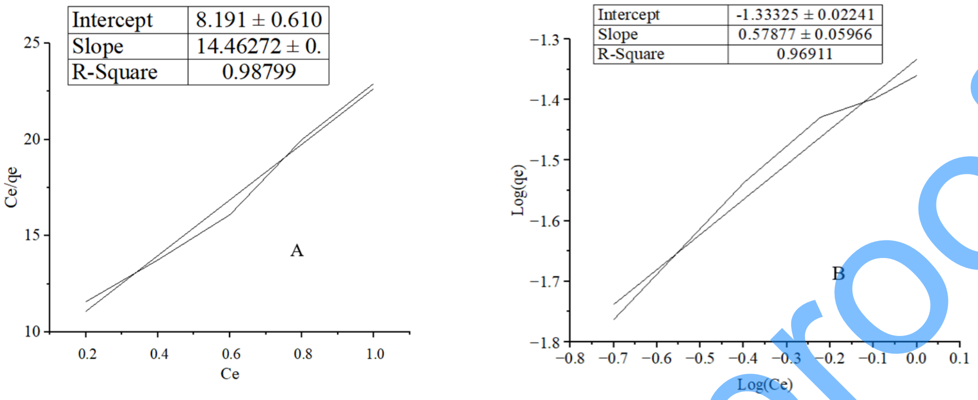

Figure 8. A and B illustrate the Langmuir and Freundlich isotherms, respectively, for the adsorption process of hexavalent chromium (Cr(VI)) using 0.55 grams of acid-activated bentonite at an equilibrium time of 40 minutes and ambient temperature.

Table 5. The results of the Langmuir and Freundlich isotherms for the removal of hexavalent chromium with acid-activated bentonite reveal.

Isotherm Model	Parameter	Value ± Error	Coefficient of Determination
Langmuir	q_m (mg/g)	0.122	0.988
	K_l (lit/mg)	0.047	
Freundlich	n	1.750	0.969
	K_f	0.047	

3.3. Kinetics of adsorption

Figure 9 shows that the adsorption of hexavalent chromium primarily follows the pseudo-second-order kinetic model, which occurs through a chemisorption process driven by interactions between Cr(VI) ions and the active sites on the adsorbent surface. In a study by Tarmizi Taher et al. [21], the pseudo-second-order model demonstrated a more precise linear fit compared to the pseudo-first-order model. In this study, the coefficient of determination (R^2) for the pseudo-second-order model exceeded 0.982, and the calculated qe value was nearly identical to the experimental qe. The results presented in Figure 9 confirm that the pseudo-second-order model more accurately describes the kinetics of Cr(VI) adsorption.

For the pseudo-first-order model, the rate constant (K_1) was 0.0146 min^{-1}, the adsorption capacity (q_e) was 0.0062 mg/g, and the coefficient of determination (R^2) was 0.8807. In contrast, for the pseudo-second-order model, the rate constant (K_2) was 13.51 min^{-1}, the adsorption capacity (q_e) was 0.041 mg/g, and the coefficient of determination (R^2) was 0.9989. These results indicate that the pseudo-second-order model provides a significantly better fit to the experimental data, as stated in Table 6.

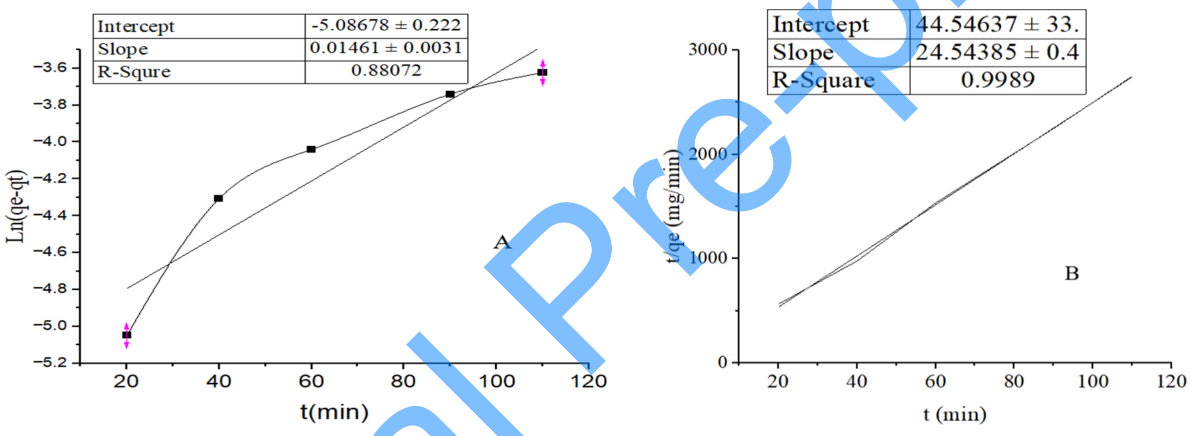

Figure 9. A) Pseudo-first-order kinetics and B) Pseudo-second-order kinetics for the adsorption of Cr(VI) onto the modified bentonite.

Table 6. Kinetic parameters of the pseudo-first-order and pseudo-second-order models for the adsorption of hexavalent chromium.

Adsorption Kinetics	Model Parameter	Value
First Order	$K_1(min^{-1})$	0.0146
	$q_e(mg.g^{-1})$	0.0062
	R^2	0.8807
Second Order	#$K_2(min^{-1})$	13.51
	$q_e(mg.g^{-1})$	0.041
	#R^2	0.9989

3.4. Thermodynamic study of the adsorption process

The thermodynamic parameters of Cr(VI) adsorption, including enthalpy (ΔH°), entropy (ΔS°), and Gibbs free energy (ΔG°), were analyzed to assess temperature effects. Experiments at 20°C–40°C determined ΔH° and ΔS° from the slope and intercept of the lnKd vs. 1/T plot. The adsorption process is exothermic if ΔH° is negative and endothermic if positive. Key parameters include Ca and Ce (adsorbed and solution-phase concentrations), q_e (equilibrium adsorption capacity), R (gas constant), T (temperature), and K_d (distribution coefficient) [22].

$$K_d = \frac{C_a}{C_e} \tag{4}$$

$$\Delta G = RTLnK_d \tag{5}$$

$$\Delta G = \Delta H - T\Delta S \tag{6}$$

$$LnK_d = \frac{\Delta S}{R} - \frac{\Delta H}{RT} \tag{7}$$

Figure 10 present the thermodynamic characteristics of chromium adsorption on acid-activated bentonite at various temperatures. The adsorption process is exothermic, with an enthalpy change (ΔH) of -24.82 kJ/mol, indicating strong interactions between the adsorbate and the surface. The negative entropy change (ΔS) of -68.94 J/mol·K suggests a decrease in molecular disorder, pointing to a more organized adsorption process. Moreover, the negative Gibbs free energy (ΔG) values confirm the spontaneity of the process. Specifically, at 20°C, ΔG is -4.60 kJ/mol; at 30°C, it is -3.91 kJ/mol; and at 40°C, it is -3.22 kJ/mol. The reduction in the magnitude of ΔG with increasing temperature indicates a slight decrease in spontaneity at higher temperatures, as shown in Table 7 [23].

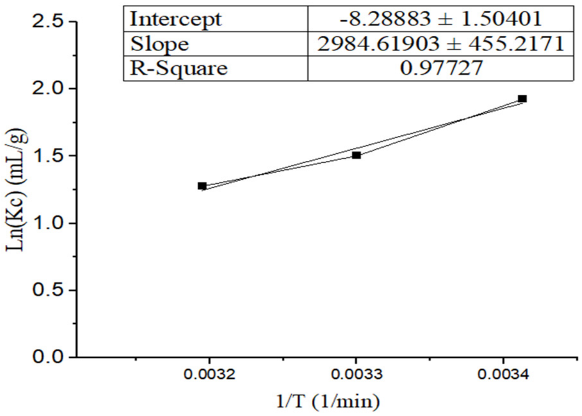

Figure 10. Thermodynamics of adsorption.

Table 7. Thermodynamic parameters governing Cr(VI) adsorption.

Parameter	**Value**	**Unit**
ΔH (Enthalpy Change)	-24.82	kj/mol
ΔS (Entropy Change)	-68.94	#j/mol.k
ΔG (kJ/mol)		
20 °C	-4.60	kJ/mol
30 °C	-3.91	kJ/mol
40 °C	-3.22	kJ/mol

3.5. Comparison of Hexavalent Chromium Removal Efficiency Using Acid-Activated and Raw Bentonite in Municipal Water of Farumad Region:

Figure 11 compares the efficiency of raw and acid-activated bentonite from the Farumad region in removing hexavalent chromium from municipal water. Raw bentonite removed only 15.38% of chromium, due to its limited adsorption capacity. In contrast, acid-activated bentonite achieved a 92.31% removal rate, showing significantly better performance. The acid activation process enhanced its surface area, active site dispersion, and reactivity, making it a more efficient and cost-effective solution for chromium removal.

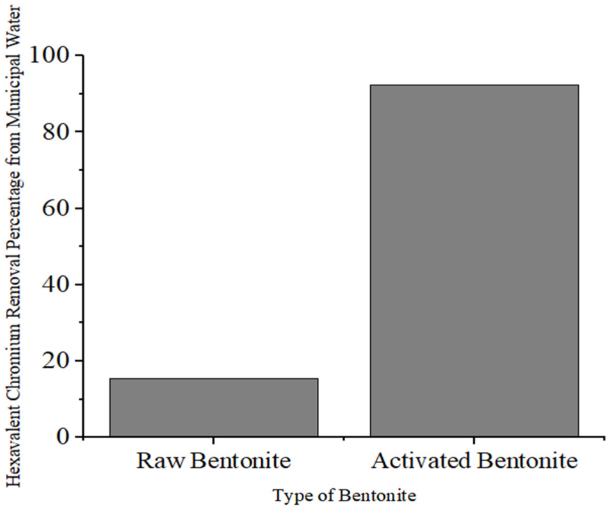

Figure 11. Comparison of hexavalent chromium removal efficiency from municipal water using raw and acid-activated bentonite.

4. Conclusion

This study demonstrates that acid-activated bentonite is an effective and cost-efficient adsorbent for removing hexavalent chromium (Cr(VI)) from contaminated water. Increasing the adsorbent dosage improves removal efficiency, while higher Cr(VI) concentrations reduce it. The optimal conditions for maximum removal efficiency are low temperatures and concentrations. The adsorption kinetics follow a pseudo-second-order model, indicating chemisorption, with a high R^2 value of 0.9989. The Langmuir isotherm model best describes the adsorption data, suggesting monolayer adsorption on uniform active sites. Thermodynamic analysis shows an exothermic process, with negative enthalpy and Gibbs free energy, confirming spontaneity. Despite lower efficiency compared to other adsorbents, acid-activated bentonite's low cost, reusability, and effectiveness make it a promising alternative for large-scale removal of heavy metals, especially in industrial applications, contributing to environmental protection and safe water access.

Acknowledgments

The authors would like to acknowledge the Semnan Provincial Office of the Department of Environment for supporting this research work.

Data availability

All data generated or analysed during this study are included in this published article.

References

[1] Zhang, P., & M. Y. (2023). Water quality degradation due to heavy metal contamination: Health impacts and eco-friendly approaches for heavy metal remediation. PMC, 11, 828.

[2] Beck, S. M., & M. M. (2016). Beyond impervious: Urban land-cover pattern variation and implications for watershed management. Environmental Management, 58, 15–30.

[3] Atieh, M. (2010). Removal of chromium (III) from water by using modified and non-modified carbon nanotubes. Journal of Nanomaterials, 2010, 232378.

[4] Ariffin, N., & M.-Z. A. (2017). Review on adsorption of heavy metal in wastewater by using geopolymer. MATEC Web of Conferences, 97, 01023.

[5] Sundaram, S. (2011). Chromium-VI reagents: Synthetic applications. Springer.

[6] Sharma, P., & S. P. (2022). Health hazards of hexavalent chromium (Cr(VI)) and its microbial reduction. PMC, 13, 4923–4938.

[7] Altun, T. (2020). Preparation and application of glutaraldehyde cross-linked chitosan-coated bentonite clay capsules: Chromium(VI) removal from aqueous solution. Journal of the Chilean Chemical Society, 65, 0717–9707.

[8] Ali, S. H., & A. M. (2020). Adsorption of heavy metals on bentonite and modified bentonite clay, factors, kinetic and thermodynamic studies: A review. Algerian Journal of Materials Chemistry, 90, 106.

[9] Gamoudi, S., & E. S. (2017). Characterization of Tunisian clay suitable for pharmaceutical and cosmetic applications. Applied Clay Science, 162, 166.

[10] Balarak, D., & A. R. (2016). Agricultural waste as adsorbent for removal of chromium (VI) from aqueous solution. Archives of Hygiene Sciences, 310, 318.

[11] Moradi, M., & A. D. (2015). Application of modified bentonite using sulfuric acid for the removal of hexavalent chromium from aqueous solutions. Environmental Health Engineering and Management Journal, 9, 106.

[12] Panda, A. K., & M. B. (2010). Effect of sulfuric acid treatment on the physicochemical characteristics of kaolin clay. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 98, 104.

[13] Ashour, E. A. (2020). Eco-friendly removal of hexavalent chromium from aqueous solution using natural clay mineral: Activation and modification effects. SN Applied Sciences, 2, 1857.

[14] Thakur, A. K., & R. K. (2021). Removal of heavy metals using bentonite clay and inorganic coagulants. Removal of Emerging Contaminants by Microbial Processes, 47, 64.

[15] Belibağlı, P., & B. N. (2020). Chromium (Cr(VI)) removal from water with bentonite magnetite nanocomposite using response surface methodology (RSM). Sigma Journal of Engineering and Natural Sciences, 1217, 1233.

[16] Bakatula, E. D. (2018). Determination of point of zero charge of natural materials. Environmental Science and Pollution Research International, 25, 7823–7833.

[17] Chang, Y. S., & P. I. (2020). Adsorption of Cu(II) and Ni(II) ions from wastewater onto bentonite and bentonite/GO composite. Environmental Science and Pollution Research, 27, 16555–16567.

[18] Maged, A., & S. K. (2020). Characterization of activated bentonite clay mineral and the mechanisms underlying its sorption for ciprofloxacin from aqueous solution. Environmental Science and Pollution Research, 27, 32980–32997.

[19] Adisu, N., Balakrishnan, S., & Tibebe, H. (2022). Synthesis and characterization of Fe_3O_4-bentonite nanocomposite adsorbent for Cr(VI) removal from water solution. International Journal of Chemical Engineering, 2022, 4441718.

[20] Najafpoor, A. A., & S. G. (2014). Study on the adsorption isotherms of chromium (VI) by means of carbon nanotubes from aqueous solutions. Environmental Health Engineering and Management Journal, 1, 5.

[21] Taher, T., & N. R. (2019). Adsorption behavior of Cr(VI) from aqueous solution by Fe-pillared acid-activated Indonesian bentonite. AIP Conference Proceedings, 2194, 020124.

[22] Taheri, M., Khajenoori, M., Shiri-Yekta, Z., & Zahakifar, F. (2023). Application of plantain leaves as a bio-adsorbent for biosorption of U (VI) ions from wastewater. Radiochimica Acta, 111(7), 513-524.

[23] Lia, G., & J. Z. (2020). Investigation of the adsorption characteristics of Cr(VI) onto fly ash, pine nut shells, and modified bentonite. Desalination and Water Treatment, 389, 402.