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Characterization and Adsorption Behavior of Rice Husk Ash for Cr(VI) Removal from Aqueous Solutions

Behris Kılıç[1], Sevgi Polat[1*]
[1]Chemical Engineering Department, Faculty of Engineering, Marmara University, 34854 İstanbul, Turkey
behris.kilic@marmara.edu.tr; *sevgi.polat@marmara.edu.tr

Abstract **-** This study investigates the potential of rice husk ash (RHA), a sustainable and waste-derived adsorbent, for the removal of Cr(VI) ions from aqueous solutions. The adsorption behavior was evaluated under various experimental conditions, including pH, adsorbent dosage, contact time, and temperature, to determine the factors influencing adsorption efficiency. To model the equilibrium data, Langmuir, Freundlich, and Temkin isotherms were applied, with the Freundlich isotherm providing the best fit—indicating multilayer adsorption on a heterogeneous surface. Furthermore, thermodynamic parameters were examined to assess the spontaneity and energetic nature of the adsorption process. As a conclusion, these findings highlight that RHA is a promising and sustainable adsorbent for the effective removal of Cr(VI) ions from aqueous solutions, offering a cost-effective solution for wastewater treatment.
Keywords**:** Adsorption; rice husk ash; isotherms; thermodynamics.

1. Introduction

Global water scarcity is an increasingly urgent issue, driven by population growth, climate change, and expanding industrial activities. By 2050, more than half of the world's population is expected to experience water stress, while over 80% of wastewater continues to be discharged without proper treatment. This situation is particularly concerning given the prevalence of hazardous contaminants, such as heavy metals, in industrial effluents. Among these pollutants, hexavalent chromium [Cr(VI)] is especially problematic due to its high toxicity, mobility, and widespread use in industries like electroplating, leather tanning, and textile manufacturing. Unlike the less harmful trivalent chromium [Cr(III)], Cr(VI) is highly soluble in water and poses serious risks to human health, including carcinogenic and genotoxic effects [1–3]. Improper industrial waste management has led to significant environmental contamination, allowing Cr(VI) to persist in aquatic systems. It exists predominantly as $HCrO_4^-$ at low pH and CrO_4^{2-} at higher pH levels—both of which are highly mobile and toxic. Exposure to these species has been linked to respiratory disorders, liver and kidney damage, and cancer, prompting strict regulatory limits for chromium levels in drinking water [2,3]. Therefore, the development of effective and sustainable Cr(VI) removal methods remains a critical environmental and public health priority. In response to these challenges, researchers have explored alternative treatment technologies capable of efficiently removing heavy metals from contaminated waters. Although conventional treatment systems are effective for removing organic and inorganic pollutants, they are often insufficient for eliminating heavy metals [4,5]. In contrast, adsorption has gained widespread attention as a promising alternative due to its operational simplicity, cost-effectiveness, and potential for adsorbent regeneration [6-7].

In this study, rice husk ash (RHA), a byproduct of rice processing and combustion, was used as the adsorbent due to its high silica content and favorable surface characteristics to remove Cr(VI) ions from aqueous solution [8-10]. The effects of operational parameters were thoroughly examined and optimized. To elucidate the underlying adsorption mechanisms, detailed kinetic, isotherm, and thermodynamic analyses were conducted. The findings offer valuable insight into the adsorption behavior of RHA and highlight its potential for practical applications in heavy metal remediation.

2. Experimental Method

All chemicals used in this research were obtained from Merck Chemicals and were of analytical reagent grade, used as received without any additional purification. Stock solutions of Cr(VI) was prepared using potassium dichromate ($K_2Cr_2O_7$). This solution was then diluted to achieve the desired concentrations for adsorption experiments. Double-distilled water was used throughout the study. Batch equilibrium adsorption experiments were carried out with 50 mL of the prepared metal ion solutions. Parameters affecting the adsorption process such as pH (2-8), adsorbent dosage (1-10 g/L), initial metal ion

concentration (50-150 ppm), contact time (10-240 minutes) and temperature (20-40°C) were studied. After the adsorption process, the solid adsorbent was separated by filtration, and the remaining concentration of Cr(VI) in the filtrate was analyzed using Atomic Absorption Spectroscopy (AAS).

3. Results and Discussion

3.1. The effect of pH and adsorbent dosage

In this study, the effect of pH on the adsorption of Cr(VI) was evaluated over a range of 2–8 (Fig. 1a). Maximum Cr(VI) removal occurred at pH 2.0, where it predominantly exists as $HCrO_4^-$ and $Cr_2O_7^{2-}$. These species are favorably adsorbed via electrostatic attraction and ligand exchange on the positively charged adsorbent surface. This trend aligns with previous findings for rice husk-based materials, which also report optimal Cr(VI) removal in highly acidic environments (pH 1.5–2.5) [11,12]. At elevated pH levels, deprotonation of the adsorbent surface reduces its positive charge, weakening interactions with anionic Cr(VI) species and thus decreasing adsorption efficiency [13]. Based on these findings, subsequent experiments were conducted at pH 2.0 for Cr(VI), where maximum adsorption was achieved.

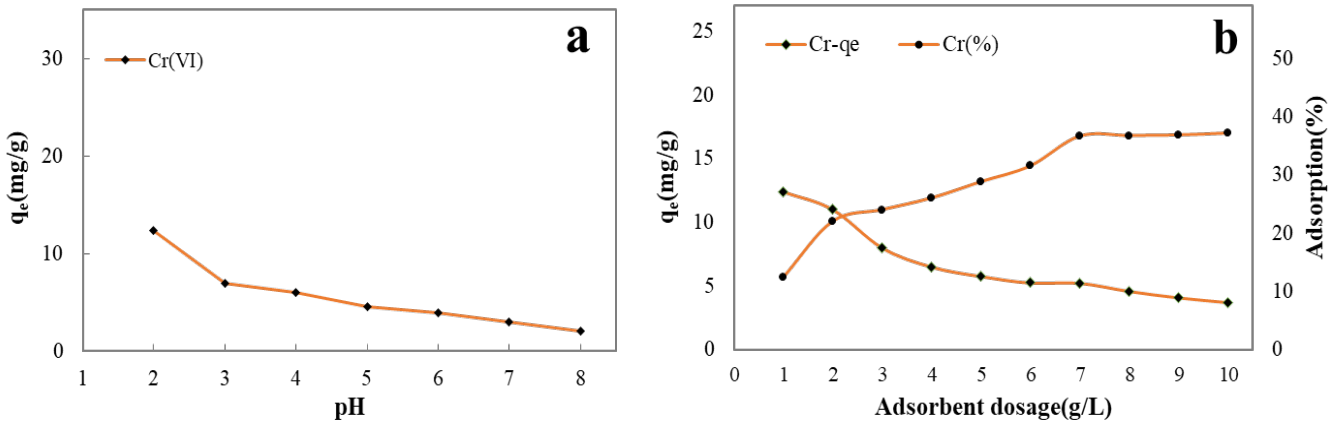

Fig. 1: Effect of (a) pH and (b) adsorbent dosage on the adsorption capacity of rice husk ash for Cr(VI) ions.

The effect of adsorbent dosage was also investigated by varying the amount of RHA between 1 and 10 g/L (Fig. 1b). The optimum dosages were determined to be 7 g/L for Cr(VI), yielding adsorption efficiency of 36.7%. Cr(VI) adsorption is predominantly governed by weak physical interactions such as van der Waals forces and electrostatic attraction, necessitating greater surface area for effective removal. Its large ionic radius and complex redox behavior may further introduce steric constraints [14,15].

3.2. Effect of metal ion concentration and contact time on temperature dependent adsorption

The impact of initial metal ion concentration (50–150 mg/L) and contact time (0–240 min) on adsorption efficiency was examined at 20, 30, and 40 °C, under optimized pH and adsorbent dosage conditions. Equilibrium times and adsorption behaviors for Cr(VI) are illustrated in Fig. 2.

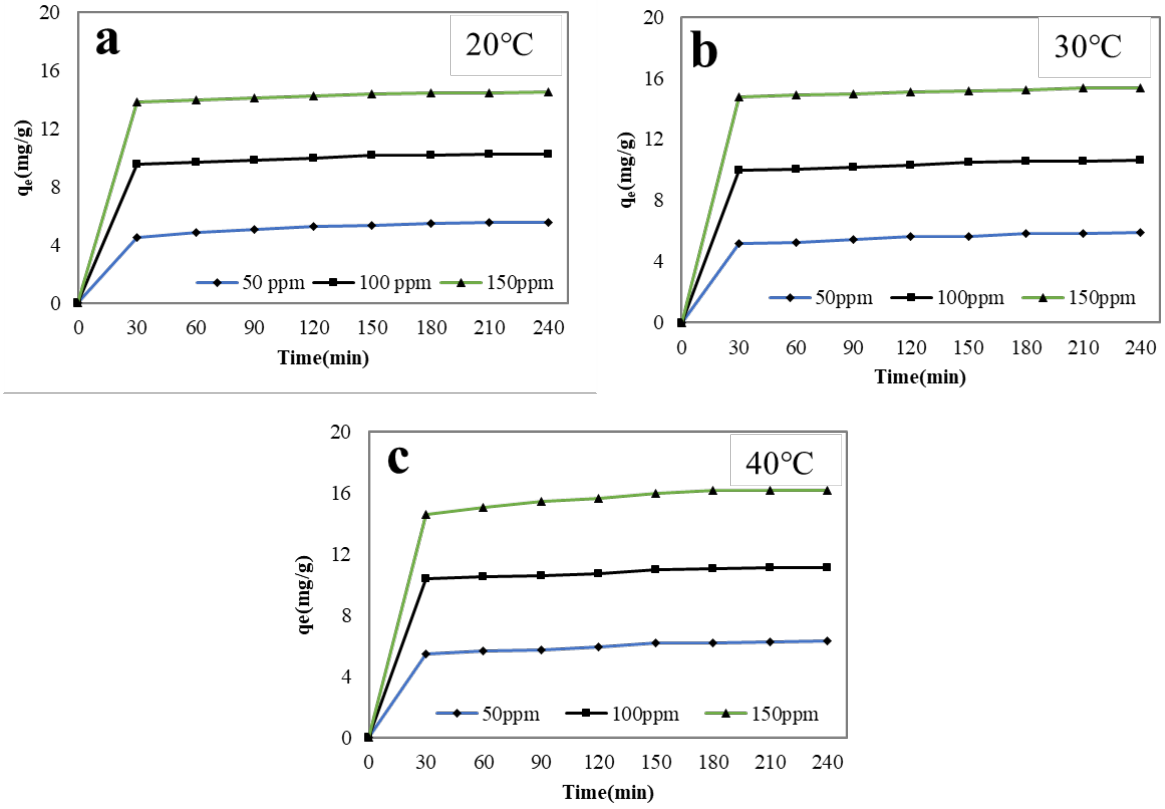

Fig. 2: Effect of initial Cr(VI) concentration and contact time on adsorption capacity of rice husk ash at (a) 20 °C, (b) 30 °C, and (c) 40 °C..

Cr(VI) exhibited two-stage kinetic profile. A rapid initial uptake phase was observed, driven by the abundance of available active sites, followed by a slower phase as these sites became progressively saturated. Equilibrium was attained at approximately 120 minutes for Cr(VI), indicating relatively fast adsorption kinetics for both ions. Temperature was also found to significantly affect the adsorption efficiency.

3.2. Adsorption Isotherms and Thermodynamics

A detailed evaluation of adsorption isotherms was conducted to elucidate the equilibrium behavior of Cr(VI) adsorption onto RHA at different temperatures. The equilibrium adsorption data were analyzed using the Langmuir, Freundlich, and Temkin isotherm models, with the calculated model parameters presented in Table 1. Among the applied models, the Freundlich isotherm provided the best fit for both Cr(VI) ions, as evidenced by the highest correlation coefficients (R^2 values).

Thermodynamic evaluation provides critical insight into the feasibility and energetic nature of the adsorption process of Cr(VI)) onto RHA. The positive values of $\Delta H°$, calculated as 27.35 kJ mol^{-1} for Cr(VI) indicate that both adsorption processes are endothermic, requiring energy input to proceed.

Table 1: Isotherm model parameters for Langmuir, Freundlich, and Temkin equations.

T(°C)	20°C	30°C	40°C
Parameters		***Langmuir***	
q_m	29.850	27.473	24.038
K_L	0.0188	0.0267	0.0474
R^2	0.9896	0.9411	0.9113
R_L	0.3470	0.2722	0.1742
		Freundlich	
n	1.8943	1.6111	1.4741
K_F	2.2791	1.4329	1.0370
R^2	0.9998	0.9961	0.9837
		Temkin	
β	6.1532	5.9068	5.3113
K_T	0.2012	0.2697	0.4630
b	396	427	490
R^2	0.9864	0.9623	0.9334

4. Conclusion

This study demonstrated the effectiveness of rice husk ash (RHA) as a low-cost adsorbent for the removal of Cr(VI) ions through batch adsorption experiments. The key findings are summarized as follows:

i. The adsorption performance of RHA for both Cr(VI) ions was significantly influenced by various operational parameters, including solution pH, initial metal ion concentration, adsorbent dosage, contact time, and temperature.

ii. Rapid adsorption occurred within the first 60 minutes, reaching equilibrium around 120 minutes. The increased adsorption with rising temperature suggests an endothermic nature.

iii. The Freundlich isotherm provided the best fit to the equilibrium data, indicating a heterogeneous surface and multilayer adsorption.

In conclusion, RHA exhibits strong potential as an effective and sustainable adsorbent for removing heavy metals from aqueous environments, supporting its application in wastewater treatment.

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