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Study on Factors Affecting the Adsorption Performance of Municipal Solid Waste-Derived Biochar for Pb^{2+} And Cr^{6+} Removal from Aqueous Solutions

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ABSTRACT: This study evaluated the factors affecting the adsorption of Pb^{2+} and Cr^{6+} from water using biochar produced from municipal solid waste. The biochar was prepared under laboratory conditions via pyrolysis. The effects of several factors, including pH, contact time, initial metal concentration, and adsorbent dosage, were investigated. The concentrations of Pb and Cr were determined using Atomic Absorption Spectroscopy (AAS). Experimental data were analyzed using statistical, comparative, and synthesis methods. The results showed that the adsorption performance was strongly influenced by the investigated factors. The highest removal efficiency was achieved at a pH of approximately 9 and a contact time of 60 min. The optimal biochar dosage ranged from 0.2 to 0.4 g. The removal efficiency of Pb^{2+} reached approximately 90–95%, while Cr^{6+} showed a comparable but slightly lower removal efficiency. The results indicate that biochar derived from municipal solid waste has considerable potential for use in treating water contaminated with heavy metals.

KEYWORDS: adsorption performance, biochar, municipal solid waste, Pb^{2+}, Cr^{6+}.

1. INTRODUCTION

Rapid urbanization and socio-economic development in recent years have significantly increased municipal solid waste generation worldwide, including in Vietnam. According to the Ministry of Natural Resources and Environment of Vietnam (2022), municipal solid waste generation in the country reached approximately 64,000 tons per day, equivalent to more than 23 million tons per year, with an average annual growth rate of 10–16% [1]. However, most municipal solid waste is still disposed of in landfills, accounting for approximately 70–80% of the total waste generated [2]. This disposal method poses several environmental risks, including greenhouse gas emissions, leachate contamination, and soil degradation. In addition, the availability of land for waste disposal is becoming increasingly limited, especially in large urban areas, creating an urgent need for sustainable waste treatment and resource recovery solutions [3].

In addition to municipal solid waste, heavy metal contamination in aquatic environments has become a serious challenge to human health and ecosystems. Among heavy metals, lead (Pb^{2+}) and hexavalent chromium (Cr^{6+}) are considered highly toxic due to their persistence and strong potential for bioaccumulation [4]. These metal ions are mainly released from industrial effluents, mining activities, and urban wastewater sources. Without effective treatment, they may cause severe impacts on human health and water quality. In response to these environmental concerns, increasing attention has been paid in Vietnam to the production and application of biochar derived from organic waste and municipal solid waste as a means of waste valorization and environmental remediation. Previous research conducted by Vu Thi Giang Chi demonstrated the feasibility of producing biochar from biodegradable municipal solid waste and indicated its potential for environmental applications [5].

Beyond domestic research, biochar has received considerable attention worldwide as a promising material for heavy metal removal. Numerous studies have confirmed that biochar is an effective adsorbent due to its large surface area, well-developed porous structure, and the presence of various functional groups on its surface [6,7]. Owing to its low production cost, abundant feedstock availability, and environmentally friendly characteristics, biochar is considered a suitable material for the sustainable treatment of heavy metal-contaminated water [7]. Previous studies have also shown that the adsorption performance of biochar is strongly influenced by pyrolysis conditions, particularly temperature and residence time, as these factors directly affect the material structure, specific surface area, and chemical properties [8,9].

For toxic metals such as Pb^{2+} and Cr^{6+}, biochar can effectively remove contaminants through several mechanisms, including surface adsorption, ion exchange, precipitation, and chemical reduction [10]. In recent years, many studies have focused on modifying and optimizing biochar materials to improve their adsorption capacity and expand their environmental applications [11]. In addition to wastewater treatment, biochar has shown potential for metal recovery from industrial effluents, thereby supporting circular economy approaches and reducing environmental burdens [12].

Despite these advances, most existing studies have focused on biochar produced from agricultural residues or individual biomass sources. Research on the use of municipal solid waste-derived biochar for the simultaneous removal of Pb^{2+} and Cr^{6+} remains relatively limited. Compared with agricultural waste-derived biochar, municipal solid waste-derived biochar has a more complex and heterogeneous composition. Consequently, its adsorption characteristics and heavy metal removal performance require further investigation. In particular, the effects of operational parameters such as pH, contact time, initial metal concentration, and adsorbent dosage on removal efficiency have not been comprehensively evaluated.

To address these research gaps, this study was conducted to evaluate the effects of pH, contact time, initial concentration, and adsorbent dosage on the adsorption of Pb^{2+} and Cr^{6+} from aqueous solutions using biochar produced from municipal solid waste. The findings of this study provide a scientific basis for the application of waste-derived adsorbent materials in the treatment of heavy metal-contaminated water and contribute to the sustainable utilization of municipal solid waste resources.

2. RESEARCH METHODOLOGY

2.1. Material Collection and Experimental Design

Material Collection: Municipal solid waste was collected from dormitory areas and households. The collected waste consisted mainly of biodegradable organic materials, including dried leaves, paper, cardboard, sawdust, and fruit peels. After removing impurities, the waste was air-dried and cut into small pieces. The prepared material was pyrolyzed under oxygen-limited conditions at 400°C for 6 h to produce biochar. The resulting biochar was ground, sieved to obtain a uniform particle size, and stored in sealed bags for use as an adsorbent.

Experimental Design: Batch adsorption experiments were conducted to investigate the effects of pH, contact time, initial concentration, and adsorbent dosage on the removal of Pb^{2+} and Cr^{6+} from aqueous solutions using the prepared biochar. Metal stock solutions were prepared from $Pb(NO_3)_2$ and $K_2Cr_2O_7$, with an initial concentration of 20 mg L^{-1}. In each experiment, a predetermined amount of biochar was added to a 250 mL Erlenmeyer flask containing 25 mL of metal solution. The mixtures were agitated at a constant shaking speed using a laboratory shaker. After the adsorption process, the samples were filtered and analyzed to determine the residual metal concentrations in solution.

The solution pH was adjusted within the range of 3–11 using HCl and NaOH solutions. Contact time was investigated from 30 to 240 min to determine the adsorption equilibrium time. Different initial concentrations of Pb^{2+} and Cr^{6+} were applied to evaluate the adsorption performance of the biochar under various contamination conditions. The adsorbent dosage was varied from 0.1 to 1.0 g. Preliminary experiments indicated that 0.2 g of biochar was the optimal dosage and was therefore selected for subsequent experiments. All experiments were conducted in duplicate, and the average values were used for data analysis to ensure the reliability of the results.

2.2. Laboratory Analysis

The concentrations of Pb and Cr in the solutions before and after adsorption were determined using Atomic Absorption Spectroscopy (AAS) with a Hitachi Z2000 instrument (Japan). The AAS method is based on the absorption of monochromatic radiation by gaseous metal atoms at element-specific wavelengths. According to the Beer–Lambert law, the absorbance is directly proportional to the concentration of the target metal in the sample.

Solution pH was measured using an HQ40D pH meter (Hach, USA). The surface characteristics and structural properties of the biochar were analyzed using Scanning Electron Microscopy (SEM) and Fourier Transform Infrared Spectroscopy (FTIR). SEM analysis was performed to observe the surface morphology and pore structure of the biochar before and after adsorption, whereas FTIR analysis was used to identify the functional groups involved in the adsorption of Pb^{2+} and Cr^{6+}.

2.3. Data Processing and Evaluation

The adsorption performance of the biochar was evaluated by comparing the concentrations of Pb^{2+} and Cr^{6+} before and after treatment. Metal removal efficiency was calculated using the initial and final metal concentrations in solution.

Experimental data were compiled and processed using Microsoft Excel software to calculate average values and removal efficiencies and to generate graphs illustrating the effects of the investigated factors on the adsorption performance of the biochar.

3. RESULTS AND DISCUSSION

3.1. Effect of pH on the Removal of Pb^{2+} and Cr^{6+} from Aqueous Solutions by Municipal Solid Waste-Derived Biochar

The results presented in Table 1 and Figure 1 show that solution pH had a significant effect on the adsorption of Pb^{2+} and Cr^{6+} by biochar derived from municipal solid waste. The removal efficiency of both metal ions increased with increasing pH and reached high values under neutral to slightly alkaline conditions. At pH 3, the removal efficiency was relatively low, reaching only 59.72% for Pb^{2+} and 60.23% for Cr^{6+}. This result can be attributed to the strong competition between H^+ ions and metal ions for the available adsorption sites on the biochar surface. When the pH increased to 5, the removal efficiency improved considerably, especially for Pb^{2+}. This improvement suggests that the deprotonation of surface functional groups facilitated the adsorption of metal ions.

Table 1. Effect of pH on the removal efficiency of Pb^{2+} and Cr^{6+} by municipal solid waste-derived biochar

pH	Removal efficiency (%)	
	Pb^{2+}	Cr^{6+}
3	59,72	60,23
5	69,84	62,78
7	86,99	89,63
9	89,8	90,81
11	89,8	90,79

*(**Source:** Experimental results)*

Within the pH range of 7–9, the removal efficiency increased markedly and reached its optimum level, ranging from 86.99% to 89.80% for Pb^{2+} and from 89.63% to 90.81% for Cr^{6+}. These results indicate that under neutral and slightly alkaline conditions, functional groups such as –OH, –COOH, and C=O on the biochar surface became deprotonated, thereby enhancing metal binding and ion-exchange processes. In addition, the difference in removal efficiency between Pb^{2+} and Cr^{6+} was relatively small, indicating that the biochar was capable of simultaneously removing both metals with high efficiency.

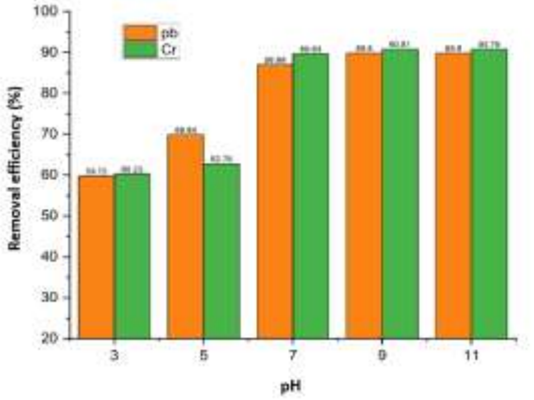

Figure 1. Effect of solution pH on the removal efficiency of Pb^{2+} and Cr^{6+} by municipal solid waste-derived biochar

(**Source:** Experimental results)

At pH 11, the removal efficiency showed little change compared with that at pH 9, suggesting that the adsorption process had approached saturation. Overall, the biochar exhibited good adsorption performance for both Pb^{2+} and Cr^{6+} over a wide pH range, with the highest removal efficiency observed under neutral to slightly alkaline conditions. These findings demonstrate the potential of municipal solid waste-derived biochar for treating heavy metal-contaminated water. Furthermore, its utilization contributes to the sustainable management of municipal solid waste and supports environmentally friendly waste management practices.

3.2. Effect of Contact Time on the Removal of Pb^{2+} and Cr^{6+} from Aqueous Solutions by Municipal Solid Waste-Derived Biochar

Contact time is one of the important factors affecting the removal of Pb^{2+} and Cr^{6+} by municipal solid waste-derived biochar. The results are presented in Table 2 and Figure 2. For Pb^{2+}, the removal efficiency increased from 85.54% at 30 min to 90.18% at 60 min. After this point, the removal efficiency remained nearly constant, ranging from 90.06% to 90.29%. This result indicates that adsorption equilibrium was reached after approximately 60 min of contact time. Most Pb^{2+} ions were rapidly adsorbed onto the biochar surface during the initial stage of the process, while extending the contact time did not significantly improve the removal efficiency.

Table 2. Effect of contact time on the removal efficiency of Pb^{2+} and Cr^{6+} by municipal solid waste-derived biochar

Contact time (min)	Removal Efficiency (%)	
	Pb^{2+}	Cr^{6+}
30	85,54	68,87
60	90,18	73,23
90	90,14	66,29
120	90,06	60,89
150	90,1	51,56
180	90,06	61,39
210	90,18	46,34
240	90,29	44,18

*(**Source:** Experimental results)*

For Cr^{6+}, the removal efficiency increased from 68.87% at 30 min to a maximum value of 73.23% at 60 min. However, the efficiency gradually decreased to 44.18% at 240 min. This trend suggests that the adsorption of Cr^{6+} by the biochar was less stable than that of Pb^{2+}. The decrease in removal efficiency over time may be related to changes in adsorption equilibrium on the biochar surface or to the chemical behavior of Cr^{6+} species in solution. The results indicate that a contact time of 60 min was sufficient to achieve the highest Cr^{6+} removal efficiency under the experimental conditions.

A comparison of the adsorption results indicated that municipal solid waste-derived biochar exhibited a greater affinity for Pb^{2+} than for Cr^{6+}. This difference may be attributed to the different chemical species of the metal ions in solution and their interactions with the functional groups present on the biochar surface. A contact time of 60 min was identified as the optimal condition, at which the highest removal efficiencies of both metals were achieved. These findings provide a basis for selecting appropriate operating conditions and further demonstrate the potential of biochar for the treatment of heavy metal-contaminated water, particularly for Pb^{2+} removal.

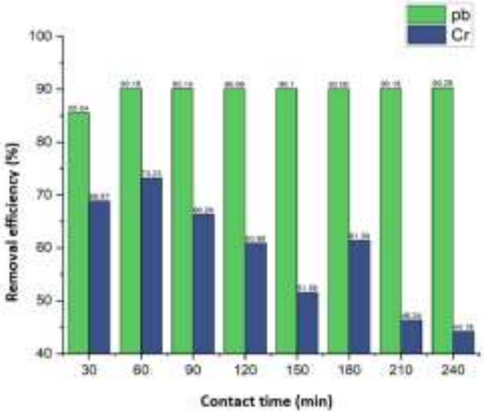

Figure 2. Effect of contact time on the removal efficiency of Pb^{2+} and Cr^{6+} by municipal solid waste-derived biochar

*(**Source:** Experimental results)*

3.3. Effect of Initial Metal Concentration on the Removal of Pb^{2+} and Cr^{6+} from Aqueous Solutions by Municipal Solid Waste-Derived Biochar

Table 3. Effect of initial metal concentration on the removal efficiency of Pb^{2+} and Cr^{6+} by municipal solid waste-derived biochar

Initial concentration (mg/l)	Removal Efficiency (%)	
	Pb^{2+}	Cr^{6+}
10	90.61	84.77
20	89.7	80.54
30	80.59	61.58
40	69.73	60.2
50	62.75	54.36
60	52.86	48.62

*(**Source:** Experimental results)*

The results presented in Table 3 and Figure 3 show that the removal efficiency of Pb^{2+} and Cr^{6+} by municipal solid waste-derived biochar decreased with increasing initial metal concentration. Within the investigated concentration range of 10–60 mg L^{-1}, the removal efficiency of Pb^{2+} decreased from 90.61% to 52.86%, while that of Cr^{6+} decreased from 84.77% to 48.62%. This decline indicates that the initial metal concentration had a significant effect on the removal performance of the biochar under the experimental conditions.

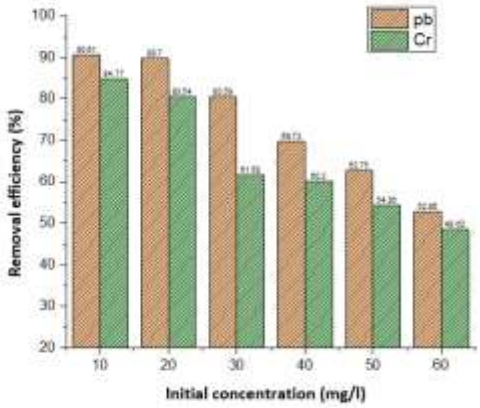

Figure 3. Effect of initial metal concentration on the removal efficiency of Pb^{2+} and Cr^{6+} by municipal solid waste-derived biochar

*(**Source:** Experimental results)*

The decrease in removal efficiency with increasing metal concentration suggests that the treatment performance of the biochar was influenced by the initial pollutant concentration. At higher concentrations, a greater number of metal ions competed for a limited number of available adsorption sites on the biochar surface, resulting in lower removal efficiencies. Throughout the investigated concentration range, the removal efficiency of Pb^{2+} was consistently higher than that of Cr^{6+}, indicating a stronger affinity of the biochar for Pb^{2+} ions. This difference may be related to the chemical forms of the metal ions in solution and their interactions with the functional groups present on the biochar surface. Although the removal efficiency decreased as the initial concentration increased, the biochar maintained a relatively good removal performance for both metals, demonstrating its potential for the treatment of heavy metal-contaminated water.

3.4. Effect of Adsorbent Dosage on the Removal of Pb^{2+} and Cr^{6+} from Aqueous Solutions by Municipal Solid Waste-Derived Biochar

Based on the results presented in Table 4 and Figure 4, the removal efficiency of Pb^{2+} and Cr^{6+} generally increased as the adsorbent dosage increased from 0.1 to 1.0 g. However, the variation was relatively small, as the removal efficiencies of both metals remained within the range of 87–91%. Specifically, the removal efficiency of Pb^{2+} increased from 88.45% to 90.81%, while that of Cr^{6+} increased from 87.45% to 90.21%.

Table 4. Effect of adsorbent dosage on the removal efficiency of Pb^{2+} and Cr^{6+} by municipal solid waste-derived biochar

Adsorbent dosage (g)	Removal Efficiency (%)	
	Pb^{2+}	Cr^{6+}
0.1	88,45	87,45
0.2	87,56	89,24

0.4	90,42	89,05
0.6	90,72	89,84
0.8	90,42	89,96
1	90,81	90,21

*(**Source:** Experimental results)*

The results indicate that increasing the adsorbent dosage enhanced the removal efficiency of both metals. This improvement can be attributed to the increase in the number of available adsorption sites and the larger contact area between the adsorbent and the metal solution, which facilitated the adsorption process. However, when the adsorbent dosage exceeded 0.4 g, only slight improvements in removal efficiency were observed, and the values remained relatively stable at around 90%. This finding suggests that increasing the adsorbent dosage beyond this level provided limited additional benefits in terms of metal removal.

The experimental data also showed that the removal efficiency of Pb^{2+} was generally higher than or comparable to that of Cr^{6+} at most adsorbent dosages, indicating that municipal solid waste-derived biochar exhibited good performance for Pb^{2+} removal. Overall, the biochar achieved high removal efficiencies for both metals across the entire dosage range investigated. Considering both treatment efficiency and material utilization, an adsorbent dosage of 0.4–0.6 g was considered the most suitable condition for Pb^{2+} and Cr^{6+} adsorption under the experimental conditions.

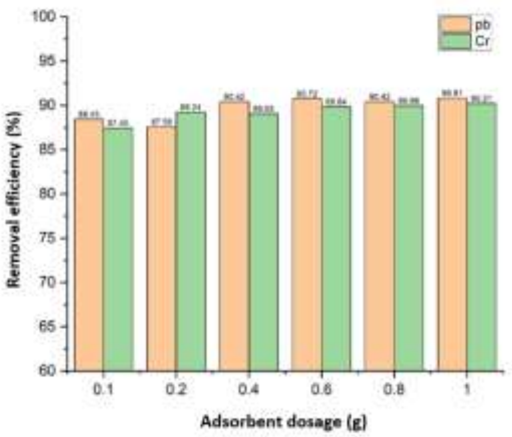

Figure 4. Effect of adsorbent dosage on the removal efficiency of Pb^{2+} and Cr^{6+} by municipal solid waste-derived biochar

*(**Source:** Experimental results)*

4. CONCLUSIONS

The results of this study demonstrated that biochar produced from municipal solid waste has a relatively high capacity for the removal of Pb^{2+} and Cr^{6+} from aqueous solutions. The investigated factors, including solution pH, contact time, initial metal concentration, and adsorbent dosage, all influenced the adsorption process. Among these factors, a pH of 9 and a contact time of 60 min were identified as the most suitable conditions, under which the removal efficiencies of both Pb^{2+} and Cr^{6+} reached approximately 90%.

As the initial metal concentration increased from 10 to 60 mg L^{-1}, the removal efficiency decreased, indicating that the metal removal performance of the biochar was limited at higher contaminant concentrations. In contrast, the removal efficiency increased with increasing adsorbent dosage; however, only slight improvements were observed when the dosage exceeded 0.4–0.6 g. Under all experimental conditions, the removal efficiency of Pb^{2+} was consistently higher than or comparable to that of Cr^{6+}, suggesting that municipal solid waste-derived biochar was more effective for Pb^{2+} removal.

Overall, this study demonstrated the feasibility of utilizing municipal solid waste as a feedstock for biochar production for the treatment of heavy metal-contaminated water. The findings provide additional scientific evidence supporting the application of municipal solid waste-derived biochar in environmental remediation. Furthermore, the results provide a basis for future studies aimed at improving the properties of biochar materials and evaluating their performance under practical treatment conditions.

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