Jurnal Pijar MIPA
https://jurnalfkip.unram.ac.id/index.php/JPM

ISSN 1907-1744 (Print)
ISSN 2460-1500 (Online)

Adsorption-Based Laboratory Hazardous Waste Treatment with a Combination of Biochar, Zeolite, and Activated Alumina as an Environmentally Friendly Solution

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Received: September 10, 2025. Accepted: October 20, 2025. Published: October 28, 2025

Abstract: Hazardous and Toxic Waste (B3) from laboratories, especially those containing heavy metals (Hg and Cr) and several physical factors such as pH, TSS, and color, poses a serious threat to the environment if not managed properly. This study aims to estimate the adsorbent for the development of laboratory-scale wastewater treatment equipment based on the adsorption method using biochar, zeolite, and activated alumina. The research method involves preparing adsorbent materials, testing their effectiveness in reducing the content of heavy metal pollutants, and designing a waste treatment device. The combination of biochar, zeolite, and activated alumina was chosen due to their complementary abilities in removing heavy metal content from B3 waste in the Soil Chemistry laboratory. The treatment results showed significant reductions ($p < 0.05$) in heavy metal (Hg and Cr) levels in laboratory waste. The optimal combination is a formulation of biochar, zeolite, and activated alumina (1:1:1). Innovations in adsorbent technology for processing heavy metal waste in soil chemistry laboratories can be applied and further developed to create a clean and healthy environment.

Keywords: Activated Alumina; Adsorption; B3 Waste; Biochar; Effectiveness; Zeolite.

Introduction

The University of Mataram has over 69 teaching laboratories across 10 faculties. These laboratories play a vital role in supporting the Tri Dharma of Higher Education: education, research, and community service. Furthermore, several laboratories provide testing services to external parties, including the Soil Chemistry Laboratory. This laboratory analyzes various samples, including soil, water, plant tissue, and organic and inorganic fertilizers.

In its operations, the Soil Chemistry Laboratory uses various chemicals that are corrosive, irritating, toxic, and flammable. Some frequently used materials include HNO_3, H_2SO_4, H_2O_2, HCl, $HClO_4$, acetic acid, NH_3, ethanol, NaOH, $K_2Cr_2O_7$, $HgCl_2$, HBO_3, NH_4F, $CuSO_4$, K_2SO_4, ammonium molybdate, and ascorbic acid [1]. According to Government Regulation No. 22 of 2021, these materials are classified as hazardous and toxic waste (B3) due to their toxic, flammable, reactive, and corrosive properties. Specifically, analytical activities in the Soil Chemistry Laboratory generate B3 waste in the form of heavy metals, including mercury (Hg) and chromium (Cr), which originate from analytical methods such as the C-organic test and mercury analysis. If not managed properly, this waste can pollute the ecosystem and pose a risk to human health.

Although regulations regarding B3 waste management have been stipulated in Ministerial Regulation No. 6 of 2021, most educational laboratories, including the Soil Chemistry Laboratory at the University of Mataram, still lack adequate waste treatment facilities [2]. Waste management carried out so far is still limited to separating waste types, labelling, and temporary storage. In fact, in practice, liquid waste is often simply diluted and disposed of directly into a landfill through the sink [3]. This condition indicates a lack of attention to the risks of environmental pollution and health impacts caused by B3 waste.

Hazardous and toxic waste from laboratories can disrupt ecosystems, pollute water sources, and disrupt soil nutrient cycles. Heavy metals such as mercury (Hg) and chromium (Cr) have bioaccumulative properties that can enter the food chain, increasing health risks, including skin irritation, respiratory problems, and even chronic diseases like cancer [4]. Therefore, effective, efficient, and environmentally friendly waste treatment methods are needed to minimize these negative impacts.

Various methods have been developed for hazardous waste treatment, such as membrane filtration, electrochemical precipitation, photochemical oxidation, coagulation, fertilization, adsorption, and ion exchange. Among these methods, adsorption is a simpler, less expensive, and more effective option for reducing the heavy metal content in liquid waste [5]. Adsorption enables the absorption of dissolved substances in waste by the adsorbent surface, thereby reducing the concentration of heavy metals before the waste is discharged into the environment.

Several adsorbents with potential for use in adsorption-based wastewater treatment systems include biochar, zeolite, and activated alumina. Biochar, produced

How to Cite:
H. R. Akhdiyat, S. Sukartono, J. Jasrodi, and H. S. Putra, "Adsorption-Based Laboratory Hazardous Waste Treatment with a Combination of Biochar, Zeolite, and Activated Alumina as an Environmentally Friendly Solution", *J. Pijar.MIPA*, vol. 20, no. 6, pp. 1199–1203, Oct. 2025. https://doi.org/10.29303/jpm.v20i6.10180

from the pyrolysis of organic materials such as agricultural waste, has a high capacity to absorb complex organic compounds and heavy metals such as Hg and Cr, and helps neutralize the pH of wastewater. Zeolite, with its unique pore structure and ion-exchange capacity, is able to capture heavy metals such as Pb and Cr, as well as remove ammonium ions ($NH4^{+}$). Meanwhile, activated alumina is effective in removing color, turbidity, and certain heavy metals such as arsenic and chromium [6-7].

The combination of these three adsorbent materials provides a more effective and comprehensive solution for treating hazardous and toxic waste. Biochar acts as the initial layer to absorb complex organic compounds and heavy metals, followed by zeolite, which captures metal ions and fine particles, and activated alumina, which improves water clarity and removes residual compounds. This system not only improves waste treatment efficiency but is also more environmentally friendly.

This research aims to design a mini adsorption-based wastewater treatment device using biochar, zeolite, and activated alumina and evaluate its effectiveness in reducing heavy metal concentrations. The results will be compared with wastewater quality standards for discharge into the environment. Therefore, this research is expected to provide a practical and sustainable solution for managing hazardous and toxic waste in educational laboratories, while contributing to environmental conservation.

Research Method

Identification of problems

Prior to the research, field observations were conducted to assess the condition of the laboratory waste management system at the University of Mataram. The primary focus of the observations was the type of waste produced, followed by an examination of the waste management system, including disposal, storage, and processing. This stage played a role in determining which laboratory would be used as a representative of laboratories producing hazardous waste.

Preparation Stages

This research aims to develop a practical solution in the form of a prototype adsorption-based hazardous waste treatment device for heavy metals Hg and Cr, utilising a combination of biochar, zeolite, and activated alumina. The methodology employed encompasses the stages of the research process, expected outputs, achievement indicators, and the division of responsibilities among team members. The research process consists of five main stages, carried out sequentially to ensure that the research results achieve the desired objectives.

The first stage is a literature study and characterization of the adsorbent materials. At this stage, a literature review is conducted to understand the properties and characteristics of biochar, zeolite, and activated alumina, which will serve as the primary ingredients in the adsorption system. Next, initial characterization of these materials is conducted to determine relevant physical and chemical parameters. The expected output of this stage is a report on the literature study and material characterization results, which will serve as the basis for the next stage. Responsibility for this stage is held by the lead researcher, a laboratory technician.

Preliminary Analysis/Preliminary Test

The second stage is characterizing the hazardous waste content produced by the University of Mataram's Soil Chemistry Laboratory. This characterization is carried out by collecting liquid waste samples from the laboratory and then analyzing them for heavy metal content, pH, color, and turbidity. The data obtained will be used to determine the level of waste pollution and to establish the necessary treatment requirements. The output of this stage is a hazardous waste characterization report, with achievement indicators including the availability of waste composition data. This stage is coordinated by a team of lecturers with expertise in environmental fields.

Effectiveness Test of Adsorbent Materials

The third stage is laboratory testing to evaluate the effectiveness of the combination of biochar, zeolite, and activated alumina in absorbing heavy metals and improving wastewater quality. This testing was conducted using previously characterized hazardous waste samples. The combination of adsorbent materials was tested to measure their ability to reduce heavy metal levels such as Hg, Cr, acidity levels, and turbidity and color of the waste. The output of this stage is a test report indicating the most effective adsorbent combination. The achievement indicator at this stage is the availability of data on the effectiveness of the adsorbent materials. Responsibility for implementing this stage is held by a lecturer who is an expert in the field of biochar, with the assistance of students involved in the research. The effectiveness of reducing hazardous waste levels after processing using waste processing equipment based on biochar, zeolite, and activated alumina adsorbents is calculated using the formula:

$$\%\mathrm{Eff.\,Decrease} = \frac{C_0 - C_1}{C_1} \mathrm{x} 100\%$$

Noted:
% Eff Decrease = Percentage Efficiency Decrease Initial
C_0 = Initial uranium concentration
C_1 = Uranium concentration after the ion exchange process

The data from the analysis using the Completely Randomized Design method were analyzed using the ANOVA statistical test using the IBM SPSS 25 program to see the effect of each treatment on the waste sample ($p<0.05$).

Results and Discussion

The treatment of heavy metal waste, such as mercury (Hg) and chromium (Cr), has become an important focus in efforts to create a clean and healthy environment. One approach that continues to evolve is the development of adsorbents based on natural and composite materials, such as biochar, modified zeolites, and nanomaterials. These adsorbents can effectively bind toxic metal ions through ion exchange mechanisms, electrostatic interactions, and complex formation, thereby reducing metal concentrations in wastewater. The application of adsorption technology not only offers high efficiency, but is also environmentally friendly and relatively cheaper than conventional methods such as chemical precipitation or electrolysis [8-11].

Furthermore, the development of innovative adsorbents directly contributes to improving people's quality of life by reducing the risk of pollution that impacts human health and ecosystems. For example, the use of biomass- or agricultural waste-based adsorbents enables the implementation of circular economy principles and sustainable solutions. This innovation is crucial for addressing the toxic impacts of Hg and Cr, which can cause neurological disorders, cancer, and organ damage if accumulated in the food chain. Therefore, research in this area provides both a scientific basis and practical application opportunities to support sustainable development goals in environmental management [12-14].

Based on preliminary experimental data (Table 1), it appears that the effectiveness of various types of adsorbents in reducing the content of heavy metals Hg and Cr exhibits a significant variation. Biochar 10 g was able to remove up to 82.9% of Hg and 70.13% of Cr, while zeolite 10 g only achieved 64.4% for Hg and 58.93% for Cr. Meanwhile, activated alumina (10 g) showed balanced performance, with an effectiveness of 74.3% for Hg and 71.27% for Cr. This indicates that biochar has a stronger adsorption capacity for mercury, while activated alumina tends to be equally effective for both metals.

The material combination showed interesting results. A mixture of 3.33 g of biochar, 3.33 g of zeolite, and 3.33 g of activated alumina provided the highest values for Hg (93.4%) and Cr (87.87%) reduction, as well as the highest efficiency in reducing TSS (61.13%). This indicates a synergistic effect between the two materials in the adsorption process. In terms of final pH, all treatments produced values between 6.06 and 6.79, which are relatively close to neutral; thus, this condition still meets water quality standards. Overall, these results confirm that the use of a combination of biochar and activated alumina has great potential as an environmentally friendly adsorbent innovation in heavy metal waste treatment (Table 2).

Table 1. Initial experimental data for waste processing

Treatment	Removal_Hg (%)	Removal_Cr (%)	TSS Removal (%)	Final pH
Biochar 10 g	82.90	70.13	41.43	6.80
Zeolite 10 g	64.40	58.93	32.87	6.06
Active Alumina 10 g	74.30	71.27	37.23	6.73
Biochar 5 g + Zeolit 5 g	64.40	58.93	42.40	6.06
Biochar 5 g + Active Alumina 5 g	85.67	72.50	49.40	6.58
Zeolite 5 g + Activated Alumina 5 g	87.30	77.10	41.30	6.74
Biochar 3.33 g + Zeolite 3.33 g + Activated Alumina 3.33 g	93.40	87.97	61.13	6.56

Table 2. Advanced waste processing experimental data

Treatment	Removal_Hg (%)	Removal_Cr (%)	TSS Removal (%)	Final pH
EXCEEDS 15 g (5.0+5.0+5.0)	95.8	91.7	68.4	6.63
EXCEEDS 20 g (6.67+6.67+6.67)	97.9	94.8	71.8	6.73
EXCEEDS 25 g (8.33+8.33+8.33)	98.8	96.6	75.5	6.78
EXCEEDS 30 g (10.0+10.0+10.0)	99.5	98.3	79.7	6.82

Table 3. One-way ANOVA results of Hg and Cr removal

ANOVA

		Sum of Squares	df	Mean Square	F	Sig.
EQA15g	Between Groups	13784.668	1	13784.668	1349233.411	.000
	Within Groups	.041	4	.010		
	Total	13784.709	5			
EQA20g	Between Groups	14364.869	1	14364.869	1060137.963	.000
	Within Groups	.054	4	.014		
	Total	14364.924	5			
EQA25g	Between Groups	14639.196	1	14639.196	74823.389	.000
	Within Groups	.783	4	.196		
	Total	14639.979	5			
EQA30g	Between Groups	14852.365	1	14852.365	46902205.474	.000
	Within Groups	.001	4	.000		
	Total	14852.366	5			

The results of further experiments showed that increasing the dose of the EQA combination adsorbent (Biochar + Zeolite + Activated Alumina) significantly ($p < 0.05$) enhanced the effectiveness of heavy metal reduction and improved water quality. At the highest dose of 30 g, the reduction of Hg reached 99.5% and Cr 98.3%, with TSS reduced to 79.7% and the final pH stable in the neutral range (6.63–6.82). This confirms that the EQA formulation is not only highly effective in absorbing hazardous heavy metals but also capable of improving water clarity without altering the chemical balance, thus demonstrating great potential as an environmentally friendly solution in waste treatment.

The EQA adsorbent combination (Biochar + Zeolite + Activated Alumina) is highly effective in reducing the levels of heavy metals Hg and Cr to near-safe levels. At a dose of 30 g, the final Hg level decreased to 0.5 mg/L with an effectiveness of 99.5%, and Cr reached 1.39 mg/L with an effectiveness of 98.3%. When compared to the wastewater quality standards according to Government Regulation No. 22 of 2021 for class II, where the maximum limit for Hg is 0.005 mg/L and the total Cr is 0.5 mg/L, the results of this experiment show a positive trend, even though the final levels are still above the threshold [15-17]. This means that the EQA formulation is capable of significantly reducing heavy metals, but to achieve the established environmental quality standards, further optimization is required, such as increasing the dose, modifying the adsorbent structure, or applying a combination with other treatment methods so that the quality of the treated water truly meets environmental requirements.

The advantage of using adsorbent materials in heavy metal waste treatment lies in their ability to effectively, economically, and environmentally reduce the concentration of hazardous pollutants. Adsorbents such as biochar, zeolite, and activated alumina possess large porous structures, active functional groups, and chemical stability, which enable strong bonds with metal ions like mercury (Hg) and chromium (Cr) [18-22]. Agricultural waste serves as the primary material for biochar, supporting the principle of a circular economy while reducing dependence on high-cost synthetic materials. The combination of adsorbents can produce synergistic effects that increase absorption capacity through ion exchange, complexation, and electrostatic interactions. Thus, adsorbent innovation is not only important in maintaining water quality and ecosystem health but also contributes to achieving sustainable development goals in the environmental sector.

Conclusion

Based on the results of further experiments, it can be concluded that the combination of EQA adsorbents (biochar, zeolite, and activated alumina) has a very high effectiveness in reducing the levels of heavy metals mercury (Hg) and chromium (Cr) in liquid waste. The increase in the adsorbent dose is directly proportional to the increase in the removal percentage. At a dose of 30 g, optimal results were obtained, with reductions in Hg of 99.5% (from 0.5 mg/L to 0.5 mg/L) and Cr of 98.3% (from 1.39 mg/L to 0.05 mg/L). In addition, the TSS value also decreased significantly to 79.7%, and the final pH remained stable, approaching neutral (6.63–6.82), so that the quality of the treated water experienced a comprehensive improvement. Although these results show the great potential of the EQA combination adsorbent, the final levels of Hg and Cr are still above the quality standards stipulated in PP No. 22 of 2021 (0.005 mg/L for Hg and 0.5 mg/L for Cr), so further optimization is needed, either through increasing the dose, engineering the adsorbent structure, or integration with other processing methods to meet environmental standards.

Author's Contribution

H. R. Akhdiyat: conceptualized the study, designed the experimental framework, and prepared the manuscript draft. Sukartono & H. S. Putra: supervised the research design, provided critical revision of the manuscript, conducted data collection, experimental analysis, and visualization. Jasrodi: assisted with material preparation and data interpretation.

Acknowledgement

The authors would like to express their sincere gratitude to the Institute for Research and Community Service (LPPM) at the University of Mataram for the financial support and research facilitation provided for this study. Special thanks are also extended to the Head of the Soil Chemistry Laboratory, Faculty of Agriculture, University of Mataram, for the laboratory access, technical assistance, and valuable support during the experimental work.

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