



LEAD (Pb) METAL CONTAMINATION AND IMPROVEMENT OF WATER QUALITY POST-REMEDIATION IN THE CINANGKA RIVER, BOGOR

KONTAMINASI LOGAM TIMBAL (Pb) DAN PENINGKATAN KUALITAS AIR PASCA REMEDIASI DI SUNGAI CINANGKA BOGOR

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ABSTRACT

The activity of post-used battery smelting industries in the Cinangka area, Bogor, has led to the accumulation of lead (Pb) heavy metal exceeding the permissible limit of river water quality standards, negatively affecting both water quality and the aquatic environment. This study aims to analyze the reduction of Pb concentration in water and the changes in water quality parameters, including temperature, pH, turbidity, and dissolved oxygen (DO), following the remediation process using various natural agents such as corn cob biochar, vetiver, and local freshwater mussel in Pb-contaminated waters. The research was conducted experimentally using a completely randomized design (CRD) with eight treatments and three replications over four weeks. Pb concentrations were measured at week 0 and 4, while water quality parameters were observed at weeks 0, 2, and 4. The results showed that the combination of the three remediation agents, biochar + vetiver + mussel (ABC), produced the highest Pb reduction of 99.3%, lowering Pb concentration to 0.009 mg/L, also significantly decreased temperature and turbidity while increasing pH and DO to levels approaching those of natural waters. Correlation analysis revealed strong negative relationships between Pb concentration and both pH and DO, as well as strong positive relationships with temperature and turbidity. Overall, remediation using the three natural agents effectively reduces Pb concentrations in water while simultaneously enhancing the overall quality of the aquatic environment.

Keywords: aquatic environment, Cinangka River, lead (Pb), remediation, water quality

ABSTRAK

Aktivitas industri pasca peleburan aki bekas di wilayah Cinangka, Bogor, telah menyebabkan akumulasi logam berat timbal (Pb) yang melebihi ambang batas baku mutu air sungai dan berdampak negatif terhadap kualitas air serta lingkungan perairan. Penelitian ini bertujuan untuk menganalisis penurunan kadar logam Pb di air serta perubahan parameter kualitas air yang meliputi suhu, pH, kekeruhan, dan oksigen terlarut (DO) setelah proses remediasi menggunakan jenis-jenis agen remediasi seperti biochar tongkol jagung, akar wangi, dan kijing lokal pada perairan terkontaminasi logam Pb. Penelitian dilakukan secara eksperimental menggunakan rancangan acak lengkap (RAL) dengan delapan perlakuan dan tiga ulangan selama empat minggu. Pengukuran kadar Pb dilakukan pada minggu ke-0 dan ke-4, sedangkan pengamatan kualitas air dilakukan pada minggu ke-0, 2, dan 4. Hasil penelitian menunjukkan bahwa kombinasi tiga agen remediasi yaitu biochar tongkol jagung + akar wangi + kijing lokal (ABC) memberikan penurunan kadar Pb tertinggi sebesar 99,3% hingga mencapai 0,009 mg/L serta secara signifikan menurunkan suhu dan kekeruhan, serta meningkatkan pH dan DO hingga mendekati kisaran optimal. Nilai korelasi antara kadar Pb dengan parameter kualitas air menunjukkan hubungan negatif kuat terhadap pH dan DO, serta hubungan positif kuat terhadap suhu dan kekeruhan. Secara keseluruhan, remediasi menggunakan ketiga agen alami efektif dalam penurunan kadar Pb di air sekaligus meningkatkan kualitas lingkungan perairan secara menyeluruh.

Kata kunci: kualitas air, lingkungan perairan, logam timbal (Pb), remediasi, Sungai Cinangka

INTRODUCTION

Indonesia's industry is advanced and increasingly vibrant, offering a wide range of services. Smelting of used lead-acid batteries generates environmental pollution and causes long-term ecological impacts. The resulting wastewater is highly toxic to the environment, slowly killing the surrounding ecosystem. Lead is extremely hazardous, making it environmentally unsafe and highly harmful to various sectors of life (Hidrawati *et al.* 2023). Cinangka Village (Bogor) is one of the areas identified as being contaminated by heavy metals following battery smelting activities. According to findings by Rahadi *et al.* (2019), Pb concentrations in the local river have exceeded the limit set by the Ministry of Environment and Forestry (KLHK), which is 0.03 mg/L (Ulumudin and Purnomo 2022). Irrigation and community waterways contaminated with lead create an unsafe and toxic environment, damaging the aquatic environment for future life (Aphrodita *et al.* 2022).

Contaminated water must undergo intensive remediation to restore its original quality (Saputri and Marni 2024). Bioremediation of lead-contaminated water must be tailored to specific needs and adhere to existing standards. Good technology also ensures high quality and long-term comfort (Retnosari *et al.* 2024). Corn cob (*Zea mays*) biochar is an effective material for adsorbing dissolved and suspended pollutants from water, thereby facilitating water treatment (Laela and Ammurabi 2024). Water pollution can be safely and effectively removed, restoring a quality and comfortable water environment. Anggraeni and Triajie (2021) also found that corn cob biochar improved several water quality parameters, including increasing wastewater pH from 7.28 to above 10 through filtration.

Vetiver (*Vetiver zizanioides*) is also widely used to remediate polluted water, restoring it to a safe and functional condition (Priantoro *et al.* 2025). Alisa *et al.* (2020) reported that vetiver could absorb Pb up to 0.298 mg/kg. Syafriliansah and Purnomo (2022) further demonstrated that vetiver-based phytoremediation of domestic wastewater increased pH from 6.2 to 7.1, raised dissolved oxygen (DO) levels from 3.5 mg/L to 6.8 mg/L, and reduced turbidity by 85% within 14 days. Local freshwater mussels (*Pilsbryconcha exilis*) also play an important role as natural biofilters due to their high filtration capacity (Sa'adah *et al.* 2024). Chen *et al.* (2023) confirmed that bivalves are capable of absorbing heavy metals through biofiltration mechanisms. Aphrodita

et al. (2022) reported that local freshwater mussels reduced water turbidity by 82% and increased DO levels from 3.4 mg/L to 6.2 mg/L after 10 days. Robi *et al.* (2021) found that mussels helped stabilize water pH within the range of 7.0–7.5.

This study focuses on water contaminated with lead to remove the heavy metal content present in the surrounding environment. This study aims to analyze the reduction of Pb concentration in water and the changes in water quality parameters, including temperature, pH, turbidity, and dissolved oxygen (DO), following the remediation process using various natural agents such as corn cob biochar, vetiver, and local freshwater mussel in Pb-contaminated waters.

METHODS

This study was conducted from July to August 2025. One sampling station was located on the Cinangka River, Bogor. The analysis was conducted at the Productivity and Aquatic Environmental Laboratory (Faculty of Marine Sciences and Fisheries, IPB University), while the Aquatic Animal Physiology Laboratory (Faculty of Marine Sciences and Fisheries, IPB University) was the location for water quality measurements studied in this study. This study used a completely randomized design (CRD) with one factor, namely the remediation agent, consisting of 8 treatments with 3 replications. The experiment was conducted in an open outdoor setting (Han *et al.* 2023). Heavy metal (Pb) concentration in water for each treatment was analyzed twice, at week 0 and week 4. Water quality parameters measured included temperature, pH, dissolved oxygen (DO), and turbidity. Measurements were taken directly from each experimental unit at three time points: week 0, week 2, and week 4. The results of water quality measurements were then associated with Pb concentrations in the water (Zaynab *et al.* 2022). Data were analyzed using ANOVA (at a 95% confidence level). Significant differences among treatments on water quality in Pb-contaminated water were further examined using Duncan's post-hoc test. Correlation analysis between Pb concentration and water quality parameters was also performed (Machado *et al.* 2024).

The formula for calculating the removal efficiency (RE) of Pb in contaminated water is as follows (Sari *et al.* 2022):

$$RE (\%) = \frac{A - B}{A} \times 100$$

Description:

RE (%) = Removal efficiency

A = Metal content before treatment

B = Metal content after treatment

Research procedure

Water and sediment were collected from a sampling point located near rice fields and adjacent to a post-battery recycling site. Initial Pb analysis and baseline measurements of water quality parameters (temperature, pH, dissolved oxygen/DO, and turbidity) were conducted before applying the treatments (Ahmad *et al.* 2021). Corn cob biochar (from *Zea mays*) was prepared by cutting the corn cobs into predetermined small sizes and pyrolyzing them at 500 °C for 60 minutes. Preparation of vetiver (*Vetiver zizanioides*) used was 15 cm of shoots and roots. Preparation of local freshwater mussels (*Pilsbryconcha exilis*) involved selecting healthy and clean individuals of uniform size (6–10 cm). The mussels were depurated and acclimatized for 24–48 h before being placed in the aquarium.

The aquarium size used was 30×30×40 cm³. It contained 26 liters of water and 12 kg of sediment. The remediation agent dosage consisted of 0.6 kg of biochar, 1.5–2 kg of vetiver, and 0.5–1 kg of local shellfish. After the treatment, sampling was performed using

polyethylene bottles or 500 mL glass bottles that had been washed with 10% nitric acid (HNO₃) and rinsed with deionized water. Samples were preserved by adding concentrated HNO₃ until pH < 2 (about 2 mL HNO₃ per liter of sample) (Priantoro *et al.* 2025). Samples were stored at 4 °C in a refrigerator until Pb analysis. Water quality parameters measured during the experiment included temperature, pH, dissolved oxygen (DO), and turbidity. Measurements were taken directly in each experimental unit at week 2 and week 4.

RESULTS AND DISCUSSION

Regulation of the Minister of Environment and Forestry of the Republic of Indonesia Number 22 of 2021 states that lead-contaminated water levels at the research site have exceeded safe limits and require remediation to restore water quality and ensure it meets the standards of the intended environment. As well as the influence of physical factors in the waters that support the absorption and deposition of heavy metals (Nazwasyawinka *et al.* 2025). Table 1 describes the water quality standards and their turbidity levels. The effect of remediation agents on Pb concentration parameters is presented in Table 2.

Table 1. Initial Pb concentration and water quality parameters at the study site prior to remediation.

Parameters	Values	Quality Standards	Methods
Lead (Pb) (mg/L)	1.278	0.03	APHA <i>et al.</i> (2023)
Temperature (°C)	26.88–26.89	25–31	SNI 06-6989.23-2005
Turbidity (NTU)	9.82–9.93	0–10	SNI 06-6989.25-2005
pH	6.76–6.79	6–9	SNI 6989.11:2019
Dissolved Oxygen (DO) (mg/L)	4.87–5.02	6.5–8	SNI 06-6989.14-2004

Table 2. Effect of different remediation treatments on Pb concentration in water after 4 weeks.

Treatments	Pb (mg/L)
	Week 4
No Remediation Agent (A0)	1.276 ± 0.103 ^a
Biochar (A)	0.072 ± 0.037 ^{bc}
Vetiver (B)	0.120 ± 0.039 ^b
Local Freshwater Mussel (C)	0.131 ± 0.064 ^b
Biochar + Vetiver (AB)	0.021 ± 0.016 ^c
Vetiver + Local Freshwater Mussel (BC)	0.016 ± 0.009 ^c
Biochar + Local Freshwater Mussel (AC)	0.029 ± 0.013 ^c
Biochar + Vetiver + Local Freshwater Mussel (ABC)	0.009 ± 0.007 ^c

Note: Different superscript letters indicate significant differences at the 5% level (p < 0.05).

Single-agent treatments, dual-agent combinations, and triple-agent combinations showed significant differences ($p < 0.05$) in reducing Pb concentration in water at week 4 compared with the control treatment without remediation agents (A0). Furthermore, the triple-agent combination of corn cob biochar + vetiver + local freshwater mussels (ABC) resulted in the lowest Pb concentration, but it was not significantly different from the other treatments except for the single-agent vetiver (B) and local freshwater mussel (C) treatments.

Based on the study results, the quality of the treated water was better than before the treatment. This treatment had a positive impact and restored the water quality to its original state. Lourembam *et al.* (2024) reported that biochar derived from agricultural waste (corn cobs) can adsorb Pb^{2+} with very high efficiency. Vetiver is known to tolerate and effectively absorb Pb from contaminated media, with most of the accumulated metal stored in the roots (Qattan 2025). Local freshwater mussels can effectively absorb Pb(II) from wastewater with high removal efficiency (Calvina *et al.* 2024). These natural remediation agents significantly reduced Pb concentrations, thereby reducing ecological risks and protecting the surrounding aquatic environment (Mohammad *et al.* 2025). The effects of remediation agents on water quality parameters are presented in Tables 3 and 4.

The single treatment of one type of remediation agent, 2 types of remediation agents, or 3 types of remediation agents significantly reduced the water temperature compared to without a remediation agent (A0), both in the 2nd and 4th weeks. Furthermore, in the 2nd week, the combination treatment of 3 types of remediation agents biochar + vetiver + local freshwater mussel (ABC) was not different from all other treatments except for the single treatment of biochar (A), vetiver (B), local freshwater mussel (C), and the combination treatment of 2 types of biochar + local freshwater mussel (AC), while the treatment without remediation agent (A0) was significantly different from all other treatments. Then in the 4th week, it was seen that the combination treatment of 3 types of remediation agents, biochar + vetiver + local freshwater mussel (ABC), was not significantly different from the combination treatment of 2 types of remediation agents, biochar + vetiver (AB) and vetiver + local freshwater mussel (BC). However, it was different from the single treatment of biochar (A), vetiver (B), local freshwater mussel (C), and the combination treatment of 2 types of remediation agents, biochar + local freshwater

mussel (AC).

The remediation process was carried out in stages over a four-week period, during which gradual improvements in water quality were observed. The sequential treatments contributed to the progressive recovery of the aquatic environment, restoring conditions that had previously been degraded by industrial activities. By the end of the remediation period, the water quality showed substantial improvement and approached the standards set by environmental authorities. The decrease in temperature was associated with a reduction in the concentration of free metal ions in the water. Pb^{2+} ions can contribute to heat transfer through their interactions with water molecules. As these ions were removed or absorbed by remediation agents such as biochar, vetiver, or local freshwater mussels, the level of ionic activity decreased. This reduction likely contributed to lower heat transfer efficiency, resulting in a decrease in water temperature. According to Raffa *et al.* (2021), The adsorption process of Pb(II) by remediation agents is endothermic and decreases Gibbs free energy (negative ΔG), making the system more thermally stable. In weeks 2 and 4, water quality improved and removed the disruptive lead pollutant caused by battery waste contaminated by an increasingly diverse industry.

Both single and combined treatments of remediation agents significantly reduced water turbidity compared to those without remediation agents (A0) for both observation periods. Furthermore, in the 2nd and 4th weeks, the combination treatment of 3 types of remediation agents, biochar + vetiver + local freshwater mussels (ABC), was not significantly different from all treatments except for the single treatment of biochar (A), vetiver (B), local freshwater mussels (C), and the combination treatment of 2 types of biochar + local freshwater mussels (AC). The turbidity value of the treatment without remediation agents (A0) was significantly different from all other treatments in the 2nd and 4th weeks.

The decrease in water turbidity is caused by a reduction in colloidal particles and suspended Pb^{2+} metal ions. Pb^{2+} ions tend to bind with organic and inorganic particles, forming deposits that increase turbidity. When Pb is adsorbed by remediation agents such as biochar, vetiver, or local freshwater mussel, these metal particles settle and are reduced in the water column, thereby increasing clarity. Romadhon *et al.* (2024) stated that the application of remediation agents in Pb-contaminated water reduces Pb levels and is followed by a decrease in water turbidity values,

indicating that the Pb adsorption process effectively improves the physical quality of water.

The single treatment of one type of remediation agent, 2 types of remediation agents, or 3 types of remediation agents significantly increased the pH value of the water compared to without remediation agents (A0), both in the 2nd and 4th weeks. Furthermore, in the 2nd and 4th weeks, the combination treatment of 3 types of remediation agents, biochar + vetiver + local freshwater mussels (ABC) had significantly different pH values from all other treatments. Meanwhile, the pH value of the 2nd week of treatment without remediation agents (A0) was not significantly different from all treatments except for the single treatment of biochar (A), the combination treatment of 2 types of remediation agents biochar + vetiver (AB), vetiver + local freshwater mussels (BC),

biochar + local freshwater mussels (AC), and the combination treatment of 3 types of remediation agents biochar + vetiver + local freshwater mussels (ABC). The pH value of the 4th week of treatment without remediation agents (A0) was significantly different from all other treatments.

The increase in pH value was caused by the reduction in the concentration of acidic Pb²⁺ ions after the adsorption process (Kholifah and Rachmadiarti 2019). When Pb is bound by remediation agents such as biochar, vetiver, or local freshwater mussels, H⁺ ions in the water decrease due to the formation of Pb(OH)₂ compounds, thus increasing the water pH. The application of natural remediation agents in Pb-contaminated water increases pH along with the decrease in Pb concentration due to the base neutralization reaction.

Table 3. Effects of different remediation treatments on water temperature and turbidity at weeks 2 and 4.

Treatments	Temperatures		Turbidity	
	Week 2	Week 4	Week 2	Week 4
No Remediation Agent (A0)	27.00 ± 0.03 ^a	27.39 ± 0.06 ^a	9.83 ± 0.02 ^a	9.85 ± 0.01 ^a
Biochar (A)	26.72 ± 0.09 ^b	26.68 ± 0.07 ^c	9.15 ± 0.05 ^c	7.66 ± 0.10 ^c
Vetiver (B)	26.84 ± 0.08 ^b	26.80 ± 0.07 ^b	9.52 ± 0.11 ^b	8.14 ± 0.08 ^b
Local Freshwater Mussel (C)	26.86 ± 0.05 ^b	26.81 ± 0.02 ^b	9.63 ± 0.13 ^b	8.24 ± 0.27 ^b
Biochar + Vetiver (AB)	26.34 ± 0.06 ^d	25.93 ± 0.02 ^e	8.49 ± 0.05 ^d	6.68 ± 0.03 ^d
Vetiver + Local Freshwater Mussel (BC)	26.25 ± 0.12 ^d	25.92 ± 0.04 ^e	8.47 ± 0.05 ^d	6.61 ± 0.07 ^d
Biochar + Local Freshwater Mussel (AC)	26.55 ± 0.04 ^c	26.49 ± 0.06 ^d	9.06 ± 0.04 ^c	7.53 ± 0.10 ^c
Biochar + Vetiver + Local Freshwater Mussel (ABC)	26.24 ± 0.10 ^d	25.88 ± 0.01 ^e	8.46 ± 0.04 ^d	6.50 ± 0.06 ^d

Note: Different superscript letters indicate significant differences at the 5% level ($p < 0.05$).

Table 4. Effects of different remediation treatments on pH and dissolved oxygen (DO) at weeks 2 and 4.

Treatments	pH		Dissolved Oxygen (DO)	
	Week 2	Week 4	Week 2	Week 4
No Remediation Agent (A0)	6.74 ± 0.03 ^c	6.73 ± 0.03 ^c	4.70 ± 0.10 ^d	4.51 ± 0.25 ^d
Biochar (A)	6.86 ± 0.02 ^d	7.00 ± 0.03 ^d	5.43 ± 0.06 ^c	5.83 ± 0.08 ^{bc}
Vetiver (B)	6.79 ± 0.02 ^{de}	6.98 ± 0.02 ^d	5.38 ± 0.32 ^c	5.61 ± 0.50 ^{bc}
Local Freshwater Mussel (C)	6.79 ± 0.03 ^{de}	6.95 ± 0.05 ^d	4.99 ± 0.25 ^d	5.21 ± 0.37 ^c
Biochar + Vetiver (AB)	6.99 ± 0.05 ^{bc}	7.21 ± 0.02 ^c	5.89 ± 0.07 ^b	6.75 ± 0.20 ^a
Vetiver + Local Freshwater Mussel (BC)	7.05 ± 0.07 ^b	7.31 ± 0.02 ^b	6.07 ± 0.06 ^{ab}	7.24 ± 0.38 ^a
Biochar + Local Freshwater Mussel (AC)	6.95 ± 0.05 ^c	7.18 ± 0.02 ^c	5.44 ± 0.22 ^c	6.02 ± 0.70 ^b
Biochar + Vetiver + Local Freshwater Mussel (ABC)	7.14 ± 0.07 ^a	7.40 ± 0.02 ^a	6.22 ± 0.10 ^a	7.31 ± 0.32 ^a

Note: Different superscript letters indicate significant differences at the 5% level ($p < 0.05$).

The application of single, dual, and triple remediation treatments significantly increased dissolved oxygen (DO) levels compared to the control (A0) in both the 2nd and 4th weeks. In the 2nd week, the triple-treatment combination (biochar + vetiver + local freshwater mussels; ABC) differed significantly from all other treatments except the dual combination of vetiver + local freshwater mussels (BC). In the 4th week, the ABC treatment remained significantly different from all other treatments except the dual combinations of biochar + vetiver (AB) and vetiver + local freshwater mussels (BC). Meanwhile, the control treatment (A0) showed significant differences from all other treatments in both weeks, except for the single-treatment mussel group (C).

The increase in dissolved oxygen (DO) levels occurs because the reduction in Pb levels reduces the metal's toxic effects on phytoplankton and aquatic microorganisms. Rizaldi *et al.* (2025) stated that when Pb is absorbed by remediation agents, photosynthetic activity and oxygen diffusion increase, and DO levels rise. This improves water quality and increases biological activity, optimizing oxygen production through photosynthesis and air diffusion.

The highest removal efficiency of Pb concentration in water was found in the combination treatment of three remediation agents, biochar + vetiver + local freshwater mussels (ABC) in week 4, with a value of 99.3% and a Pb concentration of 0.009 mg/L, which is below the quality standard. The lowest removal efficiency of Pb concentration was 0.1% in the treatment without remediation agents (A0), with a Pb concentration of 1.276 mg/L, which remains above the quality standard (Figure 1). This occurred because there was no remediation agent activity.

Figure 1 presents a bar chart depicting the Removal Efficiency (RE) of Lead (Pb) metal across different experimental treatments. The vertical axis quantifies the removal performance in percentage (%), while the horizontal axis lists the treatment codes: A0 (control), A, B, C, and their various combinations (AB, BC, AC, ABC). Visually, the chart illustrates significant variation in effectiveness among the treatments. The height of each bar directly corresponds to the percentage of Pb concentration removed from the tested medium. All treatment bars showed high Pb removal efficiency, although the values remained below 100%. The control

treatment (A0) serves as the baseline for comparison, showing the lowest removal efficiency. Among the remediation agents, the combined treatments, particularly the multi-agent combinations, appear to generate the tallest bars, indicating they may be the most effective strategies for Pb removal in this study. The results clearly demonstrate that the application of remediation agents substantially enhances the removal of Pb compared to the untreated control.

Not all treatments met the quality standard, particularly the single-agent treatments. The highest removal efficiency was observed in the combination of three remediation agents, namely biochar + vetiver + local freshwater mussels (ABC), which achieved 99.3% with a Pb concentration of 0.009 mg/L. For the combination of two remediation agents, biochar + vetiver (AB) achieved 98.3% (0.021 mg/L), vetiver + local freshwater mussels (BC) achieved 98.8% (0.016 mg/L), and biochar + local freshwater mussels (AC) achieved 97.8% (0.029 mg/L). All combination treatments (two and three agents) successfully reduced Pb concentrations below the quality standard of 0.03 mg/L. Single treatments using biochar, vetiver, or local freshwater mussels were also effective in reducing Pb levels due to their specific mechanisms. However, their effectiveness was lower compared to combinations of two or three agents, as every single agent operates through a single absorption pathway, resulting in more limited capacity and metal-binding range.

The removal efficiency of Pb concentration in each treatment showed different values. The removal efficiency and Pb concentration values for each single treatment using one remediation agent biochar (A) were 94.4% (with a Pb value of 0.072 mg/L), the vetiver treatment (B) was 90.6% (with a Pb value of 0.120 mg/L), and the local freshwater mussels treatment (C) was 89.7% (with a Pb value of 0.131 mg/L), in which all single-agent treatments were still above the quality standard was 0.03 mg/L. This occurred because the combination treatments of three or two remediation agents were more effective in reducing Pb levels, as the three agents worked synergistically through different mechanisms. This synergy expands the active surface and accelerates metal binding, resulting in higher Pb reduction efficiency compared to single treatments. The correlation between water Pb levels and water quality parameters is presented in Figures 2–5.

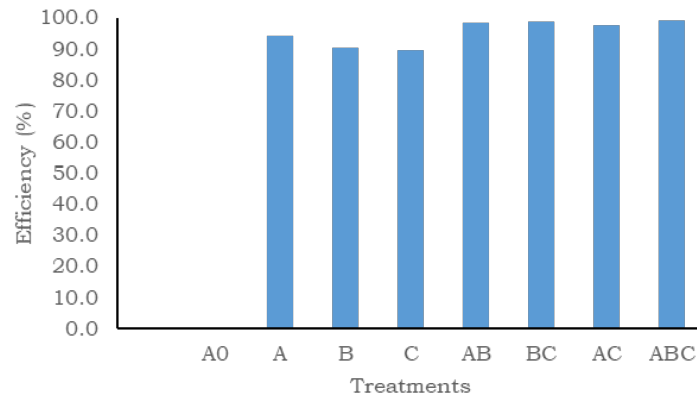


Figure 1. Removal efficiency (RE) of Pb in water for each treatment at week 4.

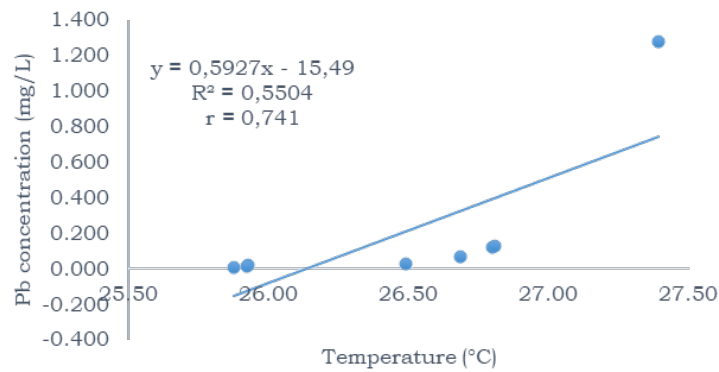


Figure 2. Correlation between temperature and Pb concentration in water at week 4.

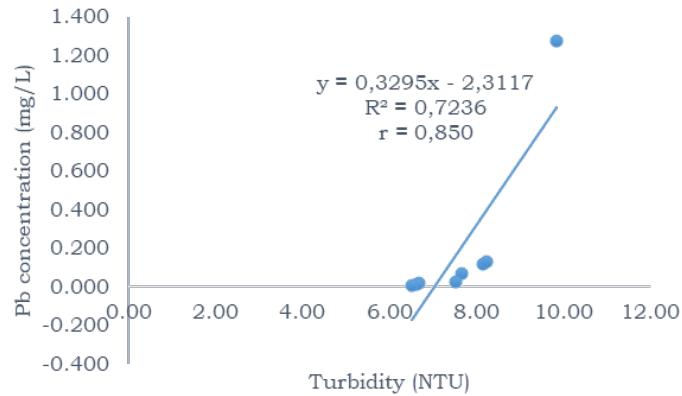


Figure 3. Correlation between turbidity and Pb concentration in water at week 4.

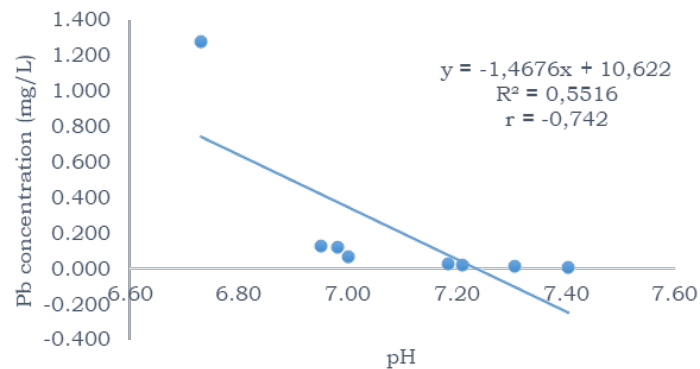


Figure 4. Correlation between pH and Pb concentration in water at week 4.

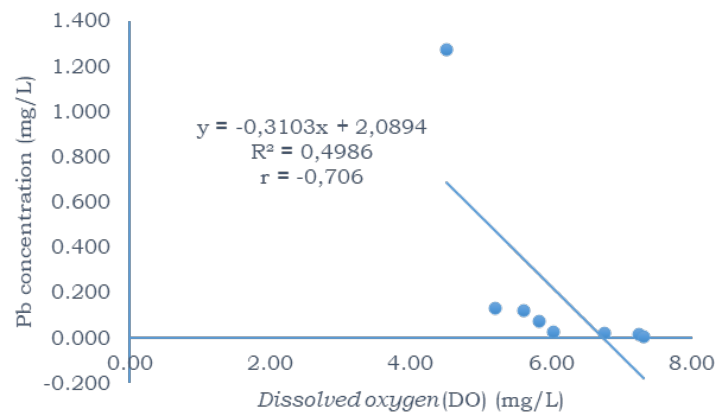


Figure 5. Correlation between dissolved oxygen (DO) and Pb concentration in water at week 4.

Figure 2 shows a correlation coefficient (r) of 0.741, categorized as a strong positive correlation, meaning that as the Pb concentration in the water decreases, the water temperature tends to decrease. This is because when Pb concentration is adsorbed by the remediation agent, the number of free metal ions decreases, thereby reducing the heat energy in the system and lowering the water temperature (Fatiha *et al.* 2025). There is a significant correlation between temperature parameters and Pb concentration, obtained from the test results, that water temperature has a significant effect at the 5% level ($p < 0.05$) on Pb levels in the water in the 4th week of observation.

Figure 3 shows a correlation coefficient (r) of 0.850, categorized as a strong and positive relationship, meaning that as the Pb concentration in the water decreases, the water turbidity value will decrease. This is because Pb^{2+} ions and their compounds tend to form complexes and suspended particles that increase water turbidity (Septiawan *et al.* 2023). Therefore, when Pb is adsorbed by remediation agents such as biochar, vetiver, or local freshwater mussels, the metal particles and fine sediment are reduced, so the water becomes clearer and the turbidity value decreases. There is a clear correlation between the turbidity parameter and Pb concentration, obtained from the test results, that water turbidity has a significant effect at the 5% level ($p < 0.05$) on Pb levels in the water in the 4th week of observation (Rohmayani *et al.* 2024).

Figure 4 shows a correlation coefficient (r) value of -0.742, categorized as a strong and negative relationship, meaning that as the Pb concentration in water decreases, the pH value of the water will increase. The increase in pH indicates water chemistry conditions that are relatively neutral to slightly alkaline, which are known to reduce the solubility and mobility of

the heavy metal Pb (Kusuma *et al.* 2015). This is because Pb^{2+} ions are acidic and can lower pH through hydrolysis reactions (Sulistyo *et al.* 2024). When Pb^{2+} is adsorbed by remediation agents such as biochar, vetiver, or local freshwater mussels, the number of H^+ ions in the water decreases due to the formation of $Pb(OH)_2$ compounds, so that the water conditions become more alkaline and the pH increases. There is a clear correlation between pH parameters and Pb concentration, obtained from the test results, that the water pH has a significant effect at the 5% level ($p < 0.05$) on Pb levels in the water in the 4th week of observation (Abiyana and Mahmiah 2021).

Figure 5 shows a correlation coefficient (r) of -0.706, categorized as a strong and negative relationship, meaning that as the Pb concentration in the water decreases, the dissolved oxygen (DO) value in the water will increase. This is because Pb^{2+} ions are toxic to photosynthetic microorganisms and aquatic organisms that play a role in oxygen production (Rizaldi *et al.* 2025). There is a clear correlation between the dissolved oxygen (DO) parameter and Pb concentration. Based on the test results, it was assessed that dissolved oxygen (DO) had a significant effect at the 5% level ($p < 0.05$) on Pb levels in water in the 4th week of observation.

CONCLUSION

Combined remediation treatments demonstrated superior effectiveness compared to single-agent applications in reducing Pb concentrations in water. The triple combination (biochar, vetiver, and freshwater mussels) achieved the highest removal efficiency and successfully reduced Pb levels below the regulatory threshold (0.03 mg/L), whereas single-agent treatments remained above

the standard. These findings highlight the synergistic advantage of multi-agent systems in enhancing Pb removal, with a significant relationship observed between Pb reduction and water quality parameters.

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