**KESANS: International Journal of Health and Science**
**2808-7178 / 2808-7380**
http://kesans.rifainstitute.com/index.php/kesans/index

# Effect of Water Hyacinth (*Eichhornia crassipes*) and Biochar on pH and Fe and Mn Concentrations in Acid Mine Drainage

**[1]Fitriyati Sholehati Albanjari, [2]Ajidirman, [3]Wiskandar***
[1]Environmental Science, Universitas Jambi, Indonesia; email: Albanjarifitriyati@gmail.com
[2] Environmental Science, Universitas Jambi, Indonesia
[3] Environmental Science, Universitas Jambi, Indonesia*
*Correspondence

**Article Information**
*Submitted:* **02 April 2026**
*Accepted:* **14 April 2026**
*Publish:* **17 April 2026**

**Keyword:** Acid Mine Drainage; Water Hyacinth (Eichhornia Crassipes); Biochar;

**Copyright holder:** Fitriyati Sholehati Albanjari, Ajidirman, Wiskandar

**Year: 2026**

This is an open access article under the CC BY-SA license.

***Abstract***
***Introduction:*** *Acid mine drainage (AMD) is a major environmental problem characterized by low pH and elevated heavy metals such as Fe and Mn that can contaminate aquatic ecosytems. Environmentally friendly treatment alternatives include water hyacinth (Eichhornia crassipes) for phytoremediation and biochar for metal adsorption and pH buffering* ***Objective:*** *To analyze the effects of water hyacinth and biochar on increasing pH and reducing Fe and Mn concentrations in AMD* ***Method:*** *An experimental study was conducted using combination treatments of water hyacinth and biochar at several dosage levels. Measured parameters included pH and Fe–Mn concentrations. Data were analyzed using ANOVA followed by Duncan's New Multiple Range Test (DNMRT) at a 5% significance level.* ***Results and Discussion:*** *Water hyacinth did not significantly increase pH but significantly reduced Fe at 15 stems. Biochar significantly raised pH toward near-neutral conditions and reduced Fe and Mn, with the best performance at 20 g $L^{-1}$. Combined treatments were more effective than single treatments, increasing pH to 6.5–7.5 and achieving >99% Fe and Mn removal* ***Conclusion:*** *Water hyacinth–biochar combinations offer a promising, low-cost, and eco-friendly AMD treatment via synergistic phytoremediation and adsorption*

| | |
|---|---|
| How to Cite | **Fitriyati Sholehati Albanjari, Ajidirman, Wiskandar/Effect of Water Hyacinth (*Eichhornia crassipes*) and Biochar on pH and Fe and Mn Concentrations in Acid Mine Drainage/Vol. 5, No. 7, 2026** |
| DOI | https://doi.org/10.54543/kesans.v5i7.616 |
| e-ISSN/p-ISSN | **2808-7178 / 2808-7380** |
| Published by | **CV. Rifainstitut/KESANS: International Journal of Health and Science** |

## Introduction

Coal mining activities in Indonesia generally use an open-pit mining system which causes materials or rocks located on the earth's surface to be directly exposed to air and water, thereby triggering chemical reactions. Overburden, coal, and bedrock in mining areas often contain sulfide minerals such as marcasite and pyrite which have great potential to generate acid mine drainage (AMD) and pollute the environment (Razi, Ilmu, & Sosial, 2021); (Adventia, Santoso, Wicaksono, Anasstasia, & Utami, 2023). Water pollution commonly occurs as a result of mining because extractive activities bring materials to the surface and can reduce water quality and quantity (Prasetyo, Baderan, & Hamidu, 2025); (Syam & Iryani, 2025); (Ariya, Novian, & Reflis, 2025). Several locations affected include PT Bukit Asam Indralaya, PT Bara Harmonis in Bungo Regency (Ishak, 2013), and the former mining area ex-Pit 7 owned by PT Sarolangun Prima Coal. Acid mine drainage cannot be directly discharged into natural water bodies because it can seriously pollute the environment, reduce water quality, damage aquatic and soil ecosystems, inhibit the growth of living organisms, and cause corrosion (Mamede, 2023). The main cause of acid mine drainage formation is the presence of rocks containing pyrite minerals ($FeS_2$) which under oxidized conditions produce dissolved heavy metals such as iron (Fe) and manganese (Mn)

Excess Fe and Mn can further deteriorate water quality and increase environmental health risks (IZZA, 2024). Elevated Fe often causes reddish-brown discoloration, turbidity, unpleasant taste/odor, and sediment deposition that can clog channels and reduce light penetration, thereby disturbing aquatic habitats. High Mn may create dark staining, worsen organoleptic quality, and contribute to chronic exposure concerns if contaminated water is used for domestic purposes (Syamsuddin, Baderan, & Lihawa, 2024). In aquatic systems, Fe–Mn precipitates can cover substrates and stress biota, making Fe and Mn reduction an important target in AMD control. One natural method that can be used to treat acid mine drainage is phytoremediation using water hyacinth (Eichhornia crassipes). This plant can absorb heavy metal ions that cause acidity such as $Fe^{2+}$, $Mn^{2+}$, and $Al^{3+}$ and release alkaline ions such as $Ca^{2+}$, $Mg^{2+}$, $K^{+}$, and $Na^{+}$ which help neutralize water pH. Its roots also support microorganisms such as sulfate-reducing bacteria that reduce acidity (Leka, 2024); (Nabil, Nurhasanah, Mulyadi, Husein, & Sari, 2026); (Hapsari, Yunus, & Sunarto, 2020). Water hyacinth biomass after decomposition can increase alkalinity through the release of alkaline compounds, supporting phytoremediation mechanisms (Fahruddin, 2020). Previous studies showed that water hyacinth increased AMD pH from 3.03 to 7.78 and reduced Cu from 8.57 mg/L to 0.11 mg/L and Zn from 7.03 mg/L to 0.00 mg/L (Yunus dan Prihatini, 2018). The use of 10 water hyacinth stems and 2 kg of organic substrate also increased pH from 3.03 to 6.01 on day 4 and reduced Fe from 5.858 mg/L to <0.0033 mg/L and Mn from 6.973 mg/L to 1.914 mg/L (Fridtriyanda, Sukmawatie, & Iashania, 2024)

In addition to water hyacinth, biochar also shows significant potential in reducing AMD impacts. Its porous structure and high surface area allow adsorption of heavy metal ions such as Fe, Mn, Cu, Pb, Zn, and Cd (Simamora, Nurcholis, Ardian, Ernawati, & Winarno, 2024). Surface functional groups (–COOH, –OH) support complexation and ion exchange, reducing heavy metals while increasing pH, and its alkaline buffering capacity makes it a sustainable option. Coconut shell biochar has been reported to increase pH from 5.19 to 8.675 while reducing sulfate and heavy metals (Dwiyanti, 2023). Increasing biochar dose also increased pH and reduced Fe and Mn with efficiencies of 98.09% and 96.98% at 10 g biochar per 1000 mL AMD

Based on the Regulation of the Minister of Environment and Forestry of the Republic of Indonesia Number 5 of 2022, wastewater quality standards for coal mining are pH 6–9, maximum Fe 7 mg/L, and maximum Mn 4 mg/L. Initial testing of AMD at PT X, Jambi Province showed pH 3.41, Fe 8.523 mg/L, and Mn 6.594 mg/L, exceeding the thresholds, indicating the need for treatment. Therefore, the combined use of water hyacinth and biochar is expected to be an alternative method to increase pH and reduce Fe and Mn concentrations in AMD. This study aims to analyze the effect of water hyacinth application, biochar application, and their interaction on increasing pH and reducing Fe and Mn concentrations in AMD.

## Method

This study was conducted from November to December 2024. Acid mine drainage samples were collected from an active settling pond in the coal mining area of PT. X in Jambi Province. Analysis of water quality parameters was carried out at the Laboratory of the Faculty of Science and Technology, Universitas Jambi. This study used an experimental method with a factorial completely randomized design (CRD) consisting of two treatment factors, namely water hyacinth and biochar. The water hyacinth factor consisted of three levels: 0 stems (E0), 10 stems (E1), and 15 stems (E2), while the biochar factor consisted of four levels: 0 g/L (B0), 10 g/L (B1), 15 g/L (B2), and 20 g/L (B3). Each treatment combination was conducted with three replications, resulting in a total of 36 experimental units.

Acid mine drainage samples were collected using the grab sampling method in accordance with SNI 6989.59:2008 standards from the active settling pond of PT. X. Biochar was produced from coconut shells through a preparation process including cleaning and drying for three days, followed by heating using an oven at 150°C for 1 hour to remove moisture content. Furthermore, the carbonization process was carried out using a furnace at 500°C for 1 hour to obtain biochar, which was then ground and sieved using a 50-mesh sieve. The biochar was then weighed according to treatment dose variations of 10 g, 15 g, and 20 g. Water hyacinth was collected from community ponds in Kenali Besar Village and Parit, Kasang Pudak Village. The plants used were young plants that had been cleaned and acclimatized using distilled water (aquades) for 7 days before being used in the experimental treatments. The parameters analyzed in this study included pH, Fe concentration, and Mn concentration before and after treatment using water hyacinth and biochar. pH measurements were carried out using a pH meter, while Fe and Mn concentrations were analyzed using the AAS (DTPA) method. Metal removal efficiency was calculated using the following equation:

$$\text{Metal Removal Efficiency (\%)} = \frac{Co - Ca}{Co} \text{ x } 100$$

Description:
Co = Initial value
Ca = Final value

Measurement data were analyzed descriptively and presented in tables and graphs to observe changes in pH values and the reduction of Fe and Mn concentrations due to the application of water hyacinth and biochar treatments.

## Result and Discussion

### Effect of Water Hyacinth and Biochar on pH of Acid Mine Drainage

The analysis of variance results showed that the interaction effect between water hyacinth and biochar application had no significant effect on the pH of acid mine drainage. However, there was a main effect of each treatment factor, namely water hyacinth and biochar, on increasing the pH of acid mine drainage as presented in Table 1. This indicates that the pH response was more influenced by each treatment applied independently.

**Table 1**
Effect of water hyacinth and biochar on pH of acid mine drainage

| Treatment | pH |
|---|---|
| **Water hyacinth (stem)** | |
| 0 | 4.97 a |
| 10 | 4.68 a |
| 15 | 4.62 a |
| **Biochar (g $L^{-1}$)** | |
| 0 | 3.49 b |
| 10 | 7.09 a |
| 15 | 7.06 a |
| 20 | 7.73 a |

Values followed by different letters in the same column indicate significant differences according to the DNMRT test ($\alpha = 5\%$).

The pH parameter is used as the main indicator in evaluating acid mine drainage quality because low pH values are closely related to increased heavy metal solubility and potential toxicity to aquatic organisms and the surrounding environment (Younger et al., 2002; Nordstrom, 2011). The observation results showed that acid mine drainage in the treatment without the addition of ameliorant materials had a very low pH value, which reflects the typical characteristics of acid mine drainage due to the oxidation of sulfide minerals, especially pyrite ($FeS_2$), which produces large amounts of $H^+$ ions (Akcil & Koldas, 2006).

The pH values of acid mine drainage in the water hyacinth stem treatment ranged from 4.62 to 4.97 and were still classified as acidic. Based on the DNMRT test at the $\alpha$ = 5% level, all water hyacinth stem treatments showed no significant differences, indicating that the addition of water hyacinth stems had not significantly increased the pH of acid mine drainage. Increasing the dose of water hyacinth stems tended to be followed by a decrease in pH values although these changes were not statistically significant. This condition indicates that the presence of water hyacinth stems in acid mine drainage was not yet effective as an acidity-neutralizing material and tended to maintain acidic conditions.

This phenomenon can be explained by the decomposition process of water hyacinth organic matter. At the initial stage of decomposition, plant tissues decompose and produce organic acids such as humic acid and fulvic acid which contribute to the increase of $H^+$ ions in the water (Stevenson, 1994). Water hyacinth does not contain sufficient alkaline mineral content to function as an alkaline ameliorant material. The main role of water hyacinth is more dominant as a phytoremediator through mechanisms of heavy metal absorption and accumulation as well as dissolved nutrient uptake rather than as an acidity-neutralizing agent (Malik, 2007; Rai, 2009).

Biochar application showed a highly significant effect on increasing the pH of acid mine drainage. In the treatment without biochar, the pH value was recorded at 3.49, indicating highly acidic conditions and high potential for environmental pollution. Biochar application at doses of 10, 15, and 20 g $L^{-1}$ increased the pH values to 7.09, 7.06, and 7.73, respectively, which were classified as neutral to slightly alkaline.

All biochar treatments based on the DNMRT test showed significant differences compared to the control but were not significantly different among biochar doses. This indicates that biochar application, even at the lowest dose, was able to effectively neutralize acid mine drainage. The increase in pH due to biochar addition is closely related to the characteristics of biochar which is generally alkaline and contains base cations such as $Ca^{2+}$, $Mg^{2+}$, $K^{+}$, and $Na^{+}$ that are capable of neutralizing $H^{+}$ ions through ion exchange mechanisms (Lehmann & Joseph, 2015). Biochar has a high specific surface area and cation exchange capacity which enables it to adsorb acidity-causing ions and suppress further oxidation processes of sulfide minerals (Ahmad et al., 2014).

Biochar not only functions as an acidity-neutralizing material but also plays a role in stabilizing the chemical conditions of acid mine drainage sustainably. The results of this study confirm that biochar has much higher effectiveness compared to water hyacinth stems in increasing the pH of acid mine drainage. Increasing pH to near-neutral conditions is very important because it can reduce heavy metal solubility, decrease aquatic toxicity, and improve overall environmental quality (Younger et al., 2002).

The distribution of pH values in each combination treatment of water hyacinth and biochar showed that the control treatment had the lowest pH value, approximately 3–3.5. In contrast, biochar treatments increased pH values to a near-neutral range of approximately 7–8. Water hyacinth treatments without biochar showed lower pH increases compared to biochar treatments. The combination treatments produced higher and more stable pH values ranging from 6.5 to 7.5 and even approaching 8. These conditions indicate a synergistic effect between biochar and water hyacinth in stabilizing the pH of acid mine drainage (Gwenzi et al., 2017; Wu et al., 2014).

The stability of pH values approaching neutral conditions is very important because it can reduce heavy metal solubility and improve the effectiveness of the acid mine drainage remediation process overall.

**Effect of Water Hyacinth and Biochar on Fe Concentration in Acid Mine Drainage**

The analysis of variance results showed that the interaction effect between water hyacinth and biochar application had no significant effect on Fe concentration in acid mine drainage. However, there was a main effect of each treatment factor, namely water hyacinth and biochar, on reducing Fe concentration as presented in Table 2. This indicates that the response of Fe concentration was more influenced by each treatment applied independently.

**Table 2**
Effect of water hyacinth and biochar on Fe concentration in acid mine drainage

| Treatment | Fe (mg $L^{-1}$) |
|---|---|
| **Water hyacinth (stem)** | |
| 0 | 4.48 a |
| 10 | 3.72 a |
| 15 | 2.06 b |
| **Biochar (g $L^{-1}$)** | |
| 0 | 3.64 a |
| 10 | 4.29 a |
| 15 | 4.06 a |
| 20 | 1.69 b |

Values followed by different letters in the same column indicate significant differences according to the DNMRT test (α = 5%).

Fe is one of the dominant elements in acid mine drainage whose presence is strongly influenced by pH conditions because at low pH Fe tends to remain in dissolved form and is toxic to aquatic organisms (Younger et al., 2002; Nordstrom, 2011).

The observation results showed that Fe concentrations in the water hyacinth stem treatment ranged from 2.06–4.48 mg $L^{-1}$, while in the biochar treatment they ranged from 1.69–4.29 mg $L^{-1}$. These variations in Fe concentration indicate that the type of material and treatment dose produced different responses to Fe dynamics in acid mine drainage. The application of 15 stems of water hyacinth showed a significant reduction in Fe concentration to 2.06 mg $L^{-1}$ compared to other treatments. This indicates that at a certain concentration water hyacinth was able to reduce Fe concentration in acid mine drainage through adsorption and accumulation mechanisms in plant tissues (Rai, 2009; Malik, 2007).

Organic matter resulting from the decomposition of water hyacinth produces humic compounds which play a role in forming complexes between Fe and organic compounds so that Fe becomes less soluble in water (Stevenson, 1994). Fe concentration in the biochar treatment decreased significantly at a dose of 20 g $L^{-1}$ to 1.69 mg $L^{-1}$. This reduction is related to the characteristics of biochar which has a high specific surface area, high porosity, and negative surface charge, making it effective in adsorbing metal ions including Fe (Lehmann & Joseph, 2015; Ahmad et al., 2014).

The increase in pH due to biochar addition also plays an important role in reducing Fe solubility through precipitation into $Fe(OH)_3$ under more neutral pH conditions (Younger et al., 2002; Nordstrom, 2011). The efficiency of Fe removal in various treatment combinations is presented in Table 3.

**Table 3**
Efficiency of Fe removal in acid mine drainage

| No | Treatment | Residual Fe (mg $L^{-1}$) | Efficiency (%) |
|---|---|---|---|
| 1 | E2B3 | 0.0018 | 99.98 |
| 2 | E2B0 | 0.0671 | 99.21 |
| 3 | E0B3 | 0.6407 | 92.48 |
| 4 | E1B2 | 0.8043 | 90.56 |
| 5 | E1B3 | 1.0535 | 87.64 |
| 6 | E2B1 | 1.3245 | 84.46 |
| 7 | E2B2 | 1.3564 | 84.09 |
| 8 | E0B1 | 1.3782 | 83.83 |
| 9 | E1B0 | 1.5180 | 82.19 |
| 10 | E1B1 | 1.5917 | 81.32 |
| 11 | E0B2 | 1.9006 | 77.70 |
| 12 | E0B0 | 2.0620 | 75.81 |

The highest removal efficiency was obtained in treatment E2B3 with a residual Fe concentration of 0.0018 mg $L^{-1}$ and an efficiency of 99.98%, while the control treatment showed the lowest efficiency of 75.81%. This indicates a synergistic effect between water hyacinth and biochar in reducing Fe concentration in acid mine drainage. Biochar plays a role through adsorption mechanisms and increasing pH which promotes Fe precipitation in the form of $Fe(OH)_3$ (Ahmad et al., 2014; Mohan et al., 2014; You et al., 2011; Stumm & Morgan, 1996). Meanwhile, water hyacinth plays a role through phytoextraction and rhizofiltration mechanisms which increase metal uptake by plant tissues (Rezania et al., 2015; Mishra & Tripathi, 2008).

The combination of both treatments produced a sequential remediation system that integrates physicochemical and biological processes, thereby significantly increasing Fe removal efficiency (Ali et al., 2013). Overall, Fe removal efficiency in most treatments exceeding 90% indicates that the combination of water hyacinth and biochar has strong potential to be applied in passive and environmentally friendly acid mine drainage treatment systems (Rezania et al., 2015).

**Effect of Water Hyacinth and Biochar on Mn Concentration in Acid Mine Drainage**

The analysis of variance results showed that the interaction effect between water hyacinth and biochar application had no significant effect on Mn concentration in acid mine drainage. However, there was a main effect of each treatment factor, namely water hyacinth and biochar, on reducing Mn concentration as presented in Table 4. This indicates that the response of Mn concentration was more influenced by each treatment applied independently.

**Table 4**
Effect of water hyacinth and biochar on Mn concentration in acid mine drainage

| Treatment | Mn (mg $L^{-1}$) |
|---|---|
| **Water hyacinth (stem)** | |
| 0 | 2.00 a |
| 10 | 1.02 b |
| 15 | 0.85 b |
| **Biochar (g $L^{-1}$)** | |
| 0 | 3.94 a |
| 10 | 0.49 b |
| 15 | 0.46 b |
| 20 | 0.28 b |

Values followed by different letters in the same column indicate significant differences according to the DNMRT test ($\alpha = 5\%$).

The analysis results showed that the application of water hyacinth and biochar significantly reduced Mn concentration in acid mine drainage compared to the control. In the treatment without plants, Mn concentration reached 2.00 mg $L^{-1}$, whereas the application of 10 and 15 stems of water hyacinth reduced Mn concentrations to 1.02 and 0.85 mg $L^{-1}$, respectively. This indicates that the presence of water hyacinth biomass significantly increased the Mn removal process in the acid mine drainage system.

The reduction of Mn concentration in the water hyacinth treatment indicates that this plant functions as a phytoremediation agent through phytoextraction and phytostabilization mechanisms, in which metal ions are absorbed by the root system and partially translocated to plant tissues (Gunnarsson & Petersen, 2007; Rezania et al., 2015). The dense root system of water hyacinth that hangs in water increases the surface contact area with contaminated water, thereby accelerating heavy metal adsorption and absorption processes (Dhir, 2014).

Increasing plant biomass was proven to increase metal uptake capacity. This is consistent with Olguín et al. (2013), who stated that the accumulation capacity of heavy metals in aquatic plants is directly proportional to the available biomass.

In the biochar treatment, the highest Mn concentration was found at the dose of 0 g $L^{-1}$, which was 3.94 mg $L^{-1}$. The application of biochar at doses of 10, 15, and 20 g $L^{-1}$ reduced Mn concentrations to 0.49, 0.46, and 0.28 mg $L^{-1}$, respectively. All biochar doses showed significant differences compared to the control but were not significantly different among doses. In general, the effectiveness of Mn reduction by biochar was greater than that of water hyacinth.

The effectiveness of biochar is related to its physicochemical properties, including a large surface area, porous structure, and active functional groups such as carboxyl (–COOH), hydroxyl (–OH), and phenolic groups which are capable of binding heavy metals through adsorption, ion exchange, and complexation mechanisms (Ahmad et al., 2014; Lehmann & Joseph, 2015). In addition, biochar is alkaline in nature and can increase the pH of acid mine drainage, which subsequently reduces Mn solubility through precipitation into $Mn(OH)_2$ (Younger et al., 2002; Johnson & Hallberg, 2005).

The significant reduction in Mn concentration at the dose of 20 g $L^{-1}$ indicates that biochar works effectively as a heavy metal adsorbent in the acid mine drainage system. The absence of significant differences among biochar doses indicates that the adsorption capacity was likely achieved at the dose of 10 g $L^{-1}$ as explained in the concept of maximum adsorption capacity in adsorption isotherm models (Inyang et al., 2012).

The control treatment showed the highest Mn concentration due to low pH conditions which maintained Mn in dissolved form (Akcil & Koldas, 2006). Biochar treatments showed more stable Mn reduction compared to single-plant treatments due to adsorption mechanisms and pH increases that promoted Mn precipitation as $Mn(OH)_2$ (Lehmann & Joseph, 2015; Gwenzi et al., 2017).

The combination treatment of water hyacinth and biochar produced the lowest and most stable Mn concentrations. This indicates a synergistic effect between the physicochemical mechanism of biochar and the biological mechanism of plants in reducing Mn concentration sustainably (Azwari, 2020). The efficiency of Mn removal in various treatment combinations is presented in Table 5.

**Table 5**

Efficiency of Mn removal in acid mine drainage

| No | Treatment | Residual Mn (mg $L^{-1}$) | Efficiency (%) |
|---|---|---|---|
| 1 | E0B0 | 2.0281 | 69.25 |
| 2 | E2B0 | 1.0142 | 84.62 |
| 3 | E1B0 | 0.8940 | 86.44 |
| 4 | E1B2 | 0.2916 | 95.58 |
| 5 | E0B1 | 0.2659 | 95.97 |
| 6 | E0B3 | 0.2258 | 96.58 |
| 7 | E0B2 | 0.1467 | 97.77 |
| 8 | E1B1 | 0.1453 | 97.79 |
| 9 | E2B1 | 0.0807 | 98.77 |
| 10 | E1B3 | 0.0259 | 99.61 |
| 11 | E2B3 | 0.0235 | 99.64 |
| 12 | E2B2 | 0.0230 | 99.65 |

Mn removal efficiency ranged from 69.25% to 99.65%, with the highest value obtained in treatment combination E2B2. These results indicate a synergistic effect between biochar and water hyacinth in significantly reducing Mn concentration.

Biochar works rapidly through adsorption mechanisms and increasing pH, while water hyacinth plays a role in absorbing residual Mn through rhizofiltration and phytoextraction processes (Rezania et al., 2015; Mishra & Tripathi, 2008). The combination of both treatments produced a sequential remediation system consistent with the concept of an integrated remediation system in waste treatment based on physicochemical and biological methods (Ali et al., 2013).

Overall, Mn removal efficiency exceeding 95% in most treatments indicates that the combination of water hyacinth and biochar has strong potential to be applied as an effective, environmentally friendly, and economical technology for acid mine drainage treatment.

## Conclusion

Based on the results of this study, water hyacinth treatment produced pH values of 4.62–4.97, which remained acidic and did not differ significantly across doses according to the 5% DNMRT test. Nevertheless, water hyacinth at 15 stems significantly reduced Fe concentration to 2.06 mg $L^{-1}$, suggesting that at an adequate biomass level it can lower Fe through adsorption and accumulation in plant tissues. In contrast, biochar application had a significant effect on both increasing pH and reducing Fe. At 20 g $L^{-1}$, biochar reduced Fe to 1.69 mg $L^{-1}$ and shifted pH toward near-neutral conditions, indicating its effectiveness as an ameliorant for acidity neutralization and heavy metal adsorption.

The combined application of water hyacinth and biochar generated the most effective improvement in AMD quality, raising pH to 6.5–7.5 and producing a clearer decline in Mn by reducing Mn concentrations to low and stable levels across treatments. This highlights a synergistic mechanism in which biochar rapidly neutralizes acidity and enhances metal immobilization through chemical processes, while water hyacinth supports ongoing stabilization via biological uptake and ecosystem buffering. Overall, these findings indicate that the hyacinth–biochar combination is a strong candidate for environmentally friendly AMD treatment because it achieves near-neutral pH while simultaneously reducing both Fe and Mn to more controlled levels.

**Reference**

Adventia, Maria Noverella, Santoso, Dian Hudawan, Wicaksono, Aditya Pandu, Anasstasia, Titi Tiara, & Utami, Ayu. (2023). Analisis Kualitas Udara Ambien pada Area Tambang Batubara Jenis Terbuka (Open Pit) PT XX di Desa Sungai Payang, Kecamatan Loa Kulu, Kabupaten Kutai Kartanegara, Provinsi Kalimantan Timur. *Prosiding Seminar Nasional Teknik Lingkungan Kebumian SATU BUMI*, *4*(1).

Ariya, Siska, Novian, Rendy, & Reflis, Satria Putra Utama. (2025). Pencemaran Tanah Dan Air Akibat Tambang Batubara Di Bengkulu: Analisis Dan Strategi. *Integrative Perspectives of Social and Science Journal*, *2*(03 Juni), 3750–3758.

Dwiyanti, Lulu. (2023). *Pengaruh Pemberian Biochar dari Tempurung Kelapa dan Sedimen Rawa terhadap Reduksi Sulfat dan Logam Berat Timbal (Pb) pada Air Asam Tambang= The Effect of Giving Biochar from Coconut Shells and Swamp Sediment on the Reduction of Sulfate and Heavy Metal Lead (Pb) in Acid Mine Drainage*. Universitas Hasanuddin.

Fahruddin, Fahruddin. (2020). Absorption of heavy metal lead (Pb) by water hyacinth (Eichhornia crassipes) and its influence to total dissolved solids of groundwater in phytoremediation. *Jurnal Akta Kimia Indonesia (Indonesia Chimica Acta)*, *13*(1), 10–15.

Fridtriyanda, Asri, Sukmawatie, Neny, & Iashania, Yunida. (2024). EFEKTIVITAS TANAMAN ECENG GONDOK (EICHORNIA CRASSIPES) DAN SUBSTRAT ORGANIK DALAM MENGELOLA KUALITAS AIR ASAM TAMBANG BATUBARA. *Jurnal Rekayasa Lingkungan*, *24*(1), 83–91.

Hapsari, Dwi Pertiwi, Yunus, Ahmad, & Sunarto, Sunarto. (2020). Pengaruh Eceng Gondok (Eichornia crassipes) Terhadap Peningkatan Kualitas Air Sumur Kecamatan Grogol Sukoharjo. *Ekosains*, *12*(1).

IZZA, NURUL. (2024). *ANALISIS RISIKO KESEHATAN PAJANAN BESI (Fe) DAN MANGAN (Mn) PADA AIR SUMUR GALI SEBAGAI AIR MINUM MASYARAKAT DI DESA SUDIMORO KECAMATAN SEMAKA TANGGAMUS LAMPUNG*. Poltekkes Kemenkes Tanjungkarang.

Leka, Emil. (2024). Metode fitoremediasi dalam pengelolaan air asam tambang batubara (Fe dan Mn) berdasarkan literatur review. *Jurnal Kimia Dan Ilmu Lingkungan: Chemviro*, *2*(1), 90–97.

Mamede, Marlia. (2023). Analisis Air Asam Tambang Untuk Mengurangi Kadar Sulfur. *Cokroaminoto Journal of Chemical Science*, *5*(1), 15–19.

Nabil, Sepianur Ahmad, Nurhasanah, Astri, Mulyadi, Paska Apriyani, Husein, Rahmatullah, & Sari, Nukhak Nufita. (2026). Peningkatan Kualitas Air Sungai di Desa Padang Batung Hulu Sungai Selatan dengan Memanfaatkan Eceng Gondok sebagai Biofilter Alami: Improving River Water Quality in Padang Batung Village, Hulu Sungai Selatan by Utilizing Water Hyacinth as a Natural Biofilter. *PengabdianMu: Jurnal Ilmiah Pengabdian Kepada Masyarakat*, *11*(1), 296–303.

Prasetyo, Mawardi Heru, Baderan, Dewi Wahyuni K., & Hamidu, Marini Susanti. (2025). Dampak Kerusakan Lingkungan Akibat Eksploitasi Sumber Daya Mineral dari Kegiatan Pertambangan. *Hidroponik: Jurnal Ilmu Pertanian Dan Teknologi Dalam Ilmu Tanaman*, *2*(2), 1–11.

Razi, Muhammad Fahrul, Ilmu, P., & Sosial, P. (2021). Dampak aktivitas pertambangan batubara terhadap lingkungan dan masyarakat Kalimantan Timur. *Ilmu Pengetahuan Sosial*, *76*.

Simamora, E., Nurcholis, M., Ardian, A., Ernawati, R., & Winarno, E. (2024). Studi Literatur: Potensi Fikoremediasi Berbasis Strain Alga Sebagai Biosorben Kontaminan Logam Berat Pada Air Asam Tambang. *Jurnal Pendidikan, Sains, Geologi, Dan Geofisika (GeoScienceEd Journal)*, *5*(3), 627–638.

Syam, Akbar Nugraha, & Iryani, A. Sry. (2025). Pengaruh Kegiatan Tambang Terhadap Pencemaran Air: Kajian Terhadap Analisis Air Limbah. *Journal of Scientech Research and Development*, *7*(1), 662–673.

Syamsuddin, Suryadi, Baderan, Dewi Wahyuni K., & Lihawa, Fitryane. (2024). Studi Kasus Aktivitas Pertambangan Batuan terhadap Kondisi Lingkungan Sungai Bolango. *Jurnal Wilayah, Kota Dan Lingkungan Berkelanjutan*, *3*(2), 238–244.