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Evaluating the Effectiveness of a Pilot-Scale Subsurface-Flow Constructed Wetland for Reducing Iron, Manganese, and Sulfate in Acid Mine Drainage from Former Coal Mining Areas

(Evaluasi Efektivitas Constructed Wetland Aliran Bawah Permukaan Skala Pilot dalam Menurunkan Kadar Fe, Mn, dan Sulfat pada Air Asam Tambang di Area Bekas Penambangan Batubara)

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Abstract: *Acid mine drainage from former coal mining areas is characterized by low pH and elevated concentrations of dissolved metals and sulfate, which may degrade receiving-water quality and create long-term environmental risk. This study evaluated the effectiveness and applied relevance of a pilot-scale subsurface-flow constructed wetland in improving acid mine drainage quality by increasing pH and reducing iron, manganese, and sulfate. The novelty of the study lies in the integrated use of gravel, sand, limestone, organic support media, and wetland vegetation within a pilot unit designed for post-mining rehabilitation conditions, while assessing pH, Fe, Mn, and sulfate simultaneously as key indicators of treatment performance. A quasi-experimental pretest–posttest approach was used by comparing influent and effluent quality after treatment through the wetland media. The influent had a pH of 3.2, Fe of 12.50 mg/L, Mn of 8.20 mg/L, and sulfate of 420.00 mg/L. After treatment, the effluent pH increased to 6.1, while Fe decreased to 3.40 mg/L, Mn to 2.70 mg/L, and sulfate to 180.00 mg/L. The corresponding removal efficiencies were 72.80% for Fe, 67.07% for Mn, and 57.14% for sulfate. These findings indicate that pilot-scale subsurface-flow constructed wetlands can provide a simple, low-energy, and environmentally compatible option for post-mining water management and may support practical rehabilitation strategies where long-term chemical dosing is difficult to sustain.*
Keywords: *acid mine drainage; coal mining; constructed wetland; iron; sulfate.*

Abstrak: *Air asam tambang pada area bekas penambangan batubara umumnya memiliki pH rendah serta konsentrasi logam terlarut dan sulfat yang tinggi, sehingga berpotensi menurunkan kualitas badan air penerima dan menimbulkan risiko lingkungan jangka panjang. Penelitian ini mengevaluasi efektivitas sekaligus relevansi terapan constructed wetland aliran bawah permukaan skala pilot dalam memperbaiki kualitas air asam tambang melalui peningkatan pH serta penurunan kadar besi, mangan, dan sulfat. Kebaruan penelitian terletak pada penggunaan terpadu media kerikil, pasir, batu kapur, media pendukung organik, dan vegetasi wetland dalam unit skala pilot yang dirancang untuk kondisi rehabilitasi pascatambang, dengan penilaian simultan terhadap pH, Fe, Mn, dan sulfat sebagai indikator utama kinerja pengolahan. Penelitian menggunakan pendekatan quasi-experimental pretest–posttest dengan membandingkan kualitas influen dan efluen setelah air dialirkan melalui media wetland. Influen memiliki pH 3,2, Fe 12,50 mg/L, Mn 8,20 mg/L, dan sulfat 420,00 mg/L. Setelah pengolahan, pH efluen meningkat menjadi 6,1, sedangkan Fe turun menjadi 3,40 mg/L, Mn menjadi 2,70 mg/L, dan sulfat menjadi 180,00 mg/L. Efisiensi penyisihan masing-masing parameter adalah 72,80% untuk Fe, 67,07% untuk Mn, dan 57,14% untuk sulfat. Hasil tersebut menunjukkan bahwa constructed wetland aliran bawah permukaan skala pilot berpotensi menjadi alternatif pengolahan air asam tambang yang sederhana, hemat energi,*

dan ramah lingkungan, serta dapat mendukung strategi rehabilitasi pascatambang ketika pengolahan kimia jangka panjang sulit dipertahankan.
Kata kunci: *air asam tambang; batubara; besi; constructed wetland; sulfat.*

Introduction

Acid mine drainage (AMD) remains one of the most persistent environmental legacies of mining because sulfide-bearing minerals exposed during excavation can react with oxygen and water to form acidic water enriched with dissolved metals and sulfate (Chen et al., 2021; Jiao et al., 2023; Baloyi et al., 2023). In coal mining settings, AMD may continue to be generated long after active production has ceased, making post-mining water management an important part of environmental rehabilitation (Du et al., 2025; Nguegang & Ambushe, 2025).

The environmental significance of AMD lies not only in its low pH but also in its ability to mobilize Fe, Mn, Al, and other contaminants that degrade surface-water quality, stain streambeds, alter aquatic habitats, and increase treatment costs (Chen et al., 2021; Jiao et al., 2023; Wibowo et al., 2024). In former coal mining areas, Fe and Mn are practical indicators of treatment performance because both metals are commonly found in mine drainage and are closely related to acidity, oxidation state, and precipitation processes (Piñon-Flores et al., 2024; Xu et al., 2025). Sulfate is also important because it is a principal product of sulfide oxidation and often remains elevated even after partial pH correction (Suryatmana et al., 2020; Du et al., 2025).

Active AMD treatment systems based on alkaline reagent dosing can be effective; however, they may generate large sludge volumes, require continuous chemical inputs, and incur significant operating costs, especially under long-term post-closure conditions (Skousen et al., 2017; Chen et al., 2021; Du et al., 2025). For this reason, passive and semi-passive approaches have received growing attention, particularly systems that reduce energy demand and utilize natural biogeochemical processes (Pat-Espadas et al., 2018; Wibowo et al., 2022; Nguegang & Ambushe, 2025).

Constructed wetlands are among the most studied passive systems for AMD treatment because they integrate filtration, sedimentation, alkalinity generation, sorption, microbial sulfate reduction, and plant-assisted contaminant retention within a single treatment train (Kadlec & Wallace, 2008; Marchand et al., 2010; Wibowo et al., 2022). Recent studies have shown that wetland performance can be improved through careful substrate selection, such as limestone, organic matter, biochar, or industrial by-products that enhance alkalinity and adsorption capacity (Chen et al., 2021; Chen et al., 2024; Zhong et al., 2024). Pilot and field studies also indicate that planted systems can improve acidity neutralization and metal stabilization relative to unplanted controls under certain conditions (Naghoum et al., 2025; Xu et al., 2025).

Site-specific evaluation remains necessary because wetland performance depends on influent chemistry, hydraulic retention time, substrate composition, climate, vegetation, and oxidation–reduction conditions within the wetland bed (Pat-Espadas et al., 2018; Vymazal, 2011; Wibowo et al., 2022). Moreover, Fe usually precipitates more readily than Mn; therefore, treatment systems that appear successful at first glance may still fail to achieve balanced removal if retention time, pH buffering, or microbial activity are insufficient (Piñon-Flores et al., 2024; Xu et al., 2025).

In Indonesia and other former coal mining regions, AMD management remains highly relevant because compliance with wastewater quality standards is mandatory, and post-mining treatment systems must remain technically feasible under long-term field conditions (Kementerian Lingkungan Hidup, 2003). Previous studies have demonstrated the general potential of constructed wetlands, sulfate-reducing bacteria, organic substrates, and wetland vegetation for AMD treatment (Suryatmana et al., 2020; Wibowo et al., 2022; Wibowo et al., 2024). However, an important research gap remains: much of the existing literature is dominated by review papers, laboratory-scale studies, or site-specific reports that do not provide an integrated pilot-scale evaluation of pH improvement together with Fe, Mn, and sulfate removal under realistic post-mining rehabilitation conditions. In addition, relatively few studies have examined subsurface-flow constructed wetlands as a combined treatment system for former coal mining areas in tropical environments, where high rainfall, fluctuating discharge, rapid vegetation growth, and substrate weathering may strongly influence hydraulic retention time and treatment stability.

Therefore, this study offers a more explicit applied contribution by evaluating a pilot-scale subsurface-flow constructed wetland that integrates gravel, sand, limestone, organic support media, and wetland vegetation, while simultaneously assessing pH, Fe, Mn, and sulfate as key indicators of AMD treatment performance. In this way, the study addresses a practical limitation in the current literature by providing a more field-relevant and rehabilitation-oriented assessment of constructed wetland performance for post-mining water management.

Based on these considerations, this study aimed to evaluate the effectiveness of a pilot-scale constructed wetland in reducing Fe, Mn, and sulfate concentrations in AMD from a former coal mining area. Specifically, the study sought to: (1) describe the influent quality of AMD; (2) quantify changes in pH, Fe, Mn, and sulfate after treatment; and (3) assess the practical suitability of constructed wetlands as a low-energy option for post-mining water treatment.

Methods

This study employed a quantitative quasi-experimental design with a pretest–posttest approach. Influent AMD quality was measured before treatment and compared with effluent quality after passing through a pilot-scale constructed wetland. The evaluation focused on the hydraulic and treatment performance of a subsurface-flow wetland receiving AMD from a former coal mining area in Indonesia.

Before the intervention, the AMD entering the treatment unit was acidic and contained elevated concentrations of Fe, Mn, and sulfate. Therefore, the treatment system was expected to increase pH and reduce dissolved contaminants to levels more suitable for discharge management and post-mining environmental rehabilitation.

The pilot unit was designed as a subsurface-flow constructed wetland consisting of three principal media layers: gravel in the bottom layer for drainage support, sand in the intermediate layer for filtration, and limestone mixed with organic support media in the reactive zone to enhance alkalinity generation and metal retention. The wetland bed was planted with an emergent species adapted to mine-water conditions to support root-zone oxygen transfer, media stability, and microbial activity (Vymazal, 2011; Suryatmana et al., 2020).

AMD samples were collected from the inlet and outlet points of the treatment unit after the wetland reached stable operation. Grab samples were placed in clean polyethylene bottles, preserved as required for laboratory analysis, and transported under controlled conditions. The measured parameters included pH, dissolved Fe, dissolved Mn, and sulfate. Analytical procedures followed recognized environmental laboratory methods based on *Standard Methods for the Examination of Water and Wastewater* (APHA, 2017).

Instrument validity and reliability were maintained through pH meter calibration using standard buffer solutions, laboratory quality control, duplicate checks, and consistent sample handling from the field to the laboratory. These procedures were applied to minimize analytical bias and ensure comparability between influent and effluent measurements.

Data analysis was conducted descriptively and quantitatively. Removal efficiency for each parameter was calculated using Equation (1):

$$\text{Removal efficiency (\%)} = \frac{C_{in} - C_{out}}{C_{in}} \times 100 \quad (1)$$

where C_{in} is the influent concentration and C_{out} is the effluent concentration. The results were then interpreted in relation to the treatment objectives and the practical requirements of AMD management in former coal mining areas.

Results

Table 1 presents the influent and effluent water quality values obtained from the pilot-scale treatment unit. The results show a clear increase in pH and simultaneous decreases in Fe, Mn, and sulfate concentrations after treatment through the constructed wetland. The data in Table 1 were derived from direct measurements of influent and effluent samples collected from the pilot unit after stable operation.

Table 1. Influent and effluent water quality values. Source: Primary data processed by the authors (2026).

Parameter	Influent	Effluent	Unit
pH	3.2	6.1	–
Fe	12.50	3.40	mg/L
Mn	8.20	2.70	mg/L
Sulfate	420.00	180.00	mg/L

The pH increased from 3.2 to 6.1, indicating that the combination of limestone, organic support media, and wetland processes provided substantial neutralization capacity. At the same time, Fe decreased from 12.50 to 3.40 mg/L, Mn from 8.20 to 2.70 mg/L, and sulfate from 420.00 to 180.00 mg/L.

The corresponding removal efficiencies are shown in Table 2. Fe exhibited the highest removal efficiency, followed by Mn and sulfate. The efficiency values were calculated from the measured influent and effluent concentrations using Equation (1).

Table 2. Removal efficiency of key AMD parameters. Source: Primary data processed by the authors (2026).

Parameter	Influent (mg/L)	Effluent (mg/L)	Removal efficiency (%)
Fe	12.50	3.40	72.80
Mn	8.20	2.70	67.07
Sulfate	420.00	180.00	57.14

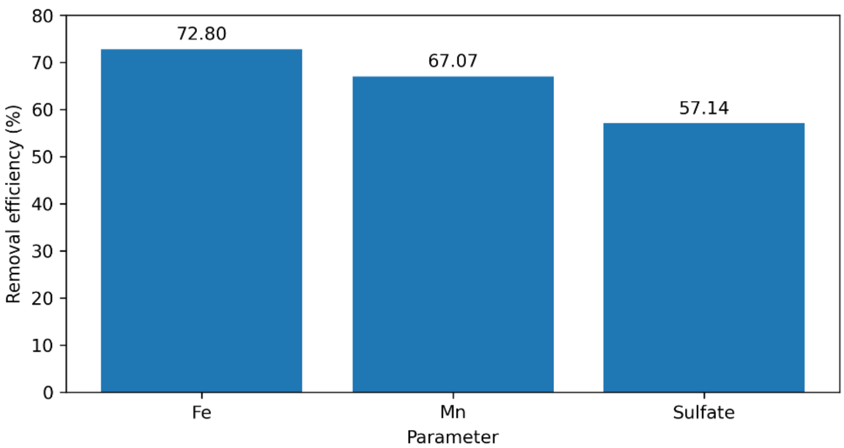

Figure 1. Removal efficiency of Fe, Mn, and sulfate in the pilot unit. Source: Primary data processed by the authors (2026).

Figure 1 confirms that Fe removal was the strongest performance outcome of the treatment unit. Sulfate removal was lower than metal removal, which is consistent with the more complex biological and geochemical pathways involved in sulfate reduction compared with Fe precipitation under rising pH conditions.

Discussion

The findings indicate that the constructed wetland improved AMD quality through a combination of alkalinity generation, filtration, metal precipitation, adsorption, and microbial transformation. The increase in pH from 3.2 to 6.1 is environmentally important because higher pH promotes the oxidation and precipitation of dissolved iron and creates more favorable conditions for downstream metal attenuation processes (Chen et al., 2021; Jiao et al., 2023).

The higher removal efficiency observed for Fe compared with Mn is consistent with the established behavior of these metals in AMD treatment systems. Iron commonly precipitates at lower pH values than manganese, whereas Mn generally requires stronger oxidation conditions, longer retention time, or higher pH to achieve comparable removal (Pat-Espadas et al., 2018; Piñon-Flores et al., 2024; Xu et al., 2025). This explains why a wetland may appear highly effective for Fe while still leaving Mn as a more difficult parameter to optimize under field conditions.

The reduction in sulfate suggests that biological sulfate reduction likely occurred in the wetland bed; however, the removal level was lower than that of Fe and Mn. Sulfate attenuation in constructed wetlands depends strongly on the formation of anaerobic microsites, the availability of organic carbon, and the activity of sulfate-reducing bacteria, all of which can vary spatially within the media (Suryatmana et al., 2020; Chen et al., 2024; Naghoum et al., 2025). Therefore, future system optimization should consider reactive media composition and hydraulic retention time more explicitly.

The results are consistent with recent studies showing that substrate engineering strongly affects mine-water treatment performance. Chen et al. (2024) demonstrated that attapulgite–soda residue composites can enhance AMD purification in wetlands through combined adsorption and sulfate-reduction pathways, while Zhong et al. (2024) reported that filler configuration influences both pollutant removal and microbial community structure. These findings support the view that constructed wetland design should be treated as a site-specific engineering problem rather than a one-size-fits-all passive treatment option.

From an applied perspective, constructed wetlands are attractive for former coal mining sites because they require relatively low external energy input, can be integrated into land reclamation strategies, and may reduce long-term operating costs relative to fully chemical treatment systems (Skousen et al., 2017; Wibowo et al., 2022; Nguegang & Ambushe, 2025). Chemical dosing systems can achieve faster neutralization and are often preferred where influent acidity or metal loading is extreme; however, they involve recurring reagent costs, sludge management, operator oversight, and a larger long-term carbon and maintenance burden (Chen et al., 2021; Du et al., 2025). In contrast, constructed wetlands are more cost-effective when land is available and when the treatment objective emphasizes low-energy, longer-term polishing within post-mining landscapes.

However, passive systems are not universally sufficient on their own. Highly acidic inflows, extreme metal loads, seasonal flow variation, substrate aging, vegetation turnover, or limited available land can reduce performance and may necessitate pre-treatment or hybrid treatment trains (Du et al., 2025; Xu et al., 2025; Naghoum et al., 2025).

This study contributes an integrated evaluation of pH, Fe, Mn, and sulfate response within a pilot subsurface-flow treatment unit, which is useful for linking environmental engineering analysis with post-mining rehabilitation practice. Its main limitations are that the evaluation was performed on a single pilot unit with a limited monitoring dataset; therefore, seasonal variability, longer-term substrate aging, plant growth dynamics, microbiological changes, and variations in influent chemistry were not directly assessed. In addition, the study did not include a side-by-side economic comparison with active treatment systems or a replicated field-scale validation; thus, the results should be interpreted as a strong pilot indication rather than a universal design value. Even so, the observed performance pattern provides a practical basis for further scaling and optimization, especially for sites where low-energy treatment, reclamation integration, and reduced chemical dependence are priority considerations.

Conclusion

This study showed that a pilot-scale constructed wetland improved the quality of acid mine drainage from a former coal mining area by increasing pH and reducing dissolved Fe, Mn, and sulfate. The influent pH of 3.2 increased to 6.1 after treatment, while Fe decreased from 12.50 to 3.40 mg/L, Mn from 8.20 to 2.70 mg/L, and sulfate from 420.00 to 180.00 mg/L. The corresponding removal efficiencies were 72.80% for Fe, 67.07% for Mn, and 57.14% for sulfate.

These results indicate that constructed wetlands can serve as a practical low-energy treatment alternative for post-mining water management, particularly when supported by appropriate media selection, hydraulic control, and continued monitoring. For wider implementation in other mining regions, pilot testing should be conducted to adjust hydraulic retention time, substrate composition, and vegetation selection to local AMD characteristics.

From a policy perspective, passive systems such as constructed wetlands may be considered part of post-mining water management and rehabilitation programs, especially for closure-stage sites that require long-term treatment with lower operational burden. Further research should evaluate longer retention times, modified substrates, replicated monitoring, seasonal performance variability, and comparative cost analysis to strengthen the design basis for field-scale implementation.

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Conflict of Interests

Penulis menyatakan bahwa tidak terdapat konflik kepentingan dalam penelitian ini.

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