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The Effect of Purun Tikus (*Eleocharis dulcis*) and Organic Material Addition in Constructed Wetland Systems on the Improvement of Acid Mine Drainage Quality

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ABSTRAK

Kegiatan penambangan batubara sering menimbulkan permasalahan lingkungan berupa air asam tambang (AAT) yang bersifat asam dan mengandung logam berat serta padatan tersuspensi tinggi. Penelitian ini bertujuan untuk menganalisis perubahan kualitas AAT melalui penerapan sistem lahan basah buatan dengan media tanaman Purun tikus (*Eleocharis dulcis*) dan kompos tandan kosong kelapa sawit (TKKS). Penelitian dilakukan dalam skala laboratorium menggunakan lima variasi perlakuan dan tiga kali ulangan selama 20 hari. Hasil menunjukkan bahwa kombinasi media tersebut, dengan atau tanpa tambahan batugamping, memberikan perubahan signifikan terhadap parameter kualitas air. Nilai pH meningkat dari 3,12 menjadi 7,97; TSS menurun dari 1.440 mg/L menjadi 25,3 mg/L; konsentrasi Fe menurun dari 33,15 mg/L menjadi 2,59 mg/L; dan konsentrasi Mn menurun dari 7,06 mg/L menjadi 0,41 mg/L dalam waktu 20 hari. Temuan ini menunjukkan bahwa sistem *constructed wetland* berbasis tanaman lokal dan bahan organik berpotensi diterapkan sebagai solusi pengelolaan air limbah tambang yang ramah lingkungan.

Kata kunci: Air Asam Tambang; *Eleocharis dulcis*; *Constucted Wetland*; Remediasi; Tandan Kosong Kelapa Sawit

ABSTRACT

Coal mining activities often cause environmental challenges, one of which is acid mine drainage (AMD) with low pH and elevated concentrations of heavy metals and suspended solids. This study aimed to assess water quality improvement through a constructed wetland system using Purun tikus (Eleocharis dulcis) and Empty Palm Oil Bunch (EPOB) compost. Laboratory-scale experiments were conducted with five treatment variations and three replications over a 20-day retention period. Results indicated that the media combination, with or without limestone addition, significantly altered the water quality parameters. The pH increased from 3.12 to 7.97; TSS decreased from 1,440 mg/L to 25.3 mg/L; Fe decreased from 33.15 mg/L to 2.59 mg/L; and Mn decreased from 7.06 mg/L to 0.41 mg/L over 20 days. These results indicate the potential of constructed wetlands using native plants and organic materials as an environmentally friendly strategy for treating mining wastewater.

Keywords*: Acid Mine Drainage; Constructed Wetlands; Eleocharis dulcis; Remediation; EPOB Compost*

I. Introductions

Coal mining contributes significantly to the national economy but also poses serious environmental challenges, one of which is acid mine drainage (AMD). AMD results from the oxidation of sulfide minerals such as pyrite (FeS_2), producing acidic water (low pH) with high concentrations of heavy metals such as iron (Fe) and manganese (Mn), along with elevated levels of total suspended solids (TSS). If left untreated, AMD can contaminate water bodies, damage ecosystems, and threaten public health (Akcil & Koldas, 2006; Gautama, 2012). Acid Mine Drainage (AMD) treatment technologies can be categorized into active and passive systems. Active systems rely on chemical inputs and mechanical equipment, which are often costly. In contrast, passive systems such as constructed wetlands offer a more environmentally friendly and cost-effective solution (Skousen et al., 1990; Sheoran, 2005).

Local plants such as *Eleocharis dulcis* (Purun tikus) are potential phytoremediation agents due to their tolerance to extreme conditions and ability to absorb heavy metals (Asikin & Thamrin, 2012; Ariyani et al., 2014). Additionally, compost from Empty Palm Oil Bunch (EPOB) can help neutralize acidity and support microbial activity in the wetland system (Perala et al., 2022).

This study is motivated by the need for simple and effective AMD treatment technologies, especially in coal mining areas such as Central Kalimantan, a region with dominant coal mining activity in Indonesia. The case study was conducted at one of the mining sites in the province. Preliminary measurements showed AMD with a pH of 2.66, TSS of 2,565 mg/L, Fe concentration of 37.34 mg/L, and Mn concentration of 7.58 mg/L, all exceeding the thresholds set by the Ministry of Environment and Forestry Regulation No. 5 of 2022. The objective of this research is to analyze the changes in AMD quality through the application of *Eleocharis dulcis* and EPOB compost in a constructed wetland system, and the modification involving a limestone layer as an additional treatment variation aims to evaluate the system design's effectiveness in improving water quality through the application of an anaerobic wetland (Zipper & Skousen, 2014).

II. METHODS

This research was conducted through a laboratory-scale experimental setup using a free water surface flow constructed wetland system, with a volume of 9 liters per treatment unit. The design followed a completely randomized design with five treatments and three replications. The treatments included: a control with no media; Empty Palm Oil Bunch (EPOB); *Eleocharis dulcis* only; a combination of *Eleochari dulcis* and EPOB; as well as a combination of *Eleocharis dulcis*, EPOB, along with limestone as show in **Figure 1**.

Treatment A	Treatment B	Treatment C	Treatment D	Treatment E

Figure 1. Design Scheme of Experimental Reactor

The media arrangement in the experimental reactors was based on the media height capacity adjusted according to constructed wetland design recommendations (Zipper & Skousen, 2014). *Eleocharis dulcis* plants were spaced 10 cm × 10 cm in accordance with root stolon length (Steenis, 2006), resulting in 32 plant clumps per reactor as shown in **Figure 2**. The media composition for each treatment is presented in **Table 1** below:

Table 1. Media Composition in Experimental Reactors

Treatment	Acid Mine Drainage (cm/liters)	Purun tikus *Eleocharis dulcis* (clumps)	EPOB Compost (cm/kg)	*Wetland* Sludge (cm)	Limestone (cm/kg)
A	14 cm (± 70 liters)	-	-	7 cm (35 kg)	-
B	14 cm (± 70 liters)	-	14 cm (45 kg)	7 cm (35 kg)	-
C	14 cm (± 70 liters)	32 clumps	-	7 cm (35 kg)	-
D	14 cm (± 70 liters)	32 clumps	14 cm (45 kg)	7 cm (35 kg)	-
E	14 cm (± 70 liters)	32 clumps	14 cm (45 kg)	7 cm (35 kg)	7 cm (45 kg)

Figure 2. Application of Treatments in Experimental Reactors

The Acid Mine Drainage (AMD) used in this study was sourced from a coal mining site in Parenggean District, East Kotawaringin Regency, Central Kalimantan. The observed parameters were pH, Total Suspended Solids (TSS), iron (Fe), and manganese (Mn), measured on days 0, 5, 10, 15, and 20 of the retention period.

All analyses were conducted using standard methods: pH was measured using a pH meter, TSS with gravimetric method, and Fe and Mn concentrations using Atomic Absorption Spectrophotometry (AAS) works by converting the metal in a sample into free atoms through a flame, then measuring the absorption of specific light by those atoms to determine the metal concentration. Laboratory testing for the analysis parameters listed in **Table 2**. Data were analyzed statistically using ANOVA at a 5% significance level to assess the effect of treatments on water quality parameters. This method is generally applied in experiments involving two factors to analysis the interaction between them (Wibisosno, 2015).

III. RESULTS AND DISCUSSION

Preliminary analysis of the Acid Mine Drainage (AMD) wastewater revealed that all measured water quality parameters significantly exceeded the permissible limits as stipulated in the Ministry of Environment and Forestry Regulation No. 5 of 2022 **(Table 2).** The pH value was notably low at 2.66, a consequence of sulfide mineral oxidation producing highly acidic conditions. Iron (Fe) and manganese (Mn) concentrations measured 37.34 mg/L and 7.58 mg/L respectively, far surpassing the regulatory thresholds of 7 mg/L for Fe and 4 mg/L for Mn. Additionally, total suspended solids (TSS) were recorded at a high concentration of 2,565 mg/L.

A visible orange precipitate was observed on the surface and walls of the wastewater pond, identified as iron hydroxide ($Fe(OH)_3$), resulting from the oxidation of dissolved Fe^{2+} ions to Fe^{3+} under low pH conditions.

Figure 3. Condition of AMD in the Wastewater Pond

3.1. Effect of Plants and Organic Material on (pH) Changes in AMD

The high intensity of coal mining activities, most of which employ open-pit mining systems, leads to the exposure of excavated materials on the soil surface. When these materials, containing sulfide minerals, come into natural contact with air and water, acid mine drainage will form which can trigger an increase in the concentration of heavy metal elements such as Fe and Mn (Munawar, 2017). This study examined the effects of various media treatments including the native plant *Eleocharis dulcis* and Empty Palm Oil Bunch (EPOB) compost, with or without limestone addition on pH changes during a 20-day retention period. Initial pH values across all treatments ranged from 3.05 to 3.12, indicating highly acidic AMD conditions. Over the observation period, treatments involving organic media showed significant pH increases approaching near-neutral levels by day 20. The combination of *Eleocharis dulcis*, EPOB, and limestone (Treatment E) produced the highest pH increase, reaching 7.97. Treatments with just EPOB (Treatment B) and the combination of

Eleocharis dulcis and EPOB (Treatment D) also exhibited significant pH rises, achieving 7.98 and 7.97, respectively. Conversely, the control treatment without media (Treatment A) and the treatment with plants alone (Treatment C) showed minimal pH increases of 3.12 and 3.39, respectively, indicating limited neutralization capacity without organic amendments.

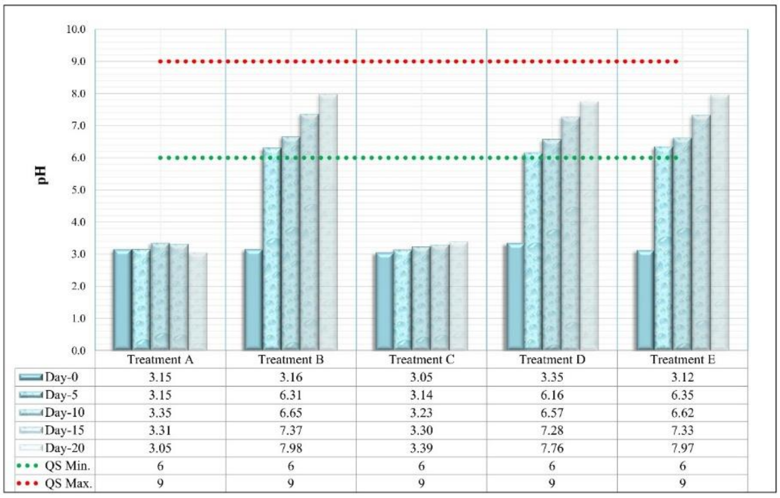


Figure 4. Graph of (pH) Increase every 5-Day Period for Various Treatments

The highest average pH increase was recorded in Treatment E (combined media with limestone modification), reaching 4.85. Treatment B (EPOB compost media) showed a similar result of 4.83, followed by Treatment D (plant and EPOB compost media) at 4.42. In contrast, Treatment C, which used only *Eleocharis dulcis*, showed a minimal increase of 0.34 and remained below the environmental quality standard. The use of EPOB compost in Treatments B, D, and E contributed to pH improvement through its natural organic carbon and basic compounds, which help neutralize acidity, in line with the sulfate reduction reaction (Zipper & Skousen, 2014). The media combination in Treatment E was enhanced by the addition of a limestone base layer, which increased alkalinity through bicarbonate ion formation and accelerated pH rise. Meanwhile, the low pH increase in Treatment C was due to the plant's adaptive nature to acidic water conditions, but with limited direct impact on neutralization.

Two-way ANOVA results indicated that treatment type, retention time, and their interaction significantly affected pH changes (calculated F count > critical F), it is concluded that the interaction of treatment factors and time has a significant effect on changes in pH according to the results of the hypothesis test F value (**Table 3**). The coefficient of determination (R^2) of 0.998 indicates that treatment variation and retention time together explain 99.8% of the pH variation during the study. The following table summarizes the pH increase at each 5-day interval.

Table 3. Hypothesis Test Analysis of pH Parameters

Variable	Factor	Test Criteria	Hypothesis	Conclusion
pH	Treatment	$F_{count} > F_{table}$ 3857 > 2.4	H_0 is rejected	Treatment factor affected the pH changes.
	Day	$F_{count} > F_{table}$ 1728 > 2.4	H_0 is rejected	The day factor affected the pH changes.
	Interaction	$F_{count} > F_{table}$ 258 > 1. 85	H_0 is rejected	The interaction of treatment and day factors affected the pH changes.

3.2. Effect of Plants and Organic Material on (TSS) Changes in AMD

Total Suspended Solids (TSS) is a key parameter in assessing the quality of acid mine drainage (AMD) wastewater. This study investigated the effects of various media treatments including the native plant *Eleocharis dulcis* and empty palm oil bunch compost (EPOB), with or without limestone addition on TSS reduction over a 20-day retention period.

Initial TSS concentrations across all treatments ranged from approximately 1,190.7 to 1,883.7 mg/L, reflecting highly polluted AMD conditions. Over the observation period, treatments involving organic media exhibited significant TSS reductions, with final values approaching or meeting regulatory limits by day 20.

The combination of *Eleocharis dulcis*, EPOB, and limestone (Treatment E) achieved the greatest reduction, lowering TSS from 1,190.7 mg/L to 137.7 mg/L. Treatments with *Eleocharis dulcis* alone (Treatment C) and the combination of *E. dulcis* and EPOB (Treatment D) also demonstrated significant TSS decreases, reaching 25.3 mg/L and 151 mg/L respectively by day 20. Treatment B with EPOB alone reduced TSS from 1,883.7 mg/L to 242.7 mg/L, while the control treatment without media (Treatment A) showed limited reduction, maintaining high TSS values throughout the study.

These results confirm the crucial role of EPOB compost and *Eleocharis dulcis* in removing suspended solids through physical filtration and microbial degradation. Limestone addition further enhances sedimentation and coagulation processes, improving TSS removal efficiency. *Eleocharis dulcis* media in Treatments C, D, and E play a role in reducing TSS through a dense and complex root and tuber system, functioning as a natural filter to capture suspended particles. This mechanism prevents particles from being lifted back up, thus improving water clarity. The addition of EPOB compost and limestone in Treatments (D and E) also reduced TSS through a porous structure capable of trapping particles (Zipper & Skousen, 2014). Meanwhile, Treatment (A) experienced a decrease in TSS due to natural sedimentation, but fine particles were still easily dispersed. Treatment A (control) maintained high and unstable TSS concentrations, failing to meet water quality standards. Treatment B (EPOB) showed substantial TSS reduction, meeting standards by day 15. Treatments C, D, and E met water quality standards as day 5 and sustained low TSS levels through day 20.

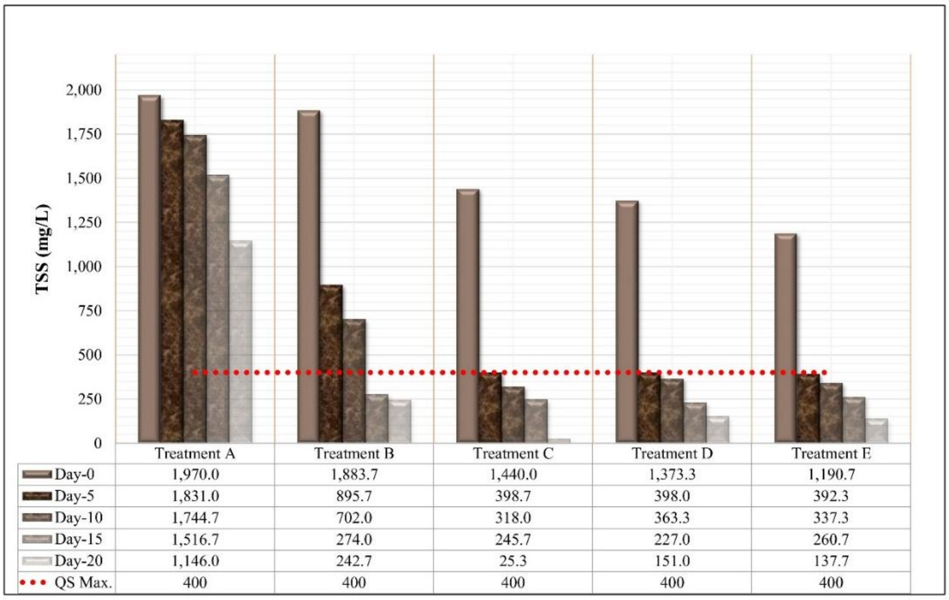


Figure 5. Graph of (TSS) Increase every 5-Day Period for Various Treatments

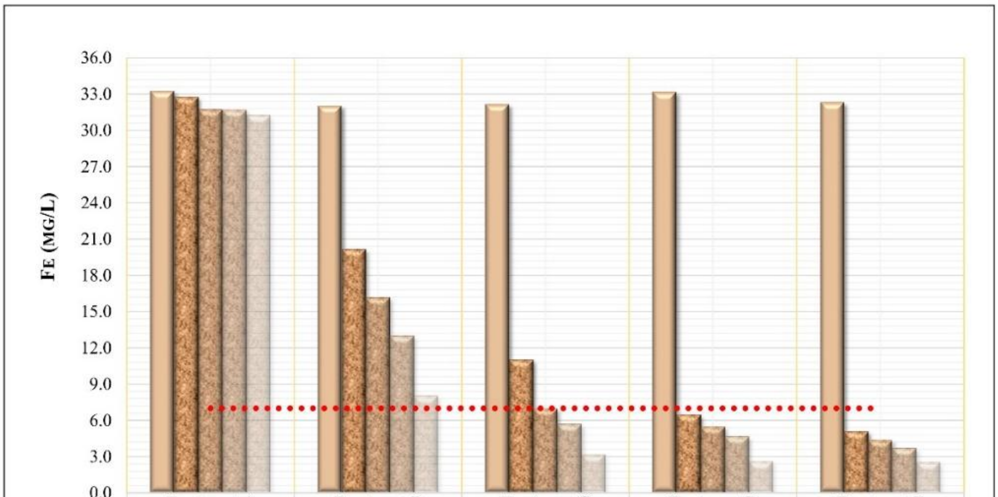
Two-way ANOVA results indicated that treatment type, retention time, and their interaction significantly affected TSS changes (calculated F > critical F), it is concluded that the interaction of treatment factors and time has a significant effect on changes in TSS according to the results of the hypothesis test F value (**Table 4**). The coeficient of determination (R^2) of 0.996 suggests that treatment variation and retention time together explain 99.6% of the TSS variation during the study. The following table summarizes the TSS reduction at each 5-day interval.

Table 4. Hypothesis Test Analysis of TSS Parameters

Variable	Factor	Test Criteria	Hypothesis	Conclusion
TSS	Treatment	$F_{count} > F_{table}$ 1531 > 2.4	H_0 is rejected	Treatment factor affected the TSS changes.
	Day	$F_{count} > F_{table}$ 1373 > 2.4	H_0 is rejected	The day factor affected the TSS changes.
	Interaction	$F_{count} > F_{table}$ 44 > 1. 85	H_0 is rejected	The interaction of treatment and day factors affected the TSS changes.

3.3. Effect of Plants and Organic Material on (Fe) Changes in AMD

Iron (Fe) concentration is a key indicator in assessing the quality of acid mine drainage (AMD) wastewater due to its presence in pyrite (FeS_2) sulfide minerals. This study evaluated the effects of various media treatments on Fe concentration changes over a 20-day retention period, with results presented in **Figure 5.** Initial Fe concentrations across all treatments ranged from approximately 32.02 to 33.15 mg/L, indicating high contamination levels. Over the observation period, significant differences in Fe reduction were observed among treatments. The control treatment (Treatment A) maintained high Fe concentrations throughout the study and failed to meet environmental quality standards. Treatment B (organic compost) reduced Fe levels from 32.02 mg/L to 8.01 mg/L after 20 days but still did not comply with the standards. Treatment C, using *Eleocharis dulcis* alone, showed a significant Fe reduction from 32.14 to 3.17 mg/L by day 20. Treatments D (plant plus compost) and E (plant, compost, and limestone) showed even more rapid reductions: Treatment D lowered Fe from 33.15 mg/L to 2.59 mg/L at 20 day, while Treatment E reduced Fe from 32.30 mg/L to 2.54 mg/L at 20 day. Both Treatments D and E met quality standards from day 5 onward.



	Treatment A	Treatment B	Treatment C	Treatment D	Treatment E
Day-0	33.23	32.02	32.14	33.15	32.3
Day-5	32.75	20.16	11.0	6.46	5.05
Day-10	31.72	16.17	6.97	5.46	4.35
Day-15	31.68	13.0	5.69	4.65	3.69
Day-20	31.26	8.01	3.17	2.59	2.54
QS Max.	7	7	7	7	7

Figure 6. Graph of (Fe) Increase every 5-Day Period for Various Treatments.

The *Eleocharis dulcis* plant media used in Treatments C, D, and E contributed to reducing Fe metal concentrations in acid mine drainage effluent through the mechanism of phytoremediation, which is the process of restoring environmental quality using plants to absorb, accumulate, or stabilize pollutants, especially by accumulating Fe metal through their root system (Asikin & Thamrin, 2012). Treatment D, which utilizes a combination of E. dulcis and EPOB compost as growth support, also plays a role in reducing dissolved metals. Meanwhile, the addition of limestone ($CaCO_3$) to the media modification of Treatment E increased the pH of the water, allowing dissolved metals in acid mine drainage effluent to precipitate under these conditions.

Two-way ANOVA results indicated that treatment type, retention time, and their interaction significantly affected changes in iron (Fe) concentration (calculated F > critical F), it is concluded that the interaction of treatment factors and time has a significant effect on changes in Fe according to the results of the hypothesis test F value (**Table 5**). confirming the effectiveness of the applied treatments. The coefficient of determination (R^2) was 0.998, demonstrating that the constructed wetland experiment utilizing *Eleocharis dulcis* and palm oil empty fruit bunch compost (EPOB), combined with retention time, explained 99.8% of the variation in Fe concentration changes.

Table 5. Hypothesis Test Analysis of Fe Parameters

Variable	Factor	Test Criteria	Hypothesis	Conclusion
Fe	Treatment	$F_{count} > F_{table}$ 3487 > 2.4	H_0 is rejected	Treatment factor affected the (Fe) changes.
	Day	$F_{count} > F_{table}$ 3407 > 2.4	H_0 is rejected	The day factor affected the (Fe) changes.
	Interaction	$F_{count} > F_{table}$ 223 > 1. 85	H_0 is rejected	The interaction of treatment and day factors affected the (Fe) changes.

3.4. Effect of Plants and Organic Material on (Mn) Changes in AMD

Manganese (Mn) concentration is a key indicator in assessing wastewater quality in coal mining operations, exhibiting characteristics similar to iron (Fe). This study examined the effects of various media treatments including the native plant *Eleocharis dulcis* and palm oil empty fruit bunch compost (EPOB), with or without limestone addition on Mn concentration changes over a 20-day retention period. Initial Mn concentrations ranged from approximately 6.99 to 7.37 mg/L, indicating substantial contamination.

During the observation period, significant reductions in Mn concentration were observed across treatments. The control treatment (Treatment A) maintained high Mn levels throughout and did not meet environmental quality standards. Treatment B (organic compost) reduced Mn concentration from 6.99 mg/L to 2.47 mg/L at day 5 and further to 1.38 mg/L at day 20. Treatment C (*Eleocharis dulcis* only) showed a more significant decrease from 7.37 mg/L to 0.79 mg/L by day 5 and to 0.47 mg/L by day 20. Treatments D (plant plus compost) and E (plant, compost, and limestone) demonstrated even more rapid reductions, lowering Mn concentrations from 7.06 mg/L and 7.09 mg/L to approximately 0.59 mg/L and 0.63 mg/L at day 5, and further down to 0.41 mg/L and 0.40 mg/L by day 20, respectively. Treatments C, D, and E met quality standards from day 5 onwards.

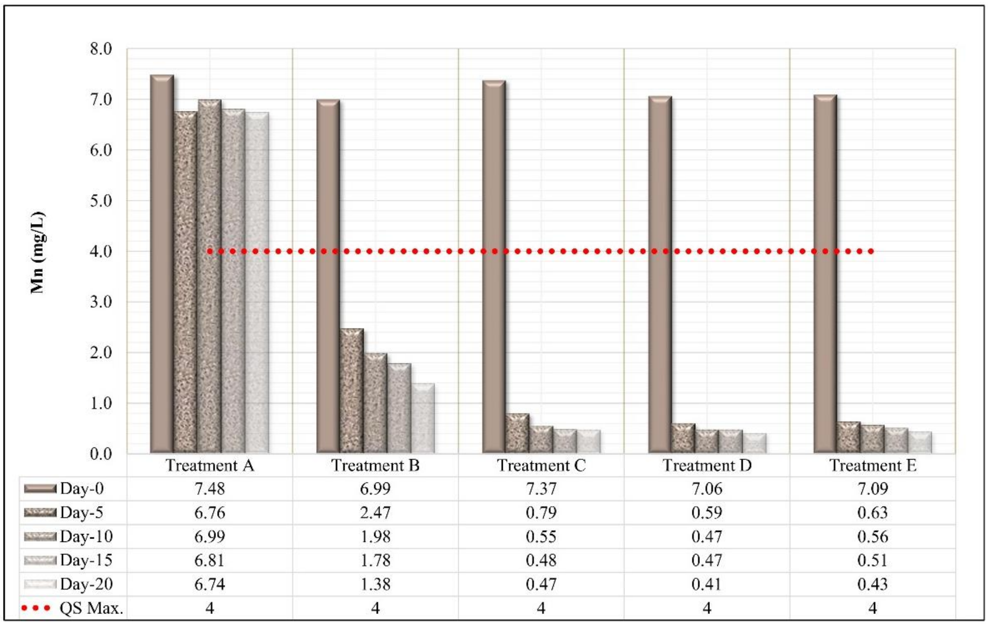


Figure 7. Graph of (Mn) Increase every 5-Day Period for Various Treatments.

In line with the decrease in Fe metal concentration, *Eleocharis dulcis* plant media in Treatments C, D, and E also contributed to reducing Mn metal concentration through a phytoremediation mechanism. This mechanism allows the absorption and accumulation of metals by the plant root system, thus gradually reducing Mn levels in acid mine drainage effluent. Although the accumulation of Mn metal was not as great as Fe, the results still showed that E. dulcis played an effective role in helping to reduce Mn concentrations from AMD.

Two-way ANOVA results indicated that treatment type, retention time, and their interaction significantly affected Mn concentration changes (calculated F > critical F), it is concluded that the interaction of treatment factors and time has a significant effect on changes in Fe according to the results of the hypothesis test F value (**Table 6**). The coefficient of determination (R^2) was 0.999, indicating that the constructed wetland experiment using *Eleocharis dulcis* and EPOB compost, in interaction with retention time, accounted for 99.9% of the variation in manganese concentration changes.

Table 6. Hypothesis Test Analysis of Mn Parameters

Variable	Factor	Test Criteria	Hypothesis	Conclusion
Mn	Treatment	$F_{count} > F_{table}$ 5173 > 2.4	H_0 is rejected	Treatment factor affected the (Mn) changes.
	Day	$F_{count} > F_{table}$ 5607 > 2.4	H_0 is rejected	The day factor affected the (Mn) changes.
	Interaction	$F_{count} > F_{table}$ 291 > 1.85	H_0 is rejected	The interaction of treatment and day factors affected the (Mn) changes.

The treatment of acid mine drainage (AMD) water using *Eleocharis dulcis* and palm oil empty fruit bunch compost (EPOB) within a constructed wetland system has proven effective in improving water quality based on parameters such as pH, Total Suspended Solids (TSS), and concentrations of iron (Fe) and manganese (Mn). Significant pH increases were observed particularly in treatments combining plants, compost, and limestone, with average increases up to 4.85 units.

The EPOB compost plays a crucial role in neutralizing acidity due to its organic carbon content and alkaline compounds that facilitate sulfate reduction reactions. Limestone further enhances pH improvement through the release of bicarbonate ions that accelerate chemical buffering. Conversely, treatments with plants alone showed smaller pH increases, likely due to the plant's adaptive tolerance to acidic conditions. Moreover, *Eleocharis dulcis* effectively reduced TSS through its dense root and shoot systems, which act as a natural filter capturing suspended particles and preventing their resuspension. EPOB compost and limestone contribute additional particulate retention through their porous structures. The TSS removal efficiency reached up to 98.24% in treatments with plants alone, indicating substantial improvement in water clarity. Significant reductions in Fe and Mn concentrations were also achieved. *Eleocharis dulcis* accumulates metals via its root system, while compost and limestone aid in precipitating dissolved metals, particularly by increasing pH to promote metal hydroxide formation. The removal efficiencies for Fe and Mn exceeded 90% and 93%, respectively, in treatments combining plants and compost, closely matching results from more complex media treatments.

Overall, the combined use of *Eleocharis dulcis* and EPOB compost not only provides optimal water quality improvement but also offers a simpler, more cost-effective, and accessible alternative compared to treatments requiring complex additives. Statistical analyses confirm that these treatments significantly and consistently improve water quality parameters over a 20-day retention period. Therefore, utilizing these two media is recommended as an effective solution for treating acid mine drainage wastewater.

IV. CONCLUSION

This study confirms that the constructed wetland system utilizing Purun Tikus (*Eleocharis dulcis*) and palm oil empty fruit bunch compost (EPOB) effectively improves acid mine drainage (AMD) water quality within a 20-day retention period. The treatment significantly increased the pH from an initial acidic level of approximately 3.12 to near-neutral values ranging between 7.97 and 7.98, depending on the treatment combination. Specifically, the highest pH increase was observed in the treatment combining *Eleocharis dulcis*, EPOB compost, and limestone (Treatment E), reaching 7.97, while the treatment with EPOB alone (Treatment B) achieved a pH of 7.98. Total Suspended Solids (TSS) experienced substantial reduction, with concentrations decreasing from initial values between 1,190.7 mg/L to 1,883.7 mg/L down to as low as 137.7 mg/L (Treatment E). Treatments involving just *Eleocharis dulcis* and in combination with EPOB (Treatments C and D) reduced TSS to 25.3 mg/L and 151 mg/L respectively, showing removal efficiencies up to 98.24%.

Iron (Fe) concentrations were dramatically lowered from initial levels near 33 mg/L to as low as 2.54 mg/L in the most effective treatment (Treatment E). Treatments combining plants and compost (Treatments D and E) met the environmental quality standard of 7 mg/L for Fe as early as day 5, with Fe levels continuing to decline throughout the study period. Similarly, manganese (Mn) concentrations decreased markedly from approximately 7 mg/L initially to below 0.47 mg/L in treatments including *Eleocharis dulcis*, with the lowest recorded concentration of 0.43 mg/L in Treatment E by day 20.

These treatments consistently met the Mn water quality standard of 4 mg/L from day 5 onwards. The addition of limestone enhanced pH neutralization and facilitated the precipitation of dissolved metals as hydroxides. *Eleocharis dulcis* contributed both by uptaking heavy metals via root absorption and by providing a habitat for microbial communities that degrade organic matter and promote nutrient cycling, thus improving overall water quality. Statistical analyses (two-way ANOVA) confirmed that both treatment types and retention times significantly influenced all measured water quality parameters, with coefficient of determination (R^2) values exceeding 0.99, indicating that nearly all variation in water quality improvement was explained by the applied treatments and exposure time. While these results indicate strong potential for an environmentally friendly, cost-effective, and practical AMD treatment method compared to active treatment which requires the continuous use of chemical substances. The study's laboratory scale and limited 20-day observation period suggest the need for further research at field scale and over longer durations to validate long- term performance and ecological impacts.

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