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RESEARCH ARTICLE

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Environmental Impact Mitigation Through Biofiltration of Mercury (Hg) from Gold Mining Effluent Using Parupuk (*Phragmites karka*)

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ABSTRACT

Mercury pollution from gold mining wastewater remains a major environmental concern due to its persistence and toxicity, driving interest in sustainable, low cost phytoremediation using native wetland plants. This research examines the phytoremediation capacity of *Phragmites karka* (locally referred to as Parupuk) in mitigating mercury contamination, with a particular focus on mercury (Hg), from wastewater derived from abandoned gold mining sites. A quasi experimental approach was implemented with exposure periods of 0, 3, 6, and 9 days. Approximately 1.5 kg (8 clumps) of live biomass was placed into custom designed 100 L glass bioreactors equipped with continuous water circulation. Key water quality indicators including pH, Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD), and Hg concentrations were systematically evaluated. Results indicated an increase in pH from 5.8 to 6.0, a 23.17% reduction in BOD (8.9 mg/L), and an 16.67% decline in COD (20 mg/L). The residual Hg concentration reached 0.0044 mg/L, which is below the permissible limit of 0.005 mg/L set by the Indonesian Water Quality Standard (Regulation No. 5/2022). These outcomes demonstrate the dual role of *Phragmites karka* as both a biological remediator and a fibrous filtration medium for water quality enhancement. Although the system is capable of meeting regulatory thresholds, further research is needed to clarify how Hg sequestration works and to determine the significant and specific contributions to plant structural attributes. This work establishes a scientific basis for further studies aimed at optimizing and scaling phytoremediation technologies for sustainable application in post-mining environments.

Introduction

Gold extraction, especially when performed through conventional techniques, commonly employs mercury (Hg) as the key reagent to separate gold from its ore [1]. This practice involves mixing the gold ore with mercury inside a grinding apparatus, facilitating the amalgamation of gold with mercury. However, such a process generates tailings containing high levels of mercury, which are frequently discharged directly into aquatic environments without adequate treatment. As a result, these wastes not only pollute surface waters but also contribute to the accumulation of toxic metals in surrounding ecosystems [2]. Mercury and other heavy metals are well recognized as persistent contaminants that resist natural degradation, enabling them to remain in the environment for extended periods and posing long-term ecological and health risks [3]. If not addressed promptly through appropriate control strategies, this problem may continue to escalate, posing serious risks to human health and threatening the long-term stability of environmental ecosystems. Accordingly, waste originating from industrial operations and healthcare services must be subjected to dedicated treatment processes before being released into aquatic environments [4].

Field investigations in the Cempaka Sub-district have consistently shown that mercury concentrations in surface waters surpass the Indonesian wastewater quality standard of 0.005 mg/L and the threshold of 0.002 mg/L set in Government Regulation No. 82 of 2001 [5]. Such findings emphasize the pressing requirement for remediation methods that combine efficiency with affordability and environmental compatibility. Phytoremediation has been increasingly recognized as a practical alternative, utilizing plants to absorb,

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immobilize, or stabilize toxic elements from contaminated soils and waters. Unlike conventional technologies, this plant-based method offers simpler on-site application and reduces ecological disturbance. Furthermore, phytoremediation stands out for its relatively low operational cost, making it a suitable option for regions with limited resources [6,7].

Phytoremediation has been increasingly recognized as an effective strategy, relying on the capacity of plants to absorb, accumulate, or immobilize pollutants from contaminated aquatic systems. In contrast to traditional remediation methods, this plant-based approach is characterized by its relatively low cost, feasibility for on-site use, and minimal environmental disturbance [8,9]. Many investigations have reported that certain species are able to survive under extreme and polluted conditions while taking up considerable amounts of heavy metals, effectively serving as natural biofilters [10,11]. Such tolerance and accumulation ability make them valuable for the restoration of degraded ecosystems. Among these species is *Phragmites karka*, locally referred to as Parupuk.

This study lies in its integrated approach that combines the use of live *Phragmites karka* (Parupuk) as a biofilter with a dual focus on both its biological phytoremediation capacity and its fibrous structural properties for mercury (Hg) adsorption. Unlike most previous phytoremediation studies that examine either plant uptake mechanisms or utilize dead biomass as adsorbents, this research uniquely investigates *Phragmites karka* in its living state under controlled contact times to evaluate its real-time biofiltration performance. In addition, the study incorporates material characterization of the plant's fiber morphology to understand its role in enhancing mercury capture. This dual functionality approach treating *P. karka* as both a living biological agent and a structural filtration medium represents a novel contribution to phytoremediation science and highlights its potential as a sustainable, low-cost solution for mercury mitigation in artisanal gold mining effluents.

Materials and Methods

This study used a quantitative experimental design involving a time series framework to evaluate the effectiveness of cracker plants in reducing mercury levels from wastewater originating from former gold and other metal mining areas. The study was conducted in a semi-outdoor laboratory for more than 2 weeks. It included plant acclimatization stages, treatment application, and supporting data collection. A total of more than 60 liters of water with mercury concentrations exceeding the threshold were purposively taken from a mine site that had completed operations in Pumpung Village, Cempaka District, South Kalimantan, which was used as a growing medium for the tested plants. Although the methodological framework of the study has been explained in sufficient detail at the beginning, several important stages such as measuring plant mass and measuring mercury absorption in plant tissue have not been explained sufficiently. This requires additional clarity so that this study can be understood with a high level of accuracy and more convincing reproducibility.

Materials and Equipment

The experiment utilized custom-made glass vessels as the growth medium containers. The primary vessel measured 60 cm in length, 40 cm in width, and 45 cm in height, with a total volume of 100,000 cm^3 (equivalent to 100 L per unit), providing adequate space for water movement. In addition, a supplementary glass container measuring 15 cm in length, 40 cm in width, and 45 cm in height was employed to support the water circulation system. A pump was used to regulate the water flow (approximately 10 L/h), ensuring consistent circulation throughout the experimental period.

The main material employed in this research was the Parupuk plant (*Phragmites karka*). Before utilization, the plants were gathered and their average stem height and root length were recorded to ensure uniformity among samples. The quantity of plants introduced corresponded to two-thirds of the total water volume of the artificial pond designated as the growth medium. Furthermore, 60 L of wastewater, verified to contain mercury, was used as the aqueous medium.

Experimental Design and Statistical Analysis

The experimental design was arranged in a completely randomized manner, where each treatment was performed in triplicate (n= 3) to ensure the reliability and reproducibility of the results. A control group, consisting of mercury-contaminated water without the addition of *Phragmites karka*, was established for comparison purposes. The treatments were structured into four exposure durations, namely 0 days (control), 3 days, 6 days, and 9 days, to evaluate the temporal dynamics of mercury (Hg) reduction. Although the design and replication provide a sound basis for statistical analysis, some methodological aspects remain insufficiently explained, particularly regarding the quantification of plant biomass before and after exposure as well as the measurement of mercury accumulation within plant tissues. Addressing these details is essential to strengthen the validity of the findings and to provide a more comprehensive understanding of the phytoremediation capacity of *Phragmites karka*.

Water samples were collected at each time interval and analyzed for mercury (Hg) concentration using Atomic Absorption Spectrophotometry (AAS). The results were expressed as means ± standard deviation (SD). Prior to statistical analysis, data were tested for normality and homogeneity of one-way analysis of variance (ANOVA) was then applied to determine the significance of differences among treatments. Post-hoc Tukey's HSD test was performed to identify specific group differences when applicable, with a significance level set at $\alpha = 0.05$.

Research Methodology

The research methodology and operational setup of the treatment are presented in Figure 1. Parupuk plants were harvested from aquatic habitats and carefully washed with distilled water to eliminate any particles or chemicals that might compromise the precision of mercury analysis. Subsequently, the plants underwent a one-week acclimation period within the planting containers. After acclimatization, the plants were placed in water contaminated with mercury. The experimental treatments involved grouping the plants according to exposure durations of 3, 6, and 9 days. Each group comprised 8 clumps, spaced at intervals of 10 cm. The initial mercury concentration in the water samples was measured prior to treatment to determine the baseline pollution level, which served as a benchmark for evaluating changes during the course of the experiment. The analysis of mercury concentration and other water quality parameters referred to the permissible limits established in Ministry of Environment and Forestry Regulation No. 5/2022 on Water Quality Standards (Republic of Indonesia), which defines national threshold values for physical and chemical characteristics of water used for environmental assessment and wastewater evaluation.

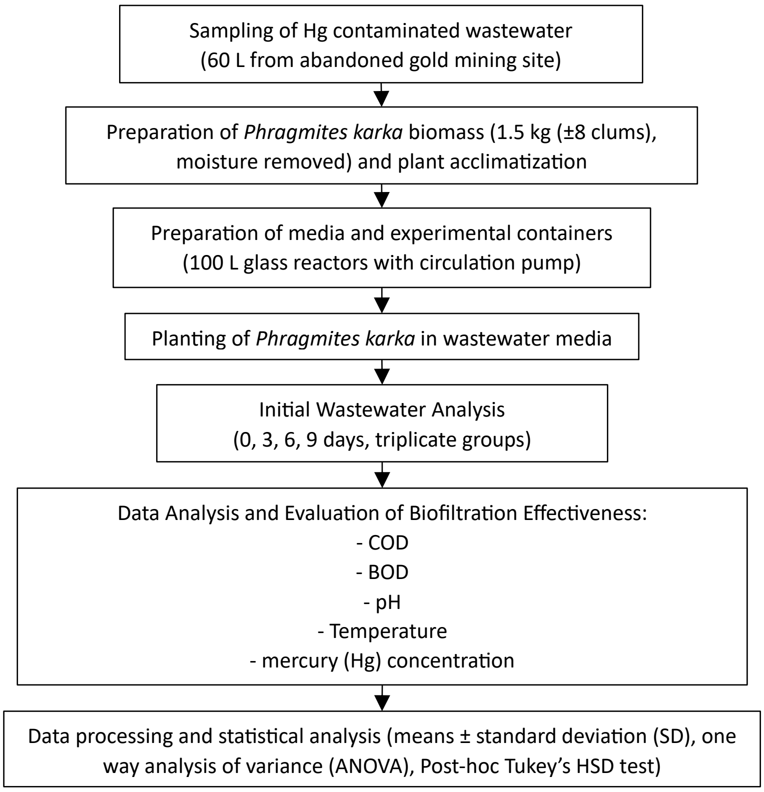

Figure 1. Workflow of the phytoremediation experiment using *Phragmites karka*. This figure depicts the sequence of steps applied to remove mercury (Hg) from gold mining wastewater with living *Phragmites karka* plants. The workflow includes sample collection and preparation, acclimatization of plants, exposure to contaminated water for varying contact times (0, 3, 6, and 9 days), and subsequent testing of mercury levels after treatment. The schematic provides a concise outline of the experimental procedure designed to assess the capacity of *Phragmites karka* in reducing mercury contamination in mining effluent.

Before commencing the treatment, the Parupuk plants (*Phragmites karka*) were acclimatized in the designated media/container for a duration of one week to confirm their stabilization and readiness for the experimental interventions. The treatment involved using a single container as the experimental unit, planted with Parupuk plants and linked to an auxiliary container specifically designed for the water circulation system, which was also planted with Parupuk. The experimental unit was filled with mercury-contaminated water obtained from the river and previously analyzed to establish the baseline mercury concentration. Mercury concentrations were subsequently measured on the 3rd, 6th, and 9th days of the treatment period.

Results and Discussion

Results

The primary objective of this study was to evaluate the effectiveness of *Phragmites karka* (Parupuk) in reducing mercury (Hg) concentrations from wastewater originating from abandoned gold mining areas. To this end, physicochemical parameters, including temperature, pH, BOD, COD, and Hg concentration, were monitored at four contact times (day 0, day 3, day 6, and day 9). Mercury levels were determined using the Atomic Absorption Spectroscopy (AAS) method, with the results summarized in Table 1. The findings revealed a progressive decline in BOD (23.17%), COD (16.67%), and Hg concentration (89.11%), accompanied by a slight but favorable adjustment in pH towards the acceptable water quality range.

In contrast to previous studies, particularly [12], which examined Phragmites karka under batch mode and static laboratory conditions, this work employed a continuous-flow system. While the batch setup provided valuable insights into the plant's phytoremediation capacity, it overlooked dynamic environmental variables commonly present in natural aquatic ecosystems, such as flow velocity, pH fluctuations, and temperature variations. The continuous-flow configuration used in this research better represents the hydrodynamic conditions of gold mining effluents, where wastewater is discharged as a flowing stream. This approach not only enhances the ecological relevance of the experimental design but also offers a more realistic indication of the applicability of *Phragmites karka* biofiltration for large-scale environmental impact mitigation. Following this general comparison, the specific effects of biofiltration period on mercury reduction and the results of statistical analyses, including ANOVA and Tukey HSD, are presented in the subsequent sections.

Table 1. Analytical results of pH, COD, BOD, and mercury levels in wastewater subjected to treatment with *Phragmites karka* over a 9-day duration. Summary of pH, COD, BOD, and mercury (Hg) levels in gold mining wastewater following treatment with *Phragmites karka* across a 9-day observation period. This table presents changes in major physicochemical indicators recorded at contact intervals of 0, 3, 6, and 9 days during the phytoremediation experiment. A consistent improvement in water quality was observed, characterized by reductions in COD, BOD, and Hg concentrations, accompanied by minor stabilization in pH values. Overall, the findings highlight the capacity of *Phragmites karka* to reduce mercury contamination and improve the chemical quality of mining effluent over time.

Parameter	Concentration in wastewater							Water quality standard (Regulation No. 5/2022)
	Time					Change in concentration (mg/L)	Reduction (%)	
	Control	Day 0	Day 3	Day 6	Day 9			
pH	0.58×10^1	0.58×10^1	0.59×10^1	0.59×10^1	0.60×10^1			6–9
BOD (mg/L)	3.82×10^1	3.82×10^1	3.53×10^1	3.34×10^1	2.95×10^1	0.89×10^1	23.17	Max 30
COD (mg/L)	1.20×10^2	1.20×10^2	1.12×10^2	1.04×10^2	1.00×10^2	2.00×10^1	16.67	Max 100
Total Mercury (Hg) (mg/L)	4.04×10^{-2}	4.04×10^{-2}	3.01×10^{-2}	1.49×10^{-2}	0.44×10^{-2}	3.6×10^{-2}	89.11	0.005

The monitoring of water quality parameters throughout the biofiltration process indicated notable alterations in several chemical components. A progressive increase in wastewater pH was observed, rising from 5.8 on day 0 to 6.0 on day 9, signifying a tendency toward neutral conditions that are typically favorable for the biological functions of aquatic vegetation and associated microbial communities. A decline in BOD from 38.2 mg/L to 29.5 mg/L, corresponding to a 23.17% decrease, suggests active breakdown of dissolved organic substances. Similarly, COD showed a reduction from 120 mg/L to 100 mg/L—a 16.67% drop—implying that the chemical constituents in the wastewater were degraded through both biological and chemical pathways. Furthermore, mercury (Hg) levels declined from 0.0404 mg/L to 0.0044 mg/L, equivalent to a 89.11% reduction, highlighting the system's ability to mitigate toxic mercury. Taken together, these results underline the efficiency of the biofiltration process, as evidenced by improvements in pH balance, reductions in BOD and COD, and mercury removal, all contributing to the effective treatment of wastewater using biological means.

The application of Parupuk (*Phragmites karka*) in the biofiltration process proved to be notably effective in mitigating pollutant levels in wastewater originating from gold mining activities. This aquatic plant played a role in moderating water pH, with values gradually increasing from 5.8 on the initial day to 6.0 on the ninth day. While the shift is relatively minor, it reflects an ongoing neutralization process that potentially enhances biological treatment performance, particularly by fostering microbial activity involved in the breakdown of organic pollutants [13,14].

A decrease in BOD concentration from 38.2 mg/L to 29.5 mg/L reflects a removal efficiency of 23.17%, indicating substantial degradation of biodegradable organic matter during the biofiltration period. This reduction is presumed to result from the synergistic interactions between rhizospheric microorganisms and the root system of *Phragmites karka*, along with the plant's inherent ability to uptake specific organic substances from the wastewater [15]. In addition, a decrease in COD concentration was observed, from 120 mg/L to 100 mg/L, indicating a removal efficiency of 16.67%. This reduction suggests that chemical contaminants were partially broken down through biological mechanisms and adsorbed by the plant-based media and the biofiltration bed [16]. Although the extent of COD removal was lower than that of BOD, the result remains noteworthy as it highlights the system's effectiveness in treating more resistant chemical pollutants [17]. A reduction in mercury concentration, specifically mercury (Hg), was observed from 0.0404 mg/L to 0.0044 mg/L, amounting to a 89.11% decrease. This result highlights the phytoremediation capability of *Phragmites karka*, potentially through mechanisms involving metal uptake and accumulation in plant tissues or through stabilization processes occurring in the rhizosphere [10,18].

Impact of Biofiltration Period on Temperature

Experimental results revealed that the water temperature in the system containing *Phragmites karka* decreased to 26°C by the ninth day, marking the end of the observation period. Water temperature is inherently affected by various environmental factors, such as solar radiation absorbed at the surface, wind-driven water movement, and vertical circulation caused by thermal layering—where denser, cooler water descends and forces the warmer layer upward. Moreover, temperature has a substantial impact on dissolved oxygen concentrations, with elevated temperatures accelerating the rate at which oxygen saturation is reached in comparison to cooler conditions [19,20].

This research employed an aeration system, utilizing a pump with a maximum flow rate of 10 L/h, to enhance the oxygen content in the water. The aeration process served to mitigate the potential reduction in dissolved oxygen levels resulting from biological processes within the aquatic environment. Its main purpose was to facilitate the transfer of oxygen from the atmosphere into the water, ensuring that dissolved oxygen levels remained within an optimal range. The aeration process facilitates air–water interaction that helps regulate water temperature, a parameter known to affect microbial dynamics and oxygen solubility in biofiltration systems. However, this variable is not specifically stipulated in the Indonesian Ministry of Environment and Forestry Regulation No. 5/2022.

Impact of Biofiltration Period on pH

Findings from the *Phragmites karka* cultivation media revealed that pH levels experienced minor fluctuations during the early phase of observation but showed a trend toward stabilization between days 6 and 9. The pH values measured on days 0, 3, 6, and 9 were 5.8, 5.9, 5.9, and 6.0, respectively, indicating a gradual shift toward slightly neutral conditions. Based on established water quality standards, these pH values fall within the permissible range of 6.0–9.0, as stipulated in the Indonesian Ministry of Environment and Forestry Regulation No. 5/2022. The fluctuation of pH during the biofiltration process represents a crucial parameter for monitoring the biochemical processes taking place within the phytoremediation system. This study investigated the influence of different contact times (0, 3, 6, and 9 days) on the pH levels of gold mining wastewater subjected to treatment with *Phragmites karka*. The corresponding results are presented in Figure 2.

Impact of Biofiltration Period on BOD and COD

The study conducted in ponds cultivated with *Phragmites karka* revealed a progressive decline in BOD levels throughout the monitoring period. The BOD concentrations measured on days 0, 3, 6, and 9 were 38.2 mg/L, 35.3 mg/L, 33.4 mg/L, and 29.5 mg/L, respectively. This indicates a clear downward trend, with significant reductions particularly evident on days 3 and 9. By the end of the observation period, the BOD concentration had fallen below the regulatory limit of 30 mg/L, in contrast to the initial measurement on day 0, which exceeded the standard. In total, the presence of *Phragmites karka* in the pond system resulted in a 23.17% decrease in BOD after nine days of treatment. The duration of biofiltration plays a vital role in assessing the efficiency of phytoremediation in decreasing concentrations of organic pollutants, particularly COD and BOD. This study employed varying contact times (0, 3, 6, and 9 days) to investigate the extent of COD and BOD reduction in gold mining wastewater treated using *Phragmites karka*. The corresponding results are presented in Figure 3.

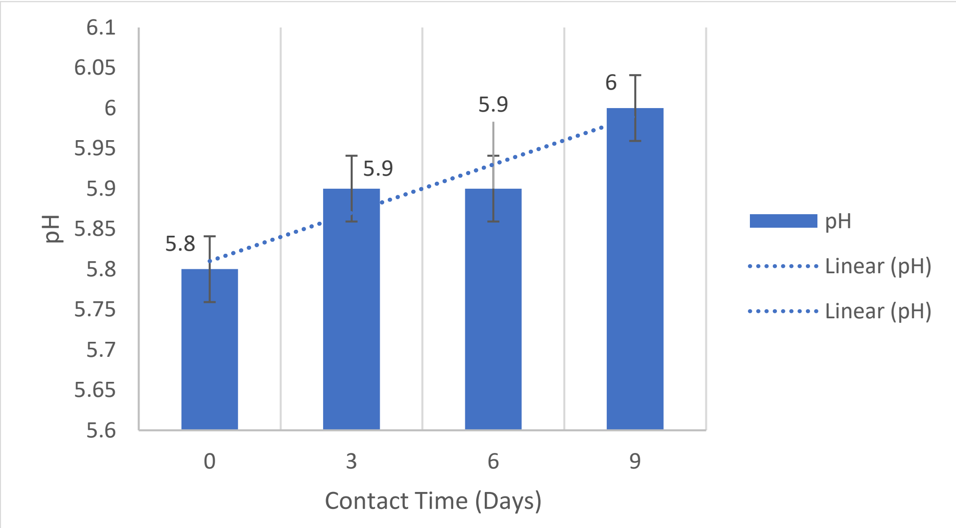

Figure 2. Effect of contact duration on pH levels shows variation in pH values over different contact durations during the phytoremediation of gold mining wastewater with *Phragmites karka*. This figure presents changes in pH recorded at contact intervals of 0, 3, 6, and 9 days under semi-outdoor laboratory conditions. A gradual rise followed by stabilization of pH levels was observed as the treatment progressed, reflecting a decrease in the acidity of the wastewater. The trend implies that *Phragmites karka* played a role in moderating the solution's pH, thereby contributing to the overall improvement of water quality throughout the experiment.

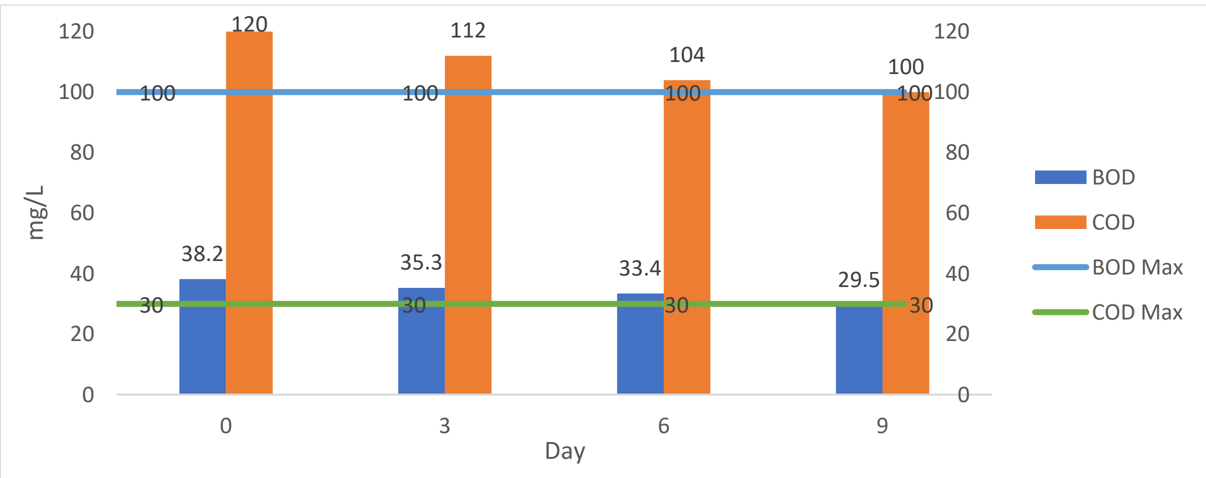

Figure 3. Effect of contact duration on BOD and COD shows changes in biochemical oxygen demand (BOD) and chemical oxygen demand (COD) during the phytoremediation of gold mining wastewater with *Phragmites karka*. This figure depicts variations in BOD and COD values measured at contact intervals of 0, 3, 6, and 9 days under semi-outdoor laboratory settings. A noticeable downward trend in both parameters was observed as the experiment progressed, indicating the breakdown of organic compounds present in the wastewater. These findings show that *P. karka* contributed to improving water quality by supporting natural biological and oxidative processes throughout the treatment period.

The application of *Phragmites karka* within the biofiltration system significantly contributed to the reduction of COD in gold mining wastewater. Laboratory measurements showed a decrease in COD levels from 120 mg/L at the start of the treatment (day 0) to 100 mg/L by day 9. This corresponds to a 16.67% decline over the course of the nine-day treatment period. By day 9, the COD concentration had declined to meet the established water quality standard of 100 mg/L, suggesting that the treated wastewater conformed to acceptable effluent criteria. In comparison, the COD level recorded on day 0 surpassed this regulatory threshold, indicating that the initial condition of the wastewater did not yet satisfy ecological suitability.

Impact of Biofiltration Period on Mercury (Hg) Reduction

The duration of contact time represents a critical parameter in assessing the effectiveness of biofiltration processes for the reduction of mercury, particularly mercury (Hg), in wastewater originating from gold mining activities. In the present study, a biofiltration system utilizing *Phragmites karka* was applied under controlled exposure periods of 0, 3, 6, and 9 days. This experimental design was intended to evaluate both the rate of mercury uptake and the overall removal efficiency achieved by the system. The corresponding results derived from these observations are presented in Figure 4.

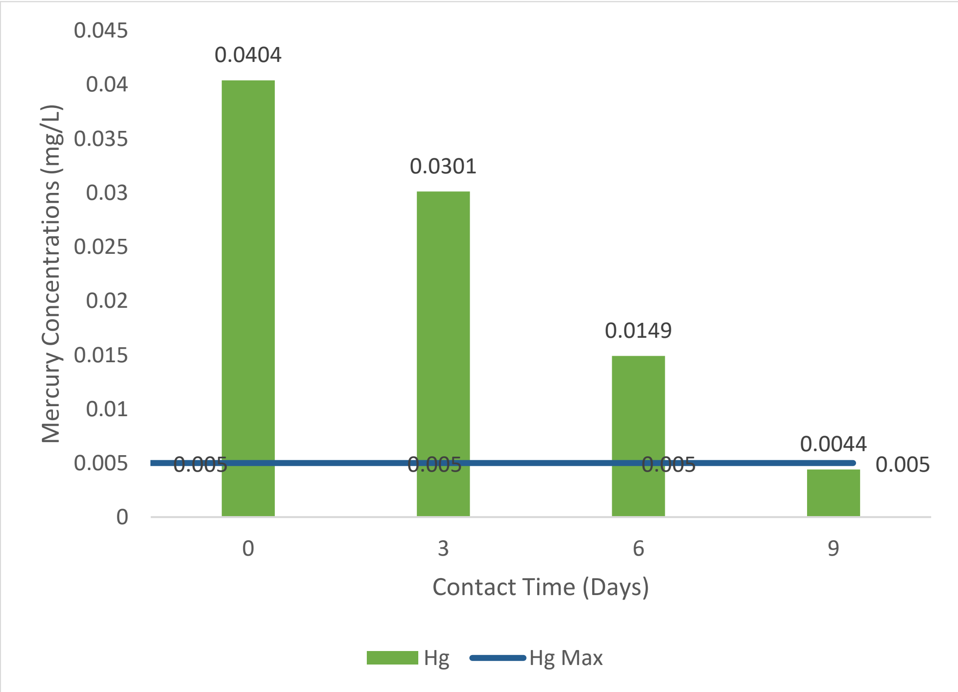

Figure 4. Effect of contact duration on mercury (Hg) reduction shows trend of mercury (Hg) decline in gold mining wastewater treated through phytoremediation using *Phragmites karka*. The figure presents variations in mercury concentrations observed at contact periods of 0, 3, 6, and 9 days, conducted under semi-outdoor laboratory conditions. A gradual and consistent decrease in Hg content was noted as the treatment progressed, indicating the active absorption and retention of mercury by the plant. Overall, the results highlight the capacity of *P. karka* to lower mercury levels in polluted mining effluent, emphasizing its promise as an environmentally friendly option for post-mining wastewater treatment.

A progressive and notable reduction in mercury (Hg) concentration was observed throughout the 9-day treatment period using *Phragmites karka*. The initial Hg concentration of 0.0404 mg/L decreased consistently to 0.0301 mg/L on Day 3; 0.0149 mg/L on Day 6; and reached 0.0044 mg/L by Day 9. This final value is marginally below the regulatory threshold for mercury in wastewater, which is 0.005 mg/L according to the Indonesian Water Quality Standard (Regulation of the Minister of Environment and Forestry No. 5/2022). The corresponding removal efficiency of 89.11% demonstrates the strong potential of *Phragmites karka* for phytoremediation of mercury-contaminated water under laboratory conditions. Nonetheless, the proximity of the final concentration to the regulatory limit warrants a cautious interpretation. Fluctuations in operational or environmental parameters such as pH, temperature, and plant physiological condition may affect the system's stability and could result in non-compliance in real-world applications [21]. As such, while the experimental results are encouraging, further research is required to validate the reliability and reproducibility of this phytoremediation strategy under diverse environmental scenarios. These findings are consistent with previous reports on the efficacy of *Phragmites* species in the uptake and stabilization of mercury [22], reaffirming the importance of robust system design and performance monitoring to ensure safe and sustained application at field scale.

ANOVA, Tukey HSD, and Graphical Analysis on the Impact of Contact Time with Parupuk (Phragmites karka) on BOD, COD, and Mercury (Hg) Reduction from Gold Mining Effluent

Laboratory analyses of the wastewater samples indicated a statistically significant reduction in BOD, COD, and mercury (Hg) concentrations during the exposure period with *Phragmites karka* (Parupuk). The dataset was subjected to statistical evaluation through a one-way analysis of variance (ANOVA), followed by Tukey's Honestly Significant Difference (HSD) test to determine pairwise differences among treatments. A detailed summary of these results is presented in Table 2. Furthermore, the outcomes were visualized using bar charts with error bars to illustrate variability, as shown in Figures 5, 6, and 7.

Table 2. The analysis on the reduction in BOD, COD, and mercury (Hg) concentrations. Statistical summary of changes in BOD, COD, and mercury (Hg) concentrations observed during the phytoremediation of gold mining wastewater using *Phragmites karka*. This table lists the mean values and standard deviations of biochemical oxygen demand, chemical oxygen demand, and mercury content recorded at contact durations of 0, 3, 6, and 9 days under semi-outdoor experimental conditions. A steady decline in each parameter was noted throughout the observation period, reflecting continuous improvement in the water's physicochemical quality. These outcomes suggest that *Phragmites karka* efficiently reduced both organic load and mercury contamination, underscoring its promise as an eco-friendly solution for treating effluents from mining activities.

Parameter	Days	Mean	Standard deviation
BOD	0	3.82×10^{1}	0.173
BOD	9	2.96×10^{1}	0.100
COD	0	1.20×10^{2}	0.152
COD	9	1.00×10^{2}	0.152
Mercury (Hg)	0	4.04×10^{-2}	0.00
Mercury (Hg)	9	0.44×10^{-2}	0.00

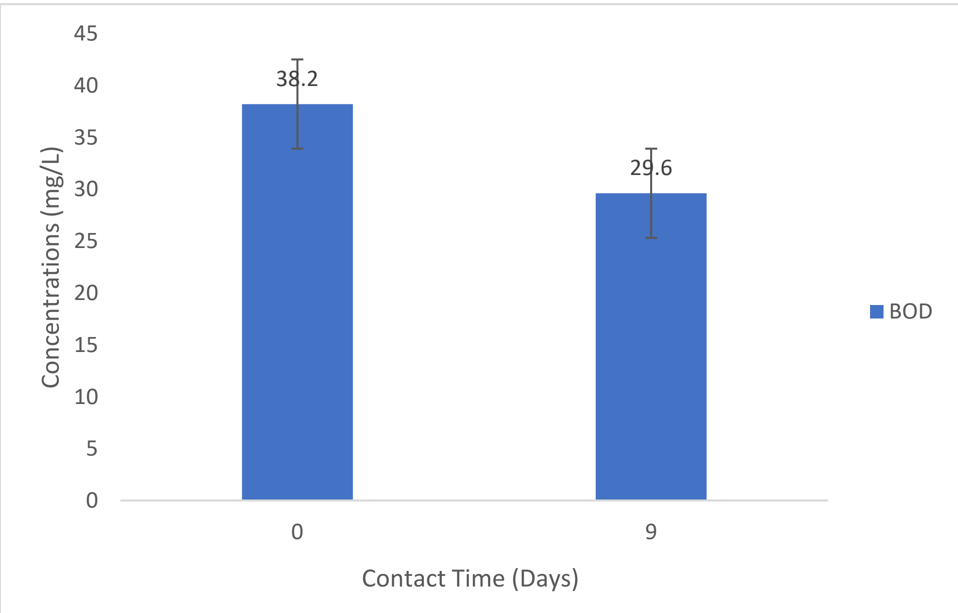

Figure 5. Impact of contact time with parupuk (*Phragmites karka*) on BOD. After being treated for about 9 days we can note that the Parupuk plant may have helped purification water contaminated with gold mining activity. The fact that the plant's roots had encouraged the growth of microbes, which helped naturally decomposing organic matter in the water in naturally ways. Therefore, the longer the Parupuk plant is contacted with contaminated water, the cleaner the water becomes from gold mining waste activity.

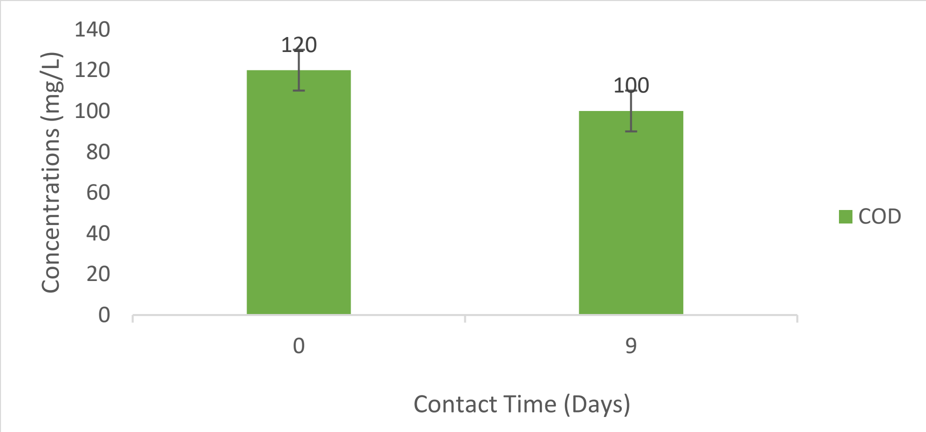

Figure 6. Impact of contact time with parupuk (*Phragmites karka*) on COD shows that the results of this experiment showed a decrease in pollution levels in the wastewater from the gold mine, which is closely related to the natural processes occurring in the cracker plant. This plant is commendable in absorbing and helping to decompose hazardous substances through its natural root system, which occurred throughout the experiment. Gradually, the water became clearer as the plant actively absorbed toxic metals organically. Therefore, this plant's natural ability indicates that the cracker plant can function as an effective natural filter without the need for excessive chemicals. Therefore, we believe this natural phytoremediation method has the potential to be an affordable, environmentally friendly, and sustainable solution for improving water quality in areas exposed to gold mining activities

What is seen in Figure 6, the COD concentration decreased drastically from 120 mg/L on day zero to 100 mg/L on day 9, which shows a decrease of 16.7%. These results demonstrate the effectiveness of the treatment process in reducing COD levels during the contact time we observed. Statistically, we observed that variations in contact time significantly affected COD concentrations ($F(3.8) = 14,168.07$; $p < 0.000001$). Further analysis using the Turkey's HSD test also revealed that each treatment interval showed a statistically significant difference. During the experiment, we observed a gradual decrease in COD levels, from 120 mg per liter to even lower levels after 9 days of testing. We believe this trend reflects the biofiltration system's ability to successfully reduce the organic pollutants naturally present in the environment in wastewater. We believe this system's ability to operate gradually reduces organic pollutants in wastewater. From an environmental management perspective, we found the potential of *Phragmites karka* as an effective, sustainable approach to reducing organic contamination in aquatic ecosystems impacted by gold mining activities.

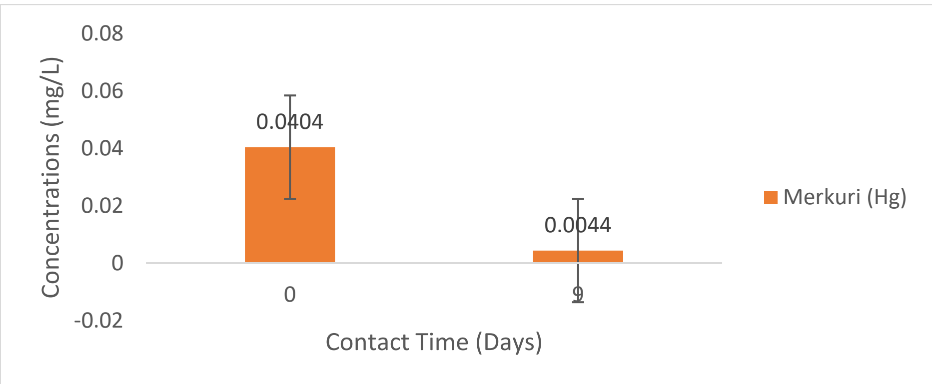

Figure 7. Impact of contact time with parupuk (*Phragmites karka*) on mercury (Hg) shows variation in mercury (Hg) concentration in gold mining wastewater treated with *Phragmites karka* across different contact durations. Therefore, we can conclude that mercury levels in air exposed to gold mining waste treated with *Phragmites karka* plants showed a decrease with increasing contact time, i.e., air immersion. We observed a steady and clear decrease from day zero to day 3, 6, and 9 in a slightly open environment. We believe that the *Phragmites karka* plant has a convincing role in absorbing metals that cause wastewater. This working method demonstrates the plant's potential as a natural, active, and environmentally friendly biofiltration solution. Therefore, this plant is highly useful as an alternative water purification effort in areas exposed to waste or gold mining activities.

We can explain that the display in Figure 7 has experienced a very significant decrease in mercury concentration HG where we see from the figure of 0.04 mg per l since the first day of the experiment, namely 0.00 mg/L until the last day of the 9th day with a reduction of nearly 90%, this is a very significant decrease. Therefore, we can confirm the ability of the experimental system based on *Phragmites karka* plant, namely the effort to remove active mercury ingredients efficiently from ex-gold mine wastewater. As we explained above, the ANOVA test also shows that contact time has a very significant impact on changes in mercury concentration. The high f value shows a drastic difference between contact time groups. Meanwhile, the difference between replications is very relatively small as we noted from the consistency of the results of the AAS method analysis. Further analysis, we used the Turkey's HSD test, which also strengthened our findings where each time interval was very significant ($p < 0.001$). Where the decrease in mercury levels from 0.0404 mg/L to 0, which confirms the effectiveness of the Pragmatic Karka plant in the process of reducing and absorbing heavy metals. At the same time, this confirms the great potential as a natural, efficient, effective and sustainable filtration and remediation medium for water management projects polluted by former mining activities.

Discussion

Experimental results reveal that *Phragmites karka* plays a significant role in mercury (Hg) removal and overall improvement of water quality in gold mining wastewater treatment. In this study, water temperatures were generally higher than the typical tropical water average of 25°C. The observation period was determined by the predefined biofiltration durations (0, 3, 6, and 9 days). During this period, temperature was recorded only as an environmental parameter to assess its potential influence on the biofiltration process, and not as a basis for determining the length of the observation. Despite this, the measured values stayed within the allowable deviation of ±3°C, as outlined in Government Regulation No. 82 of 2001. Temperature stability observed up to the ninth day created a conducive environment for both chemical reactions and microbial processes to occur in equilibrium. Shallow aquatic systems, such as the experimental pond used, are inherently more prone to thermal fluctuations than deeper water bodies. Nonetheless, aquatic organisms depend on relatively consistent temperatures with minimal variation [23]. The implementation of an aeration system, as previously discussed, helped to effectively reduce temperature variability. Throughout the experiment, water temperatures ranged from 25°C to 32°C, aligning with the optimal conditions for mesophilic bacterial growth. Within this range, these bacteria are able to carry out ammonia oxidation via nitrification processes [24]. Within the biofiltration system, water temperature could influence or regulated by surface solar radiation, which can be moderated by the shading effect of the relatively dense canopy of *Phragmites karka* (in this research environment). In contrast, factors such as wind-driven circulation and vertical thermal stratification are more characteristic of larger natural aquatic environments. The distribution of mercury in water is strongly influenced by temperature conditions within the medium cultivated with *Phragmites karka*. Typically, lower temperatures are associated with elevated concentrations of mercury in the surface layer of the water.

Lower pH levels in water are generally associated with elevated concentrations of dissolved mercury [25]. This trend was also evident in the present study, where a gradual rise in pH within the *Phragmites karka* cultivation system correlated with a decrease in mercury concentrations. The underlying mechanism is that acidic conditions enhance the solubility of mercury, increasing their likelihood of remaining in the dissolved state. Several factors influence the adsorption process of mercury, including the adsorbent's surface area, the physicochemical properties and concentration of the adsorbate, solution pH, contact duration, and temperature [26]. Under acidic conditions, mercury become more bioavailable due to their increased mobility and dissolution. In contrast, at higher pH values, these metals are more likely to precipitate out of the solution, thereby reducing their concentrations in the water column [27]. Findings from this study suggest that the gradual increase in pH observed during the treatment period with *Phragmites karka* was associated with a corresponding decrease in the concentration of mercury in the water. This inverse relationship is consistent with previous findings [28], which indicate that lower pH values enhance the dissolution of mercury compounds. In our experiment, the gradual increase in pH from day 0 to day 9 may have favored the transformation of dissolved mercury into less soluble forms, thereby contributing to the observed decrease in aqueous mercury concentrations within the treatment system.

From a chemical perspective, metal ions exhibit greater solubility in aqueous environments under acidic conditions, leading to elevated concentrations in solution. In contrast, as pH increases, the solubility of mercury decreases, causing them to precipitate out of the water. This phenomenon is primarily attributed to adsorption mechanisms, which are influenced by factors such as the surface characteristics of the adsorbent, the physicochemical properties and concentration of the adsorbate, solution pH, contact time, and temperature, rather than by precipitation processes [29]. Within this framework, *Phragmites karka* plays a vital role in the reduction of mercury concentrations through two key pathways: phytoremediation processes and its influence on stabilizing water quality indicators such as pH. This plant demonstrates both phytostabilization and phytoextraction properties, allowing it to absorb and immobilize mercury via its root and stem systems. Additionally, its extensive root structure improves the microbial environment in the medium and enhances metal binding through rhizospheric microbial interactions and biofilm development [30,31]. As a result, the increase in pH observed on day 9 appears to favor mercury transformation into less soluble forms, thereby lowering its dissolved concentration in the water. While this study did not measure mercury accumulation in sediments or plant tissues, previous research has suggested that *Phragmites karka* are capable of metal uptake, which may further support their potential as natural agents for biofiltration.

The observed decrease in COD suggests that *Phragmites karka* is effective in the phytoremediation of organic pollutants present in wastewater. This reduction is largely influenced by the rhizosphere, which facilitates the proliferation of both aerobic and anaerobic microbial communities capable of breaking down complex organic substances into simpler, less toxic compounds. Additionally, the plant's root system plays a crucial role by offering a supportive surface for biofilm development and improving the circulation of dissolved oxygen, thereby enhancing natural oxidative reactions within the biofiltration environment [32,33]. As previously noted, the rise in dissolved oxygen levels within the treated water is largely influenced by the role of *Phragmites karka*, which facilitates oxygen release into the water column. This is further complemented by natural aeration driven by the movement of water. Together, these mechanisms are essential in maintaining sufficient levels of dissolved oxygen, which support the continuity of biological functions in the biofiltration system. The synergistic relationship among oxygen, aquatic vegetation, and microbial communities establishes a self-sustaining cycle: microorganisms break down organic matter into simpler, less harmful substances that can be taken up by plants as nutrients. In turn, the plant roots contribute oxygen to the aquatic environment, stimulating microbial metabolic activity by acting as a biological catalyst [34].

Recent advancements in phytoremediation research suggest that prolonging exposure duration, increasing plant biomass, and incorporating amendments like biochar or beneficial microbes can enhance the efficiency of metal removal by wetland plant [8,35]. Furthermore, integrating phytoremediation with engineered systems such as constructed or floating wetlands has proven effective in achieving regulatory compliance for mercury removal [36]. Although *Phragmites karka* exhibits strong potential as a green alternative for treating mercury-contaminated water, additional investigations are warranted to fine-tune critical parameters, including treatment duration, system scalability, and safe disposal or reuse of metal-enriched plant biomass to ensure long-term sustainability and regulatory adherence. It should be acknowledged, however, that this study did not quantify Hg concentrations in plant tissues. While the observed decrease in aqueous Hg concentration demonstrates the phytoremediation potential of *Phragmites karka*, direct measurement of Hg accumulation within plant biomass would provide stronger evidence of the uptake mechanism. Future investigations are therefore warranted to address this aspect.

We used ANOVA to determine the effect of contact time on BOD levels. This gradually decreased from 38.2 mg/L to a lower concentration after 9 days of treatment. Although the decrease appeared delayed, it occurred consistently, as *Phragmites karka* actively participated in the decomposition of organic matter in the wastewater. We also observed that the plant root system also impacted the microbial process and participated in the overall degradation process through a combination of biochemical and biological interactions. Over time, these changes increased water content by facilitating the decomposition of organic compounds. From an environmental management perspective, the study results highlight the potential of *Phragmites karka* as part of a biofiltration system that appears environmentally friendly in areas exposed to gold mining activities. In this case, plants are understood not only to function as natural filters but also as ecological partners that strengthen natural remediation efforts. Further analysis using the Turkey's HSD test also revealed that each treatment interval showed a statistically significant difference. During the experiment, we observed a gradual decrease in COD levels, from 120 mg per liter to even lower levels after 9 days of testing. We believe this trend reflects the biofiltration system's ability to successfully reduce the organic pollutants naturally present in the environment in wastewater. We believe this system's ability to operate gradually reduces organic pollutants in wastewater. From an environmental management perspective, we found the potential of *Phragmites karka* as an effective, sustainable approach to reducing organic contamination in aquatic ecosystems impacted by gold mining activities.

Overall, it can be concluded that our research on *Phragmites karka* has great potential as a phytoremediation agent in the management of industrial wastewater or gold mining activities contaminated with mercury, while also being able to reduce the levels of other organic pollutants. The application of the plant-based biofiltration method that we manage has the potential to be developed further, such as in artificial wetland systems where community wastewater is managed in fisheries and other areas. However, this study requires more critical monitoring of the resilience of the plants we develop, which have high mercury exposure, to ensure safe and sustainable implementation. Furthermore, the management of biomass that absorbs more mercury must be carried out in a truly safety-oriented manner, such as controlling the combustion process, stabilization, and conversion to biochar to prevent further contamination. Consideration needs to be made considering the importance of implementing phytoremediation technology that considers safety and sustainability, environmentally friendly, to maintain the sustainability of ecosystems, both aquatic and other, from the impacts of mining. *Phragmites karka* offers a sustainable, low cost, and environmentally friendly solution for mercury-contaminated water treatment in post mining areas. However, proper management of harvested biomass such as stabilization or conversion into biochar is essential to prevent secondary contamination and ensure safe disposal.

Conclusions

This study demonstrated the potential of Parupuk (*Phragmites karka*) as an effective agent for reducing mercury (Hg) levels in gold mining wastewater, achieving an 89.11% decrease from 0.0404 mg/L to 0.0044 mg/L over a 9-day period. While the final concentration approached the permissible limit defined by Regulation No. 5 of 2022 (0.005 mg/L), its proximity to the threshold warrants cautious interpretation. Given the potential variability due to environmental or operational factors, the observed compliance should not be overstated. Additional studies and experimental replications are recommended to confirm the robustness and reproducibility of this phytoremediation approach under varying conditions.

Author Contributions

LN: Conceptualization, Methodology, Investigation, Writing - Review & Editing; **AS:** Writing - Review & Editing; **MAA:** Writing - Review & Editing; **HAS:** Writing - Review & Editing.

AI Writing Statement

The authors did not use any artificial intelligence assisted technologies in the writing process.

Conflicts of Interest

There are no conflicts to declare.

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