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COMPARATIVE STUDY OF SURFACE AND SUBSURFACE FLOW CONSTRUCTED WETLANDS FOR TREATMENT OF GOLD MINE WASTE ROCKS LEACHATE WATER

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ABSTRACT

The mining industry poses significant environmental challenges, particularly in relation to the generation of mine waste rocks and leachate water. These waters contain low pH and elevated metals, making them difficult to manage. Constructed wetlands (CW) have emerged as a promising technology for the treatment of industrial wastewater due to their cost-effectiveness, low energy consumption, and minimal maintenance requirements. This study aimed to investigate the use of surface flow (SFCW) and subsurface flow (SSFCW) for potentially treating mine waste rock leachate water from gold mines. Both types of CW were planted with *Pennisetum purpureum*, and the results showed that the SSFCW had better performance in terms of metal removal, reduced the levels of metals such as Fe, Zn, and Cu from 48 mg/L to 8.16 mg/L (Fe), 9 mg/L to 2.52 mg/L (Zn), and 3.5 mg/L to 0.99 mg/L (Cu), respectively. This translates to a removal efficiency of 83%, 72%, and 71.7%, respectively. On the other hand, the SFCW achieved a removal efficiency of only 31%, 36%, and 22%, respectively. These results clearly show that the use of SSFCW planted with *P. purpureum* is a promising technology for treating gold mine waste rock leachate water during and after mine closure.

Keywords: Constructed wetland, mine leachate water, metals, surface and subsurface flow constructed wetland, mining

1. INTRODUCTION

Mining activities involving the generation of various mine wastes, such as waste rocks and tailings, can lead to the production of mine drainage, including acid mine drainage (AMD). This solution contains highly toxic contaminants and poses a threat to the environment [1]. AMD is a byproduct of mining activities and often contains heavy metals that can have a detrimental impact on the environment if proper measures are not in place.

The management of mine waste is one of the component of sustainable mining practices of which reduce the impact to environment [2]. In the past various treatment methods were implemented but there is needed on the sustainable management of mining waste [3]. Wetlands are now attracting attention from many countries worldwide as an effective remediation technology for treating wastewater [4]. Some African countries have already started using constructed wetlands (CWs), specifically the Subsurface Flow Constructed Wetland (SSFCW), which has been shown to improve water quality and is cost-effective compared to mechanical wastewater treatment methods [5], [6]. As compared to SFCWs, SSFCWs are highly effective in removing organics, suspended solids, and heavy metals [7]. In addition, in tropical regions where developing countries are concentrated, climatic conditions are favorable for implementing SSFCWs [8]. When it comes to treatment efficiencies, SSFCWs have higher removal rates, but the cost for SFCWs is lower. Similarly, the land required for SSFCWs is also lower [9]. A CW is an artificial shallow basin filled with substrate such as soil, gravel, and plants [10], [4]. CWs are divided into two categories: surface flow (SF) and subsurface flow (SSF) [11]. In SF, water is exposed to atmospheric pressure, while in SSF, the water level is maintained below the surface of the gravel or other media [12]. However, the choice of CW type depends on the existing environmental conditions and the appropriateness for wastewater treatment[4].

The use of constructed wetlands (CW) for the treatment of wastewater containing heavy metals has been widely studied. Some studies [13] have reported that the removal efficiency in CW can vary greatly depending on the concentration levels. In a study by [14], it was suggested that Zn and Cu removal in SF was >90%, while other studies [15] reported that Zn removal was <60%. When selecting between SF and SSF CW, SFCW is the best option in terms of construction and also provides a more diverse habitat for wildlife. However, SF requires more land than SSF [15]. In terms of removal efficiency, SF wetlands are best suited for treating wastewater containing net alkalinity, as they can neutralize metal acidity and facilitate metal precipitation [16]. The removal mechanisms in both SF and SSF involve supporting metal oxidation and hydrolysis in aerobic surface layers, as well as chemical reduction reactions in the subsurface layers. The treatment in SSF can be further enhanced by the formation and precipitation of metal sulfides [15], [16]. Generally, the removal efficiency in CW systems, both SF and SSF, has been well-discussed by [17], who clearly discussed both abiotic and biotic mechanisms. Abiotic mechanisms include settling/sedimentation, sorption, and chemical oxidation, while biotic mechanisms involve aerobic/anaerobic biodegradation, phytoaccumulation, phytostabilization, photodegradation, rhizodegradation, and phytovolatilization [17]. CW can work with both vascular plants (higher plants) and nonvascular plants (algae). These plants act as the main trapping and retention points for contaminants [18]. Studies have indicated the presence of high concentrations of contaminants within the root systems of most wetland vegetation [19]. In the study by [20], the use of *Pennisetum purpureum* plants in the treatment of industrial wastewater was reported, and it was observed that the plant removed the highest amount of metals. Wetland plant *P. purpureum* was reported to grow quickly and be durable against environmental conditions [21].

For the enhancement of sustainability in wastewater management, the use of constructed wetlands (CW) has been implemented for the treatment of various forms of wastewater, except for mine water [22], [4]. Other researchers have also acknowledged that there is no single universal remediation method suitable for all types of contaminants, therefore, the implementation of two or more methods is critical [23], [4]. The aim of this study was to compare the efficiency of using surface and subsurface flow constructed wetlands for the treatment of gold mine waste rock leachate water.

2.0 MATERIALS AND METHODS

2.1. Materials collection

Mining waste rocks weighing 30 kg were collected from small-scale miners in Tarime, Tanzania. A container with a capacity of 80 liters was used to construct a wetland, and it was filled with 50 liters of tap water to achieve the required mixing with the leachate water from the gold mine waste rocks for the experimental setup. The substrate used in the SSFCW was obtained from the local market in Dar Es Salaam. For this study, *P. purpureum*, a plant that can tolerate harsh conditions, was selected.

2.2 Experimental set up and operation of SF and SSFCW

As Constructed wetland, this study used a slope of 0.5 to 1% as is recommended for ease of construction and proper draining [24]. The dimensions of both SF and SSFCW were as follows: a length of 0.9m. width of 0.3 m with a height of 0.172m, and a flow rate of $1.16\text{x}10^{-6}\text{m}^3/\text{s}$ in each treatment unit. The operational factors, such as flow rate, play a significant role in the pollutant removal efficiencies of CWs, as they affect the hydraulic retention time [25]. In this study, the design criteria used for improving removal efficiencies in the CW were adopted from [26], which recommends an aspect ratio of length to width of 4:1 or less. There were four treatments in total: one containing mine water leachate with only plants (SSF), one without plants (control for SF), one with plants and gravel as the media (SSF), and one with plants and mine water leachate (control for SSFCW) (Table 1). Each container received mine leachate water from an elevated tank, and the leachate then flowed into each wetland cell at a rate of 1.16x10$^-$

^{6}m^{3}/s. The gravel media in the SSFCW was used as a substrate to promote anaerobic conditions in the system.

Table 1: Treatment design

Treatment unit	Substrate	Plant
SFCW	NA	*P.purpureum*
SFCW - Control	NA	Without plant
SSFCW	gravel	*P.purpureum*
SSFCW	gravel	Without plant

2.3 Water sampling and analysis

Water samples were collected from the SF and SSF CW unit cells and sent to the environmental engineering laboratory at Ardhi University for laboratory analysis. The sampling exercises were taken for a period of eight weeks (56 days), during which water samples were collected and measurements were conducted each week. The pH and electrical conductivity were measured using the potentiometric method with Sension378. Zinc and copper were analyzed with AAnalyst 100 and a PerkinElmer Instrument (Atomic Absorption Spectrometer), while iron was analyzed using the 1-1-Phananthroline Method with a DR/4000U spectrophotometer.

2.4 Plant growth characteristics in SF and SSFCW

During the eight weeks of the experiment, the growth of plants was measured on a weekly basis in both the SF and SSF CW to observe any differences in growth.

2.5 Calculation and statistical analysis

Removal percentage of heavy metals from mine leachate water was calculated as follows: %Removal = (Co-Ce)/Co × 100, where Co is the initial concentration and Ce is the final concentration of the heavy metal parameter in the mine leachate water. The unit of this calculation is a percentage. Treatment efficiencies were tested using ANOVA and the differences between means were tested using the Least Significant Difference (LSD) test in the SPSS statistical program.

3.0. RESULTS

3.1. Gold mine waste rock leachate water characterization

In Table 2, the physical and chemical characteristics of leachate water from gold mine waste rock are presented. The quality of water leached from gold mine waste rock is observed to have a low pH of 5.2. Additionally, high levels of Zn (9 mg/L), Fe (48 mg/L), and Cu (3.5 mg/L) were observed. This study highlights the water quality of leachate from gold mine waste rock, with the concentration levels in the following order: Fe>Zn>Cu. The electrical conductivity of leachate from mine waste rock was measured at 1259 µs/cm.

Table 2: Physical and chemical properties of the leachate water from gold mine waste rocks

Parameter	Units	Value
pH		5.2
Ec	µs/cm	1259
Fe	mg/L	48
Zn	mg/L	9
Cu	mg/L	3.5

3.2. Plant growth characteristic in surface flow and subsurface flow constructed wetlands

Growth characteristics were measured using height for about 8 weeks and results are presented in Figure 1. In the treatment units, the height of P. purpureum in the SFCW showed to be lower compared to the SSFCW. The total height of the plant after 8 weeks of the experiment was 98 cm in the SSFCW and 67 cm in the SFCW.

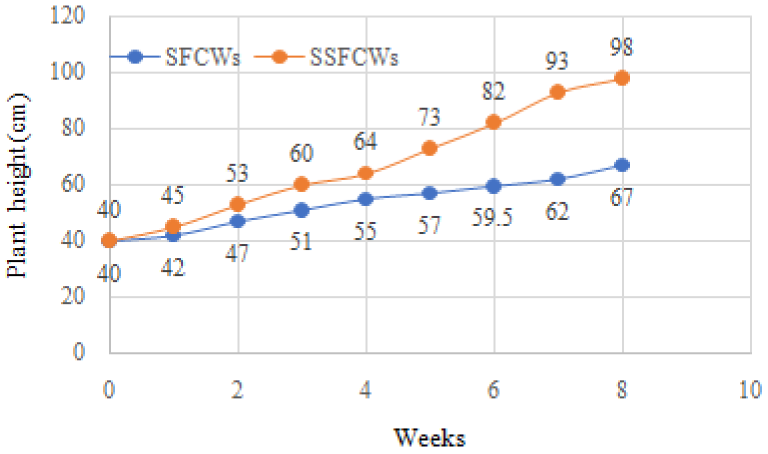
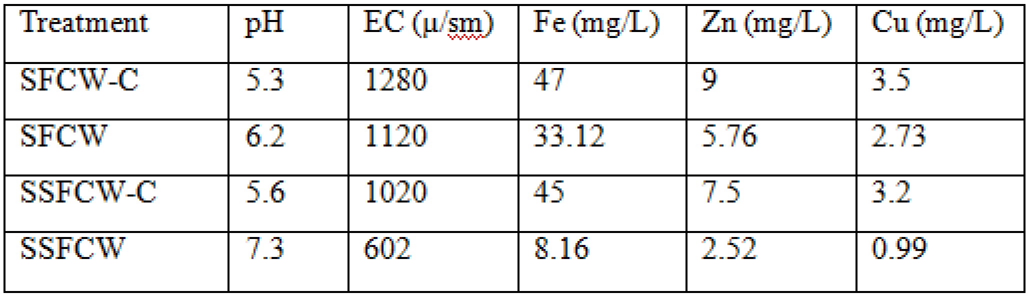


Figure 1: Plant growth of *P. purpureum* in the SFCW and SSFCW during treatment of mine leachate water

3.3. Performance of SFCW and SSFCW in the treatment of leachate water from gold mine waste rock.

The results of SFCW and SSFCW for physicochemical parameters are presented in Table 3. In SSFCW, the pH was higher compared to SFCW, with an increase to 7.3. Additionally, heavy metals were significantly reduced, with iron decreasing to 8.16 mg/L, zinc to 2.56 mg/L, and copper to 0.99 mg/L (Table 3). Figure 2 shows the removal efficiency in treating gold mine waste rock leachate water. The results indicate that Fe, Zn, and Cu were removed in the following order: Fe>Zn>Cu. There was an increasing trend in removal for all metals from week 1 to week 8 (Figure 2). Based on the metal removal, ANOVA tests were used to compare the effectiveness of SFCW and SSFCW. The results showed that SSFCW performed better than SFCW with a p-value of 0.004 for Fe, 0.025 for Zn, and 0.022 for Cu (Tables 4, 5, and 6). These results confirm that there is a statistically significant difference between SFCW and SSFCW.

Table 3: Performance of SFCW and SSFCW for treating gold mine leachate water after 8 weeks



Treatment	pH	EC (μ/sm)	Fe (mg/L)	Zn (mg/L)	Cu (mg/L)
SFCW-C	5.3	1280	47	9	3.5
SFCW	6.2	1120	33.12	5.76	2.73
SSFCW-C	5.6	1020	45	7.5	3.2
SSFCW	7.3	602	8.16	2.52	0.99

Table 4: One-way ANOVA Calculation for Iron Removal in SF and SSFCW

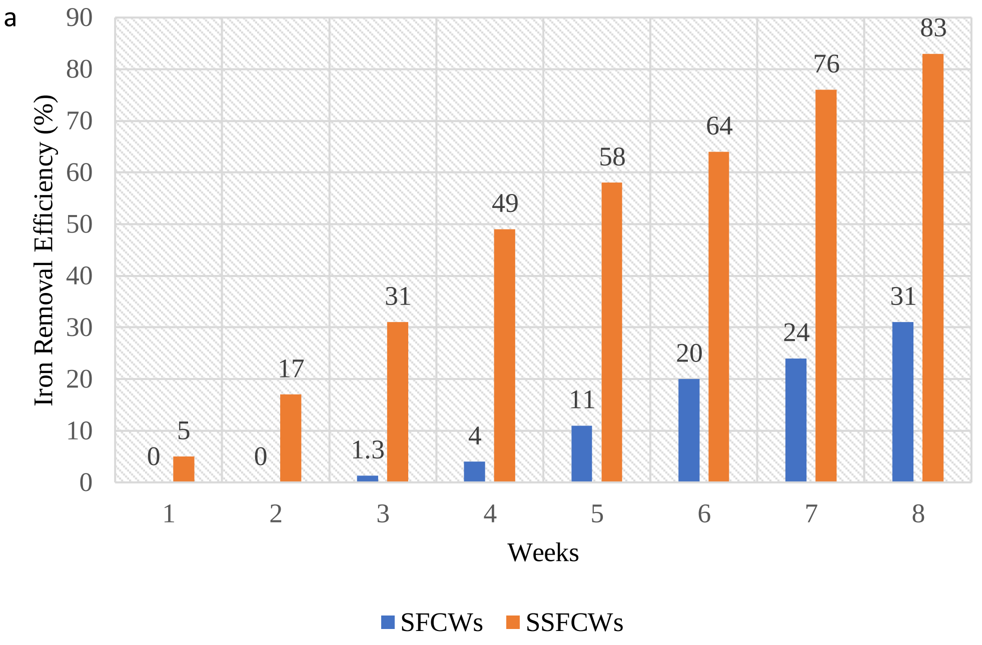
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1223.6	1	1223.6	11.44809	0.004457	4.60011
Within Groups	1496.354	14	106.8825			
Total	2719.955	15				

Table 5: One -way ANOVA Calculation for Zinc Removal in SF and SSFCW

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	21.48323	1	21.48323	6.217477	0.025789	4.60011
Within Groups	48.37415	14	3.455296			
Total	69.85738	15				

Table 6: One -way ANOVA Calculation for Copper Removal in SF and SSFCW

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2.410256	1	2.410256	6.559301	0.022624	4.600109937
Within Groups	5.144388	14	0.367456			
Total	7.554644	15				



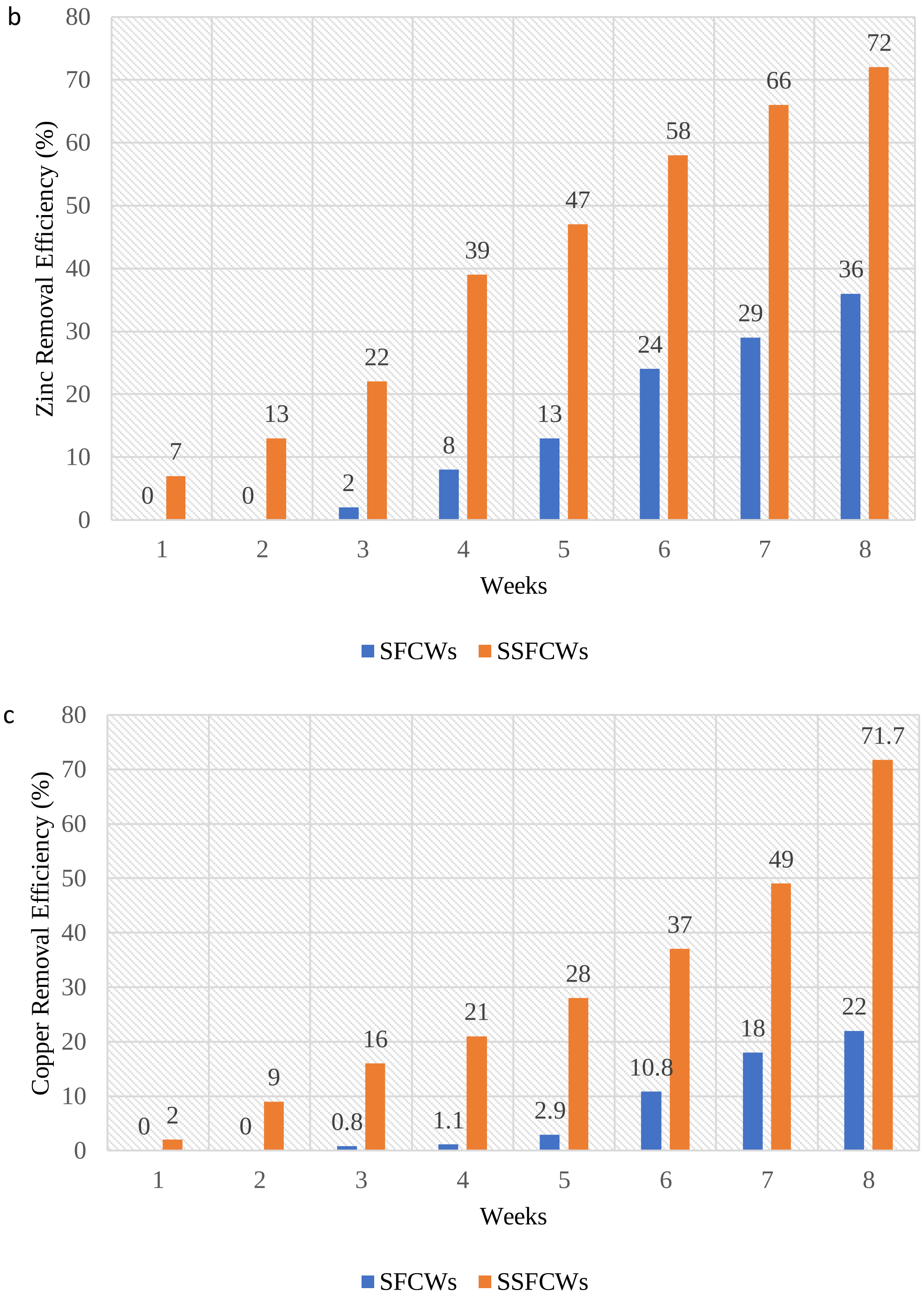


Figure 2: Removal efficiency; (a) iron (b) zinc (c) copper

4. DISCUSSION

4.1 .Mine waste rock characterization

The results obtained from this study showed that the mine waste rock was leached with mine drainage of low pH and elevated levels of heavy metals (Table 2). Other studies have also reported similar results [27]. In addition, the study by [28] on mine drainage reported a pH range of 5.9 to 5.5, an electrical conductivity of 3600 µs/cm, and a metal (Zn) concentration of 11 mg/L

4.2. Plant growth characteristics

P purpureum, commonly known as napier grass, is a fast-growing tropical grass, in this study observed to reach up to 1 meter in just two months (Figure 1). This plant has many advantages for biomass generation when compared to other plants [29]. A study by [1] reported that this plant is highly productive in terms of biomass and has a high tolerance for heavy metals, particularly copper and its robust rhizomatous root system makes it well-suited for phytoremediation. Additionally, *P. purpureum* has a high ability to accumulate high levels of pollutants [29].

4.3. SFCW and SSFCW treatment performance

This study observed that surface flow CW increased the pH from 5.3 to 5.6, as compared to SSFCW, which showed improved leachate water quality with a high pH (7.3) level, nearly neutral. This result was aligned with [30], who reported a similar increase in the pH of mine water using SSFCW up to 7.22. The increase in pH in the SSFCW can be associated with organic decomposition within the cell of the SSFCW and the anaerobic conditions that favor the growth of anaerobic bacteria to break down organic material, causing an increase in organic carbon. Additionally, the leaching of gravel, in the form of calcium carbonate, may also play a role in increasing the pH in the SSFCW. However, other studies have reported that the leaching of potential impurities, such as calcium and magnesium carbonates present in the quartz gravel, can influence the increase in alkalinity in the constructed wetland [31].

This study also observed a significant decrease in heavy metal concentration from its initial levels. For example, zinc levels were reduced from 9 mg/L to 2.56 mg/L, and copper levels went down from 3.5 mg/L to 0.99 mg/L in the SSFCW treatment. In a similar study by [32], they used *P. Puerperium* plant in the SSFCW and found that the plant had a high uptake of zinc, suggesting that it could be placed near mine wastes to effectively remove zinc. In another study, [33] applied SSFCW for heavy metal removal and reported that the removal efficiency was in the order of Cd>Pb>Zn>Cu. This trend is consistent with the results of this study, where zinc and copper removal were in the order of Zn>Cu (Figure 2b and 2c).Other studies [34] have reported the performance of SSFCW with a metal removal efficiency of 74.1% for Fe and 48.3% for Cu. However, in this study (Figure 2a), the SSFCW showed a higher Fe removal efficiency of 83%, compared to 31% in the SFCW. Similarly, the Cu removal efficiency was significantly higher in the SSFCW (71.7%) compared to the SFCW (22%). Overall, the removal efficiency trend for Fe>Zn>Cu was observed, which is consistent with the findings of [35]. They reported a higher Fe removal rate in the CW compared to other heavy metals, and attributed it to co-precipitation mechanisms. However, in the study conducted by [30], there was reported inconsistency in the treatment performance of SSFCW, with a trend of Fe>Cu>Zn. Additionally, a study by [36] revealed that using mine water with SSFCW resulted in higher removal efficiencies for Zn compared to SFCW. The performance results of SFCW and SSFCW indicated different characteristics in treatment performance. In this scenario, the results obtained showed lower treatment performance in SFCW compared to SSFCW. [16] Suggested that the use of SFCW is more convenient for wastewater that contains net alkalinity, and it can treat more wastewater because its construction does not require more media within the cell, leaving more space to contain wastewater [15]. The difference between SFCW and SSFCW was also reported by [37], who noted that the co-existence of aerobic and anaerobic conditions, as well as the longer hydraulic retention time in SSFCW, enhanced performance. The removal performance in SSFCW was also contributed by both abiotic and biotic factors in the wetland system. This is because SSFCW has a larger area for sorption, such as gravel media, compared to SFCW, which lacks any media for sorption. This study is in line with previous research [38] that recommend higher removal of metals in SSFCW due to abiotic removal mechanisms such as sorption and photo degradation. Abiotic mechanisms involve sorption materials binding or transferring contaminants to physical surfaces. Additionally, other studies [39] have shown that relying solely on abiotic factors may be insufficient and suggest combining them with biotic factors for more effective removal. In this study, both abiotic and biotic factors were applied in SSFCW (Table 1). The results obtained from the ANOVA test also showed a significant difference between SFCW and SSFCW in terms of pollutants removal from leachate water of a gold mine waste rock.

CONCLUSION

The aim of this study was to compare the effectiveness of Subsurface Flow Constructed Wetlands (SSFCW) and Surface Flow Constructed Wetlands (SFCW) in treating leachate water from gold mine waste rock. The results showed that SSFCW had a significantly higher treatment efficiency compared to SFCW. The system was able to increase the pH of the leachate water from 5.2 to nearly neutral (7.3) with a percentage improvement of 63.9%. Additionally, the levels of metals such as Fe, Zn, and Cu were also significantly reduced by 83%, 72%, and 71.7%, respectively. These findings demonstrate the potential and feasibility of using SSFCW as a treatment option for leachate water from gold mine waste rock. Further studies should be conducted to explore the potential of combining SSF and SF CW systems, as well as optimizing plant species and various substrates, to enhance the treatment efficiency of gold mine waste rock leachate water.

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