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Performance of vetiver grass and aeration on chemical oxygen demand, total nitrogen, and total phosphorus removal from surface water of the Chiang Mai moat

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ABSTRACT

The polluted water of Chiang Mai's iconic moat negatively impacts the city's image, affecting perceptions among both residents and visitors. Furthermore, contamination of the moat poses significant risks to public health, underscoring the urgent need for cost-effective and sustainable remediation strategies. To achieve this goal, the implementation of bio-phytoremediation, using vetiver grass (*Chrysopogon zizanioides* L. Roberty), was proposed as a promising solution to this problem. This study aimed to assess the effectiveness of vetiver grass, in combination with aeration, for removal of chemical oxygen demand (COD) and nutrients from the moat's water. Water samples collected from the moat were used in experimental setups, where hydroponically grown vetiver grass was cultivated on floating platforms, with some setups incorporating aeration and others without. A control group without vetiver platforms or aeration was also included. The results obtained demonstrated that the combination of vetiver grass and aeration yielded the highest removal efficiencies, achieving 96.38% COD removal (kCOD = -5×10^{-4} h^{-1}), 91.57% NH_3-N removal, and 70.59% total nitrogen (TN) removal (kTN = -0.115 h^{-1}). Total phosphorus (TP) removal efficiency was approximately 70% for both the vetiver platform with aeration, and the vetiver platform alone (kTP = -1×10^{-4} h^{-1}). This study demonstrates the potential of vetiver grass as an effective bio-phytoremediation agent for the treatment of urban surface water. Implementing this approach in Chiang Mai's moat could improve the city's appearance, protect public health, promote sustainable water management, and do so in a cost-effective manner.

Keywords: vetiver grass; bio-phytoremediation; nutrients treatment; eutrophication; Chiang Mai moat

1. INTRODUCTION

Chiang Mai's old city, surrounded by a rectangular moat, is a famous tourist destination adored for its distinctive identity and scenic recreational areas (Figure 1a). The vicinity of the old city and the Chiang Mai moat is home to many communities and commercial establishments, such as markets and street food restaurants. Unfortunately, the moat has inevitably become a recipient of wastewater from these activities and communities for decades. It frequently experiences stagnant conditions, resulting in a lack of continuous flow. Stagnant water leads to the accumulation of organic and inorganic sediments, including leaves, debris, silt, and soil particles. The stagnant conditions also promote the accumulation of excessive soluble nutrients, leading to eutrophication and algae blooms (Figure 1b).

In a collaboration with the Chiang Mai municipality, the water quality of the moat was closely monitored and analyzed. The monitoring results indicated that the surface water falls within categories 3–4 (moderately polluted), rendering it unsuitable and unsafe for various uses. This status fails to achieve the city's target of category 2 (good) water quality. Eutrophication is common at sampling sites near Chaeng Hua Rin, where water circulation is limited. The measured parameters indicated a pH of 8.1 and a chemical oxygen demand (COD) of 2,145 mg/L, which far exceeds the maximum level concentration (MLC) for surface water from the irrigation canal (100 mg/L), total nitrogen (TN) was recorded at 9.52 mgN/L, ammonia nitrogen (NH_3-N) at 0.84 mgNH_3/L, and total phosphorus (TP) at 0.57 mgP/L. Although TN and TP level do not surpass MLC standards, they exceed the nutrient thresholds that support good ecological status (0.40–1.40 mgN/L for TN and 0.009-0.073 mgP/L for TP), which could lead to eutrophication (Poikane et al., 2022). The concentration of chlorophyll A, an indicator of eutrophication, was found to exceed 10 µg/L. Comparatively, another study reported 3.23–19 µg/L (Guo et al., 2018).

While several methods can be used to improve water quality in the moat, such as the addition of chlorine, as well as the planting of water hyacinth and lotuses (City News, 2018; Sattha, 2013), this study seeks to evaluate the efficacy of employing vetiver grass (*Chrysopogon zizanioides* L. Roberty) as a bio-phytoremediation, which is a nature-based solution. Specifically, the study assesses the performance of vetiver grass and aeration in mitigating contaminants including COD, NH_3-N, TN, and TP, present in water samples collected from the surface of the Chiang Mai moat.

Vetiver grass (*Chrysopogon zizanioides* L. Roberty) is a highly versatile plant, renowned for its deep root system and ability to thrive in diverse conditions with minimal maintenance or management requirements. Its robust root structure enhances soil stabilization, prevent erosion, and facilitates pollutant absorption, making it an ideal choice for introducing bio-phytoremediation in urban waterways like the Chiang Mai moat. In environments with poor water quality and limited human resources for regular upkeep, vetiver grass offers sustainable and practical solution. Bio-phytoremediation using vetiver grass is recognized as a cost-effective and high-performance approach for removing both inorganic and organic substances from water. This method is simple to implement and suitable even for remote areas, and does not cause environment disruptions (Jeevanantham et al., 2019). Numerous studies have demonstrated the significant potential of vetiver grass in treating polluted water, showcasing its sufficient removal capacity and high tolerance towards various toxic organic and inorganic pollutants (Phenrat et al., 2017; Teeratitayangkul et al., 2019).

The objectives in this study were to evaluate the effectiveness of bio-treatment on surface water and develop a sustainable water management technique that can be directly implemented in the real-world context of the moat.

(a) (b)

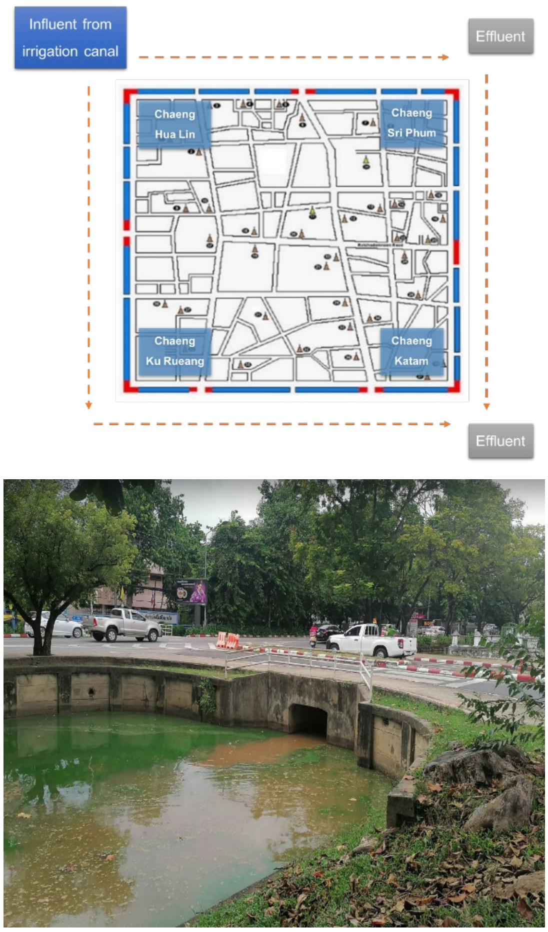

Figure 1. (a) Chiang Mai moat and (b) eutrophication effect

2. MATERIALS AND METHODS

2.1 Experimental design and operation of the experiments

All batch experiments were conducted in a laboratory, at room temperature (31±1°C). Vetiver grass (*Chrysopogon zizanioides* L. Roberty), the Surat Thani ecotype, was used for this study. Prior to experimentation, 50 vetiver grass plants were hydroponically cultivated in coconut dust, serving as the adhesion medium, for approximately 4 weeks on floating platforms before being transferred to the water sample (Figure 2). Robust vetiver grass with a survival rate of 95% exhibited root with an average length of 25.24 ± 8.58 cm, covered by a thin biofilm. Most leaves displayed a greenish coloration, and reached a similar height of 25.24 ± 8.58 cm. The experimental setup consisted of 4 systems: experiment 1 served as the control, without a vetiver platform and aeration (Exp. 1); experiment 2 included aeration (Exp. 2); experiment 3 combined a vetiver platform with aeration (Exp. 3); and experiment 4 utilized a vetiver platform (Exp. 4). Aeration was provided using ceramic diffusers, supplying air at a rate of 15 L/min.

The initial chemical parameters of the water sample (n = 4) were as followed: COD 3,360 ± 57 mg/L, TN 9.52 ± 1.02 mgN/L, NH_3-N 0.87 ± 0.12 mgNH_3/L and TP 0.0865 ± 0.03 mgP/L.

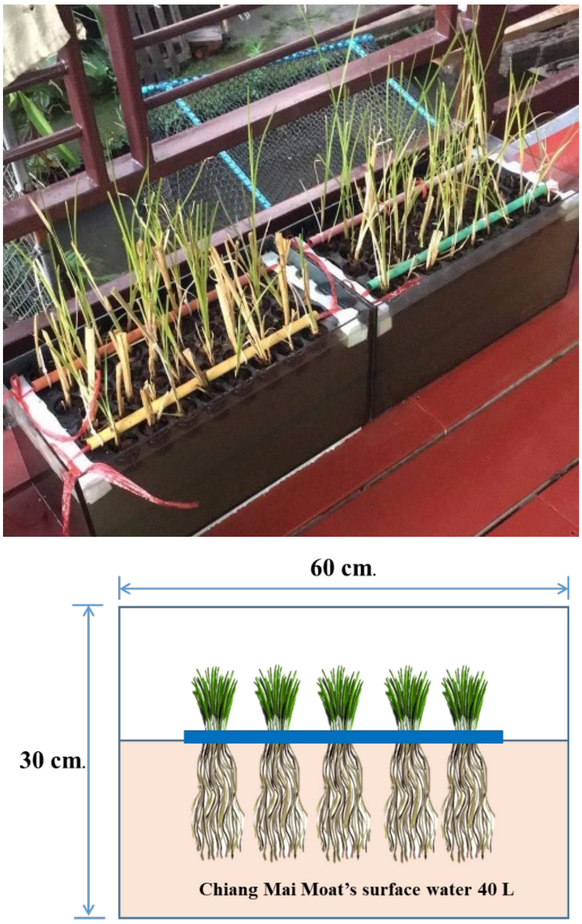

Figure 2. Schematic diagram of vetiver platforms in the experiments

2.2 Water sampling and analysis

Weekly composite water samples were collected from each batch experiments. The samples were prepared and subjected to physicochemical parameter analysis, in accordance with the established protocols of the American Public Health Association (APHA) (Rice et al., 2012). The characterization and performance evaluation of the samples involved determining various parameters based on the standard methods for water and wastewater examination. Specially, TN was measured using the Kjeldahl test; NH_3-N was analyzed via distillation methods; TP was determined using the ascorbic acid colorimetric method; and COD was assessed using the closed reflex method. Temperature and pH measurements were conducted during sample collection, using a digital thermometer and a pH meter, respectively. We purposely utilized water from the Chiang Mai moat to conduct the experiment and assess the efficacy of using vetiver grass as a nature-based solution to enhance the water quality of the moat.

While the initial experiments were conducted under controlled laboratory conditions that mimic the moat, we recognize that conducting similar experiments in the moat itself may yield different results. This disparity might be attributed to additional factors and complexities inherent in the natural environment, such as variations in water flow, nutrient levels, and interactions with other organisms.

2.3 Data analysis

The experiments were continued until the COD concentration in at least one of the four systems was below the maximum contamination level (MCL) of 100 mg/L. Removal rates were calculated assuming first-order kinetics, and were fitted using non-linear regression, as shown in Equation (1) (Phenrat et al., 2017; Teeratitayangkul et al., 2019). The removal rates of nutrients, including TN and TP, were determined using linear correlation regression, as shown in Equation (2). Pollutant removal efficiency, expressed as a percentage, was calculated using Equation (3) (Seroja et al., 2018).

$$C_t = C_0\, e^{-kt} \quad (1)$$

$$C_t = -kt + C_0 \quad (2)$$

$$\text{Removal efficiency (\%)} = 100 - (C_0 - C_t / C_t) \times 100 \quad (3)$$

where C_t and C_0 are COD concentration by time t and the initial time (0 h), k is the reaction rate coefficient (in units of 1/time), and t is the unit of time in h.

3. RESULTS AND DISCUSSION

The treatment units exhibited a range of values for pH, temperature, and conductivity in water sample. Specifically, pH values ranged from 4.86 to 8.85, temperature ranged from 26°C to 37°C, and conductivity values ranged from 1,914 to 7,836 µS/cm. These observed ranges for pH and temperature fell within the recommended operating conditions for optimal macrophytes performance (pH 4–9; temperature 15–38°C) (Shah et al., 2014; Sitarska et al., 2023; Tan et al., 2023). During the 3-week (approximately 500 h) experimental period, the vetiver grass on the platforms (Exp. 2 and Exp. 4) survived, although signs of moderate stress such as mild chlorosis and drying leaf tips were observed.

3.1 COD removal

Exp. 1 to Exp. 4 initially had a COD concentration of 3,146 mg/L. The treatments were carried out until each experiment reached the MLC of 100 mg/L, as stipulated by the Royal Irrigation Department's water quality order 73/B.E. 2554. The removal rates of COD in the experiments were fitted to a first-order kinetics regression (Eq. 1) (Figure 3). Figure 3 and Table 1 display the COD removal rate (kCOD) for the various treatment systems. The highest performance observed in Exp. 3, with combined the vetiver platform with aeration, followed by Exp. 2 (aeration only), Exp. 4 (vetiver platform only), and Exp. 1 (control). The corresponding kCOD values were -7×10^{-3} h^{-1}, -5×10^{-3} h^{-1}, -4×10^{-3} h^{-1}, and -3×10^{-3} h^{-1}, respectively, resulting in COD removal efficiencies of 96.88%, 90.03%, 87.13%, and 73.38%, respectively.

When comparing the experiments with aeration (Exp. 2 and Exp. 3), it is evident that both systems exhibit similarly high COD removal efficiencies of 90.03% and 96.88%, respectively. This similarity can be attributed to aerobic microorganism degradation, where organic pollutants are utilized as a carbon source, with the support of aeration. However, it is important to consider the kCOD values in both experiments. The removal rate in Exp. 3 was 1.5 times faster than in Exp. 2. Previous research demonstrated that plants can utilize nutrients in water for the growth of leaves, roots, and stems through complex mechanisms. Phytodegradation involves the direct degradation of organic pollutants, release of enzymes from roots, and metabolic activities within plant tissues, including peroxidase, nitroreductases, glycosyl and glutathione transferases, phosphatases, nitrilases, and dehalogenases. Moreover, plant roots serve as hosts for rhizomicrobial and other planktonic microorganisms (Akansha et al., 2020; Lakshmi et al., 2017). The synergistic interaction between plants roots and microorganisms, especially under aerobic conditions, can thus significantly accelerate COD removal. Therefore, the observed increase in COD degradation rate in Exp. 3 is likely attributed to the combined effects of vetiver roots and acclimated microorganisms, which have adapted to the COD-rich environment.

Exp. 4, which involved the vetiver platform without aeration, demonstrated a 87.12% COD removal efficiency, with a COD removal rate of -4×10^{-3} h^{-1}. It was observed that the growth of vetiver grass on the platform remained stable but gradually declined. After two weeks of treatment, the leaves and roots became slightly brownish, compared to those in the system with aeration. This deterioration can be attributed to the lack of aeration, as it supports the growth of plants and microorganisms. Additionally, organic pollutants and nutrients settle down or remain stagnant without aeration. This finding aligns with Mahmoudpour et al. (2021), who concluded that an aerated vetiver platform achieved higher COD removal efficiency than a non-aerated vetiver platform. It is essential to remark the maturity of vetiver grass, with the optimal age being around 2 to 3 weeks (Teeratitayangkul et al., 2019).

The control system in Exp. 1, which lacked both a vetiver platform and aeration, exhibited a COD removal efficiency of 73.38%, with a removal rate of -3×10^{-3} h^{-1}. This removal can likely be attributed to the biotransformation activities of indigenous microorganisms present in the water, as well as natural process such as photolysis and hydrolysis (Acuña et al., 2015; Arunkumar & Soundarapandian, 2017).

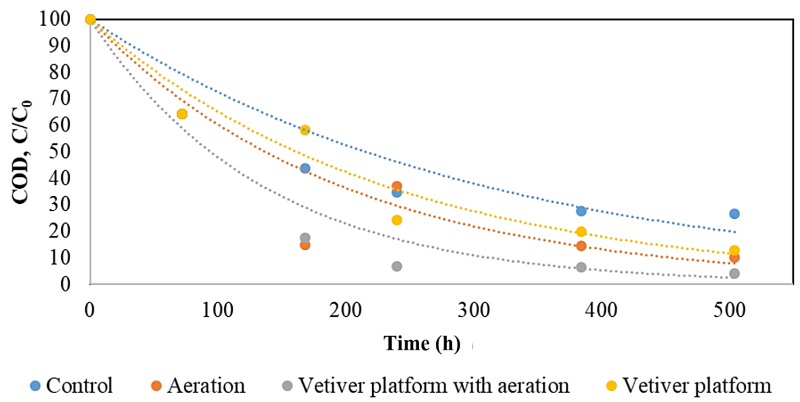

Figure 3. Removal of COD concentration relative in 4 experiments: control, aeration only, vetiver platform with aeration, and vetiver platform only

Table 1. Kinetic fitting of COD removal in the experiments: control, aeration only, vetiver platform with aeration, and vetiver platform only

Experiment	COD concentration (mg/L)		k_{COD} ($\times10^{-3}$ h^{-1})	r^2	%COD removal efficiency
	T = 0 h	T = 500 h			
1. Control	3,146	837	3	0.7744	73.39
2. Aeration only	3,146	313	5	0.7158	90.05
3. Vetiver platform with aeration	3,146	114	7	0.8532	96.38
4. Vetiver platform only	3,146	405	4	0.9314	87.12

3.2 Nitrogen removal

The nitrogen removal efficiencies of the 4 experiments (Table 2), indicated that Exp. 3 achieved the highest removal percentages for both NH_3-N and TN, with values of 91.57% and 70.59%, respectively. This was followed by Exp. 2, Exp. 4, and Exp. 1 over the experimental period. Several studies have reported that treatments using plants generally exhibit higher nitrogen removal efficiency than treatments without plants, highlighting the beneficial role of plants in nitrogen removal (Panja et al., 2020; Xinjie et al., 2019). The potential reduction of NH_3-N and TN can be attributed to the combined effect of phytoremediation and aeration. Vetiver grass can absorb and accumulate TN within its biomass. For example, in the Surat Thani ecotype, TN accumulation in shoots and roots ranged from 2.765 to 5.985 mg/g dry weight, and from 6.860 to 8.133 mg/g dry weight, respectively (Boonsong & Chansiri, 2008).

Nitrogen removal occurs via nitrification and denitrification mechanisms, both of which are influenced by the presence of aeration. Nitrification primarily takes place in oxygen-rich environment, while denitrification typically occurs when sufficient oxygen is available (Pongthornpruek, 2017; Srb et al., 2022). A continuous supply of oxygen enhances the metabolic activity microorganisms, thus enhancing nutrient removal. as demonstrated in Exp. 3. Chen et al. (2018) reported that increasing the aeration rate, or extending the aeration duration, can improve efficiency of nitrogen and phosphorus removal in wastewater treatment processes. By contrast, the performance of vetiver grass without aeration resulted in a TN removal efficiency of 52.94%. This finding is consistent with the TN removal efficiency reported for vetiver grass cultivated with the floating platform technique in domestic wastewater treatment, which ranged from 29% to 49%, by Boonsong and Chansiri (2008). In Exp. 1, the control experiment, the reduction of NH_3-N and TN could be attributed to indigenous microorganisms present in the water sample.

As shown in Figure 4a, the TN removal rates in all experiments were evaluated using linear regression. The analysis indicated a linear correlation between the experiment period and TN concentration ($r^2 = 0.72–0.90$). The rate constants for TN removal were 0.0115 h^{-1}, 0.0103 h^{-1}, 0.0100 h^{-1}, and 0.0076 h^{-1} for Exp. 3, Exp. 2, Exp. 4, and Exp. 1, respectively. These results indicate no significant difference in TN removal rates among the vetiver and/or aeration treatments over the experimental period, while the control (Exp. 1) showed a slower removal rate. On the other hand, the removal of NH_3-N in the treated experiments (Exp. 2, 3, and 4) was rapid during the first 150 h (Figure 4b). This could be explained by the utilization of NH_3-N by indigenous microorganisms and its adsorption onto vetiver roots. Consequently, NH_3-N gradually decreased as it was converted from TN through mineralization processes.

Table 2. Kinetic fitting of TN removal and NH_3-N removal in the control, aeration only, vetiver platform with aeration, and vetiver platform only

Experiment	TN concentration (mgN/L)		k_{TN} ($\times 10^{-4}$ h^{-1})	r^2	%TN removal efficiency	NH_3-N concentration (mg NH_3/L)		%NH_3-N removal efficiency
	T = 0 h	T = 500 h				T = 0 h	T = 500 h	
1. Control	9.52	5.04	76	0.7224	47.06	0.87	0.30	65.18
2. Aeration only	9.52	3.22	103	0.8954	66.18	0.87	0.13	85.35
3. Vetiver platform with aeration	9.52	2.80	115	0.8990	70.59	0.87	0.07	91.57
4. Vetiver platform only	9.52	4.48	100	0.9091	52.94	0.87	0.30	65.78

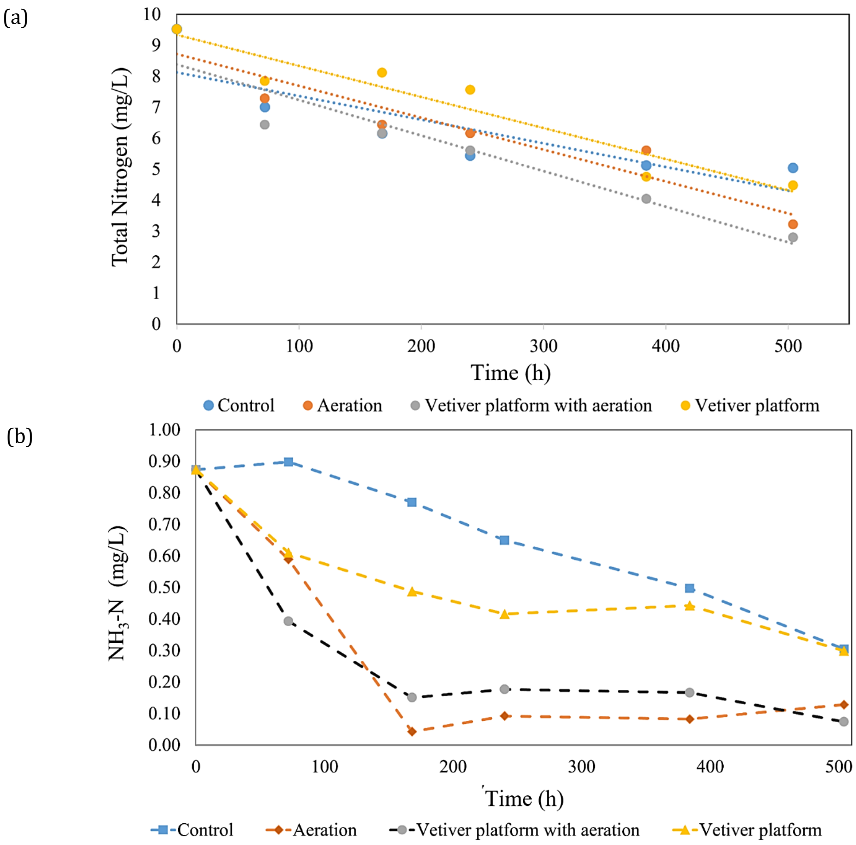

Figure 4. Removal of (a) TN and (b) NH_3-N concentration in 4 experiments setups: control, aeration only, vetiver platform with aeration, and vetiver platform only

3.3 Phosphorus removal

Phosphorus is a crucial nutrient necessary for the growth of all life forms. It plays a necessary role in various plant and animal metabolic reactions. However, high phosphorus concentrations can lead to excessive undesirable growth of aquatic plants, such as algae and waterweeds. The effectiveness of phosphorus removal depends on the treatment technologies employed, including biological reduction and chemical precipitation. These technologies aim to mitigate the presence of excessive TP in water bodies (Shah et al., 2014). Figure 5 depicts the removal of TP in Exp. 1 to Exp. 4.

The TP removal efficiencies in experiments with vetiver were significantly higher than those observed the control. The results demonstrated that vetiver could reduce TP levels by up to 70% in both Exp. 3 and Exp. 4 (Table 3), while TP removal efficiencies in the experiments without vetiver were 37–47%. The TP removal rate was analyzed using linear regression, showing a linear correlation between the experiment period and TP concentration (r^2 = 0.76–0.97). The TP removal rate (k_{TP}) ranged between -7×10^{-5} to -9×10^{-5} h^{-1} for vetiver-free experiments (Exp. 1 and Exp. 2), and -1×10^{-4} to -2×10^{-4} h^{-1} for vetiver experiments (Exp. 3 and Exp. 4). This suggests that the presence of vetiver notably increased the TP removal rate (Figure 5), with the kinetic rate constant in vetiver treatments (k_{TP} with vetiver/ k_{TP} without vetiver), being approximately 10 to 15 times higher than in those without vetiver. Although aeration was found to support the removal of COD and nitrogen in this study, it did not have the same effect on TP removal. It should be noted that excessive aeration can negatively impact the biological efficiency of TP removal, leading to a cessation of phosphorus uptake (Brdjanovic et al., 1998; Peng et al., 2006; Ma et al., 2022).

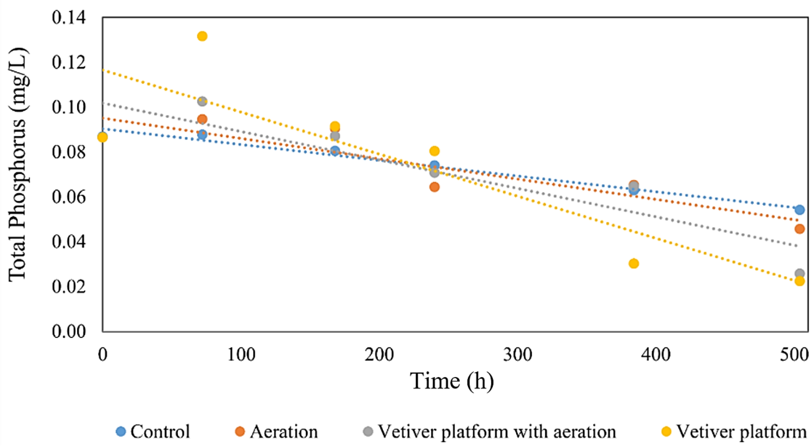

Figure 5. Removal of TP concentration in 4 experiments setups: control, aeration only, vetiver platform with aeration, and vetiver platform only

Table 3. Kinetic fitting of TP removal in experiments in the control, aeration only, vetiver platform with aeration, and vetiver platform only experiments

Experiment	TP concentration (mgP/L)		k ($\times10^{-4}$ -h)	r^2	%TP removal efficiency
	T = 0 h	T = 500 h			
1. Control	0.0865	0.0541	0.7	0.9745	37.67
2. Aeration only	0.0865	0.0457	0.9	0.8122	47.23
3. Vetiver platform with aeration	0.0865	0.0258	1	0.8162	70.23
4. Vetiver platform only	0.0865	0.0224	2	0.757	74.1

The synergistic effect of aquatic plants and microorganisms plays a crucial role in the removal of nutrients, including TP. The reduction in TP levels can likely be attributed to mechanisms such as uptake of soluble phosphorus by plants, filtration of particulate matter through plant roots, and sedimentation processes (Shah et al., 2014).

In this study, a hydroponics technique was employed in experiments with vetiver, both with and without aeration, as well as in a control experiment lacking both vetiver and aeration. The results demonstrated that the presence of vetiver grass significantly reduced COD, nitrogen, and phosphorus, by providing a favorable habitat for microorganisms in the rhizosphere. These microorganisms played an indirect role in breaking down the organic matter present in wastewater. The rhizosphere, which refers to the root zone of the hydroponic treatment system, served as an active reaction zone supported by aeration. In this zone, physical, chemical, and biological processes occur by interacting with plants, microorganisms, and pollutants. Additionally, vetiver grass directly contributed to the reduction of nutrients through the uptake of substances from the water solution. The moderate reduction of pollutants observed in the control experiment without vetiver grass could be attributed to processes such as oxidation, facilitated by indigenous microorganisms like bacteria and algae, and anaerobic microbiological conversion. To ensure the sustained removal of pollutants from wastewater, it is recommended to periodically harvest the plant biomass growing above the floating mat, based on the age and growing season. The harvested biomass can be utilized as fertilizer, biofuels, or animal fodder, providing additional benefits, and enhancing the overall sustainability of the system (Worku et al., 2018). Bio-phytoremediation with vetiver grass offers a practical and cost-effective alternative to conventional engineering methods for on-site water treatment. This nature-based solution requires minimal maintenance and shows remarkable resilience, as the grasses quickly resume growth after any interruption, while their efficiency improves over time (Kafil et al., 2019; Mahmoudpour et al., 2021).

Future research should concentrate on pilot-scale studies to validate laboratory findings and assess the feasibility of implementing vetiver grass bio-phytoremediation on a larger scale. It is essential to conduct further research to optimize vetiver grass systems, explore synergies with other nature-based treatment methods, and thoroughly assess the broader environmental and socio-economic benefits of this approach. Widespread implementation of vetiver grass bio-phytoremediation has the potential to significantly improve water quality in the Chiang Mai moat, thereby making a substantial contribution toward achieving the SDGs.

4. CONCLUSION

A laboratory-scale study was conducted to assess the performance of vetiver grass and aeration in removing pollutants from the polluted surface water of the Chiang Mai moat. The findings showed that the vetiver platform with aeration achieved impressive removal efficiencies for various pollutants. COD, NH_3-N, and TN were removed at rates of 96.38%, 91.57%, and 70.59%, respectively, while TP removal efficiencies were approximately 70% for both the vetiver platform with aeration, and the vetiver platform alone. This significant reduction in pollutants can be attributed to the bio-phytoremediation process, wherein vetiver grass roots absorbed COD, NH_3-N, TN, and TP from the water. In addition, the vetiver grass provided essential nutrients and created an environment conducive to the proliferation of indigenous microorganisms, demonstrating the crucial relationship between the host and endophytes. The combination of vetiver grass and microorganisms, further supported by aeration, played an essential role in effective removal of pollutants.

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