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Research Article

Enhancement of Nutrient Removal in a Hybrid Constructed Wetland Utilizing an Electric Fan Air Blower with Renewable Energy of Solar and Wind Power

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The sewage treatment efficiency of hybrid constructed wetlands (CWs) was evaluated under different ventilation methods. The removal efficiencies of biochemical oxygen demand (BOD), total nitrogen (TN), and total phosphorus (TP) in the vertical flow-(VF-) horizontal flow (HF) CWs using an electric fan air blower by the renewable energy of solar and wind power were higher than those by natural ventilation, excluding only suspended solids (SS). The TN treatment efficiency in the CW using the air blower especially increased rapidly by 16.6% in comparison with the CW employing natural ventilation, since the VF bed provided suitable conditions (aerobic) for nitrification to occur. The average removal efficiencies of BOD, SS, TN, and TP in the effluent were 98.8, 97.4, 58.0, and 48.3% in the CW using an electric fan air blower, respectively. The treatment performance of the CWs under different ventilation methods was assessed, showing TN in the CW using an electric fan air blower to be reduced by 57.5~58.6% for inlet TN loading, whereas reduction by 19.0~53.3% was observed in the CW with natural ventilation. Therefore, to increase the removal of nutrients in CWs, an improved ventilation system, providing ventilation via an electric fan air blower with the renewable energy, is recommended.

1. Introduction

Constructed wetlands (CWs) are considered as low-cost alternatives for the treatment of municipal, industrial, domestic, and agricultural wastewater [1]. Removal of nitrogen compounds in CWs is governed mainly by microbial nitrification and denitrification, while other mechanisms such as plant uptake and ammonia volatilization are generally of less importance [2]. While the efficiency of constructed wetlands for the removal of biochemical oxygen demand (BOD) and suspended solids (SS) is very high, nitrogen removal in most of the currently operating wetland systems (predominantly horizontal flow beds) is deficient, mainly due to insufficient supply of oxygen [3–5]. Higher nitrification efficiency was noted in vertical flow beds based on the Seidel model [6]. In the nitrification process, ammonia is oxidized mainly to nitrate. Nitrate is subsequently reduced to gaseous nitrogen by denitrification, where biomass or other organic residues are utilized as carbon and electron sources [2].

The most common CW systems are designed as horizontal flow (HF) systems in Europe [7]. Various types of CWs may be combined to achieve higher treatment effect (especially for nitrogen). However, hybrid systems comprise most frequently vertical flow (VF) and HF systems arranged [8]. HF CW systems for secondary treatment proved to be very satisfactory where the standard required only BOD, chemical oxygen demand (COD), and SS removal. However, there has been a growing interest in achieving fully nitrified

Table 1: Chemical characteristics of raw sewage and treated water in 1st and 2nd treatments.

Stage	Ventilation method	BOD	SS	TN ($mg\,L^{-1}$)	TP	DO
Raw sewage		58.5 ± 25.5	38.3 ± 21.0	11.8 ± 3.4	1.30 ± 0.38	0.82 ± 0.13
Treated water from the 1st bed (VF bed)	Natural ventilation	7.0 ± 5.5	5.0 ± 6.5	9.8 ± 3.2	1.02 ± 0.28	5.42 ± 1.5
	Electric ventilation	5.5 ± 1.1	6.3 ± 1.7	8.1 ± 1.8	0.84 ± 0.08	6.97 ± 1.3
Treated water in the 1st (VF) and 2nd (HF) beds (effluent)	Natural ventilation	1.2 ± 0.7	0.7 ± 0.4	6.5 ± 2.0	0.66 ± 0.19	1.57 ± 0.41
	Electric ventilation	0.7 ± 0.1	1.4 ± 0.3	5.7 ± 0.8	0.64 ± 0.15	1.61 ± 0.23

Table 2: Physicochemical characteristics of filter media used.

Bed	Porosity (%)	Bulk density ($g\,cm^{-3}$)	d_{10} (mm)	d_{60} (mm)	Uniformity coefficient (d_{60}/d_{10})	pH ($1:5H_2O$)	EC ($dS\,m^{-1}$)	O.M. (%)
VF bed	44.8	1.48	2.0	2.9	1.45	7.9	0.05	0.54
HF bed	37.0	1.59	0.13	1.4	10.7	7.5	0.05	0.42

effluents. HF CW systems cannot do this due to their limited oxygen transfer capacity. On the other hand, VF CW systems do provide a suitable condition for nitrification (but no denitrification occurs in these systems). In the 1990s and early 2000s, VF-HF systems were built in many European countries and now this type is getting more attention in most European countries [1, 8]. In hybrid systems, the advantages of the HF and VF systems can be combined to complement each other [8]. It is possible to produce an effluent low in BOD, COD, SS, and TN (nitrification and denitrification occur in VF-HF CWs) [1, 9].

The main goal of this study was to evaluate a VF-HF hybrid constructed wetland system for the treatment of domestic sewage from agricultural villages under different ventilation methods in order to enhance the organics and nutrient (N and P) removal performance through the VF-HF hybrid CWs. The specific objectives were (1) to evaluate the removal efficiency of pollutants in a VF-HF hybrid constructed wetland under different ventilation methods and (2) to obtain the treatment performance of pollutants in VF-HF hybrid wetlands constructed with different ventilation methods.

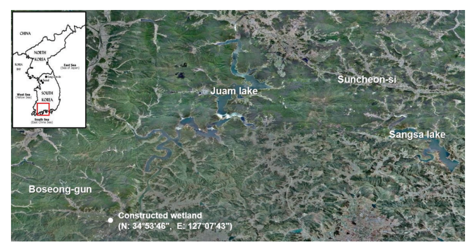

Figure 1: Location of hybrid constructed wetland.

2. Materials and Methods

2.1. Characterization of Materials. The domestic sewage used in this study was collected from a village located in Boknae-ri, Bongnae-myeon, Boseong-gun, Jeollanam-do, South Korea. Domestic sewage from this village had a BOD, SS, TN, and TP of 58.5, 38.3, 11.8, and 1.30 $mg\,L^{-1}$, respectively (Table 1). The physicochemical characteristics of the filter media used in the VF-HF CWs are listed in Table 2.

2.2. Hybrid Constructed Wetlands Experiment. The hybrid constructed wetlands (located in Boknae-ri, Bongnae-myeon, Boseong-gun, Jeollanam-do, South Korea, at 34°53′48.34N latitude and 127°07′43.91E longitude) evaluated herein consisted of 2-stage CWs containing coarse sand (Figure 1). The beds consisted of vertical flow (VF; aerobic conditions) and horizontal flow (HF; anaerobic conditions) and are shown in Figure 1. The VF-HF 2-stage CWs were constructed using a 5.0 m (width) × 7.0 m (length) × 1.0 m (height) bed for VF with a total volume of 35 m^3 and a 5.0 m (width) × 7.0 m (length) × 1.0 m (height) bed for HF with a total volume of 35 m^3, for which a 1.5 mm thick high density polyethylene (HDPE) liner was used (Figure 2). In the VF bed, a ventilation pipe was installed at 50 cm above the bottom in order to maintain natural ventilation during the 11 months from May 2012 to March 2013. From March 2013 to May 2013, an electric fan air blower which used the renewable energy of solar and wind power was installed at the end of the ventilation pipe to enhance the performance of organics and nutrient (N and P) removal in one of the hybrid CWs. The HF bed was also divided into five sections to maximize the hydraulic retention time in the bed. Domestic sewage was added to the VF bed using the vertical flow method, and the water leaving the bed flowed into the HF bed via horizontal flow.

The VF bed was a planted filter bed for 1st treatment of domestic sewage that was drained at the bottom. In the VF bed, the water flowed vertically down through the filter matrix to the bottom of the basin where it was collected in a drainage pipe. The hydraulic retention time in the VF

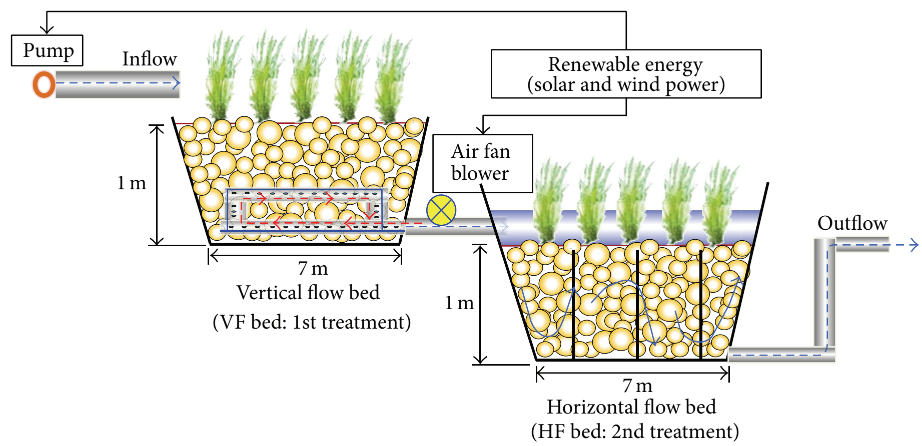

FIGURE 2: Diagrams of a VF-HF hybrid constructed wetland with ventilation using ventilation pipe and an electric air fan blower by renewable energy of solar and wind power for treating sewage.

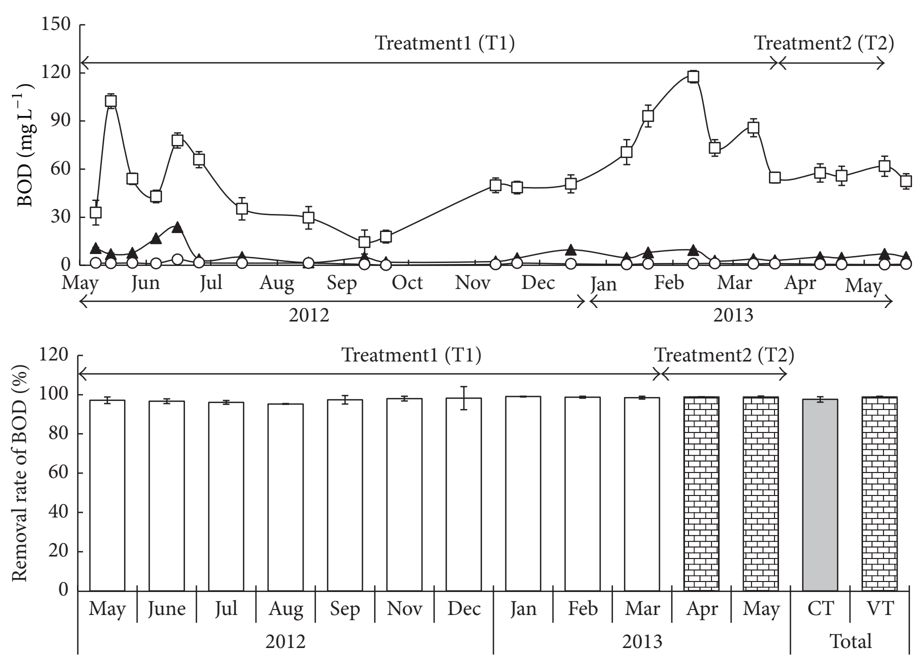

FIGURE 3: The concentration and removal rate of BOD in the water with time in a VF-HF hybrid constructed wetland under different ventilation methods (□: inflow; ▲: 1st treatment; ○: 1st + 2nd treatment; Treatment1 (T1): VF-HF CWs with natural ventilation; Treatment2 (T2): VF-HF CWs with ventilation using an electric air fan blower).

bed was about 1 h. The horizontal bed was always saturated with water. The filter media used in the VF-HF 2-stage CWs were coarse sand. *Phragmites communis* plants were transplanted in the VF bed, and *Iris pseudacorus, Typha orientalis, Zizania latifolia*, and *Phragmites communis* plants were transplanted in the HF bed. The applied hydraulic load was added at the rate of 143 L m^{-2} day^{-1} (5000 m^3 day^{-1}). Samples of the influent and effluent were taken and analyzed over a period of 13 months. The analyses of BOD (5-day BOD test), SS (suspended solid dried at 103–105°C), TN, and TP (ascorbic acid method) were performed in accordance with the standard methods [10].

3. Results and Discussion

3.1. Removal Efficiencies of Pollutants in VF-HF Hybrid Constructed Wetlands under Different Ventilation Methods

3.1.1. Biochemical Oxygen Demand (BOD). The concentrations and removal efficiencies of BOD, SS, TN, and TP in the raw water, treated water from the 1st bed (VF bed), and water treated in the 1st (VF) and 2nd (HF) beds (effluent) in the VF-HF CWs for 13 months are shown in Figure 3. BOD in the inflow ranged from 14.5 mg L^{-1} to 117.6 mg L^{-1}, with

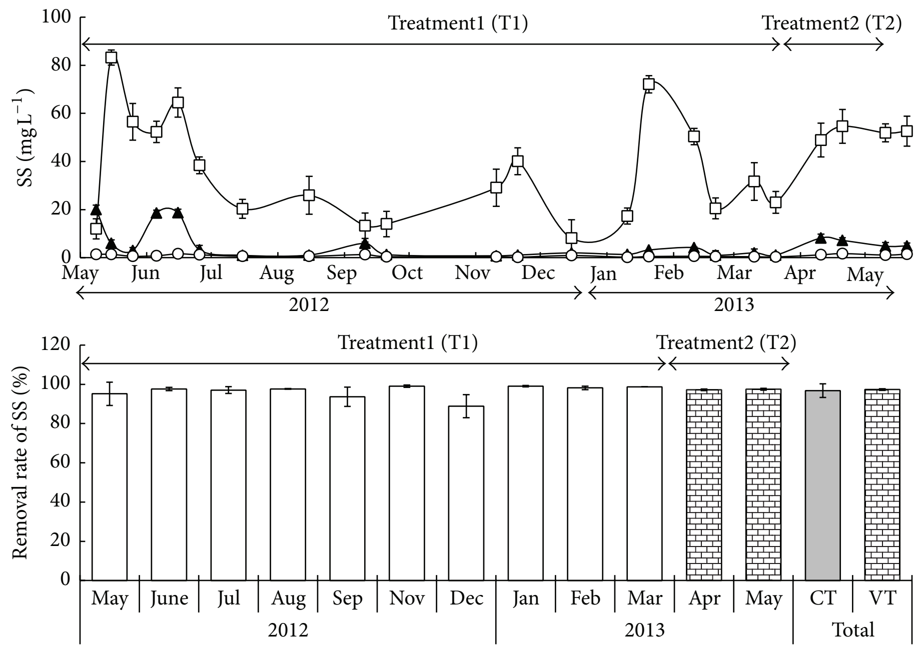

Figure 4: The concentration and removal rate of SS in the water with time in a VF-HF hybrid constructed wetland under different ventilation methods (□: inflow; ▲: 1st treatment; ○: 1st + 2nd treatment; Treatment1 (T1): VF-HF CWs with natural ventilation; Treatment2 (T2): VF-HF CWs with ventilation using an electric air fan blower).

an overall mean of 58.5 ± 25.5 mg L^{-1} during the 13 months. The highest BOD was found in February 2013 (Figure 3). In the VF-HF hybrid CW utilizing natural ventilation through a ventilation pipe, BOD in the effluent ranged from 0.2 mg L^{-1} to 3.7 mg L^{-1}, with an overall mean of 1.2 ± 0.7 mg L^{-1}. The removal of BOD in the VF bed was much higher than that in the HF bed. The rate of BOD consumption by microbes was also higher in the VF bed, likely due to the activity of aerobic bacteria, which provided greater oxidation of the organic matter than anaerobic bacteria [9]. In the effluent, the removal efficiency of BOD was 97.6% (95.3–99.0%) in the VF-HF hybrid CW with natural ventilation. On the other hand, in the VF-HF CWs ventilated using an electric fan air blower with the renewable energy of solar and wind power, BOD in the effluent ranged from 0.5 mg L^{-1} to 0.8 mg L^{-1}, with an overall mean of 0.7 ± 0.1 mg L^{-1}. In the effluent, the removal efficiency of BOD was 98.8% (98.8–98.9%) in the VF-HF CWs utilizing the electric fan air blower. Vymazal [11] reported that VF-HF systems at Colecott exhibited high removal of BOD and suspended solids. Therefore, the removal efficiency of BOD in the VF-HF CWs with electric ventilation was slightly higher than that in the VF-HF CWs utilizing natural ventilation. Öövel et al. [12] used a VF-HF constructed wetland for the treatment of school house wastewater in Estonia and reported the removal rates of BOD, TSS, TN, and TP of 94%, 87%, 70%, and 91%, respectively.

3.1.2. Suspended Solids (SS). The concentration of SS in the inflow ranged from 8.1 mg L^{-1} to 83.2 mg L^{-1}, with an overall mean of 38.3 ± 21.0 mg L^{-1} over the experimental period (Figure 4). In the VF-HF CW ventilated naturally using a ventilation pipe, SS in the effluent ranged from 0.2 mg L^{-1} to 1.6 mg L^{-1}, with an overall mean of 0.7 ± 0.4 mg L^{-1}. In the case of electric ventilation, SS in effluent ranged from 1.1 mg L^{-1} to 1.7 mg L^{-1}, with an overall mean of 1.4 ± 0.3 mg L^{-1}. The removal of SS in the VF bed was much higher than that in the HF bed in both cases, with 96.8% (88.9–99.1%) efficiency in the VF-HF CW with natural ventilation and 97.4% (97.2–97.5%) with electric ventilation. Thus, both ventilation methods showed similar removal efficiency of SS in the VF-HF CWs. The SS removal efficiency in the first stage was much higher than that in the second stage, because most of the SS had filtered or settled out within the first few centimeters past the inlet. In general, suspended solids in constructed wetlands are effectively removed by filtration and settlement [9]. Sayadi et al. [13] also reported that the hybrid constructed wetlands were effective in the removal of organic matter and suspended solids.

3.1.3. Total Nitrogen (TN). TN concentration in the inflow varied between 4.4 mg L^{-1} and 18.1 mg L^{-1}, with an overall mean of 11.8 ± 3.4 mg L^{-1} for the 13-month period (Figure 5). In the VF-HF CW with natural ventilation, TN in the effluent ranged from 2.0 mg L^{-1} to 10.1 mg L^{-1}, with an overall mean of 6.5 ± 2.0 mg L^{-1}. In that with electric ventilation, it ranged from 4.7 mg L^{-1} to 6.7 mg L^{-1}, with an overall mean of 5.7 ± 0.8 mg L^{-1}. In effluent, the removal efficiency of TN was 41.4% (19.0–53.3%) and 58.0% (57.5–58.6%) in the VF-HF CW with natural and electric ventilation, respectively. Therefore, the removal efficiency of TN in the VF-HF CW with electric ventilation was higher than that in the VF-HF CW with natural ventilation. A reasonable explanation for these results is that nitrification efficiency in the VF-HF CW with

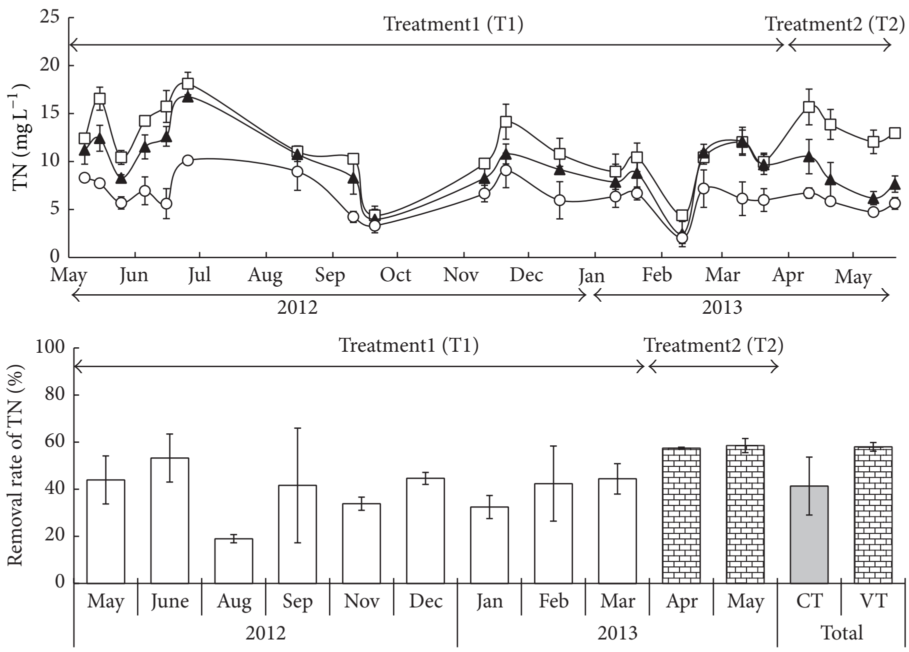

Figure 5: The concentration and removal rate of TN in the water with time in a VF-HF hybrid constructed wetland under different ventilation methods (□: inflow; ▲: 1st treatment; ○: 1st + 2nd treatment; Treatment1 (T1): VF-HF CWs with natural ventilation; Treatment2 (T2): VF-HF CWs with ventilation using an electric air fan blower).

electric ventilation (DO concentration was 6.97 mg L^{-1} in the VF bed) was higher than that in the VF-HF CW with natural ventilation (DO concentration was 5.42 mg L^{-1} in the VF bed).

Compared to single HF systems, a much higher removal of the total nitrogen was observed, as a result of high nitrification in the VF section. Nitrate produced in the VF section was successfully removed in the HF section [1]. In the VF-HF CWs, the 1st stage provided suitable conditions (aerobic) for nitrification, while the 2nd stage provided suitable conditions (anoxic/anaerobic) for denitrification to occur [9, 14]. Similar results were reported by Vymazal [15], showing that hybrid constructed wetlands were more efficient in total nitrogen removal than single HF or VF constructed wetlands. Thus, the removal efficiency of TN in the VF-HF CW ventilated using an electric fan air blower rapidly increased by 16.6% in comparison with that in the VF-HF CW with natural ventilation.

3.1.4. Total Phosphorus (TP). The concentration of TP in the inflow ranged from 0.55 mg L^{-1} to 2.23 mg L^{-1}, with an overall mean of 1.30 ± 0.38 mg L^{-1} over the experimental period (Figure 6). The highest TP values were observed in May 2012. In the VF-HF CW with natural ventilation, TP in the effluent varied between 0.30 mg L^{-1} and 0.99 mg L^{-1}, with an overall mean of 0.66 ± 0.19 mg L^{-1}. In the case of electric ventilation, TP varied between 0.48 mg L^{-1} and 0.79 mg L^{-1}, with an overall mean of 0.64 ± 0.15 mg L^{-1}. Removal efficiency of TP in the effluent was 47.0% (28.8–63.2%) in the VF-HF CW with natural ventilation and 48.3% (48.1–48.6%) in that with electric ventilation. According to Sayadi et al. [13], removal of nutrients such as N and P components is dependent on the system properties and operational conditions. Removal efficiency of TP in the VF-HF CW ventilated using an electric fan air blower was slightly higher than that in the VF-HF CW employing natural ventilation. This is because the VF bed in VF-HF systems with electric ventilation provides suitable aerobic conditions for P uptake by polyphosphate accumulating organisms (PAOs) compared to the VF bed in VF-HF systems with natural ventilation. Namely, for P uptake by polyphosphate accumulating organisms (PAOs), aerobic condition in the VF bed with electric ventilation (DO concentration was 6.97 mg L^{-1}) was more suitable than that in the VF bed with natural ventilation (DO concentration was 5.42 mg L^{-1}). In general, PAOs do release and uptake orthophosphate under anaerobic and aerobic conditions, respectively [16].

Based on the above results, removal efficiencies of BOD, TN, and TP in the VF-HF CW ventilated using an electric fan air blower were higher than those by natural ventilation, excluding only SS.

3.2. Relationship between Pollutant Loading and Removal in VF-HF Hybrid Constructed Wetlands under Different Ventilation Methods. The removal of BOD, SS, TN, and TP was proportional to the influent load in the CWs for the treatment of sewage. The linear relationship between nutrient removal and nutrient loading is illustrated in Figure 7. In the VF-HF CW with natural ventilation, linear regressions for BOD were BOD removal (g day^{-1}) = 0.0428 × BOD loading (g day^{-1}) + 22.264 (r = 0.217) for the VF bed and BOD removal (g day^{-1}) = 0.0057 × BOD loading (g day^{-1}) + 4.4503

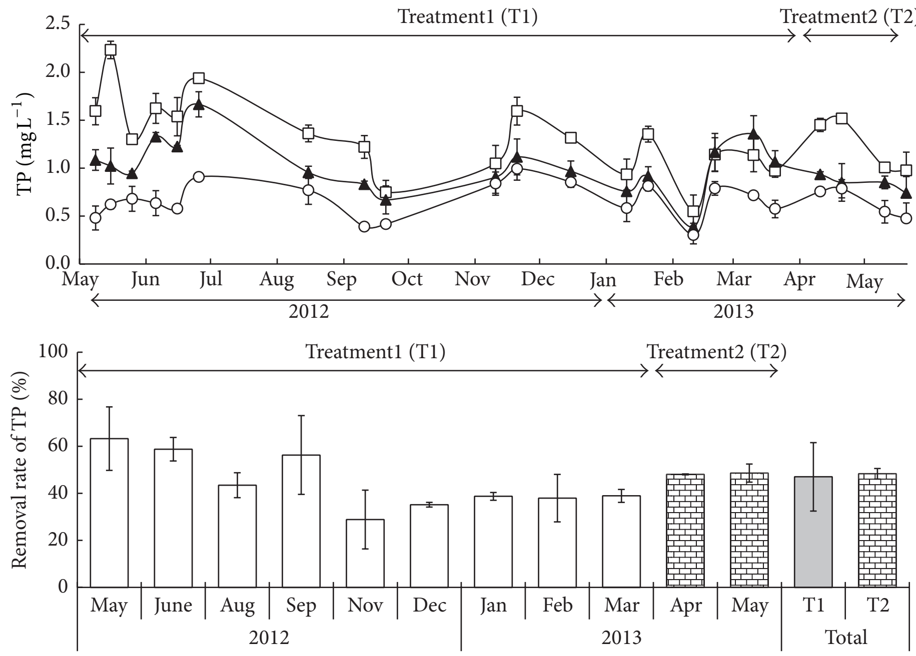

Figure 6: The concentration and removal rate of TP in the water with time in a VF-HF hybrid constructed wetland under different ventilation methods (□: inflow; ▲: 1st treatment; ○: 1st + 2nd treatment; Treatment1 (T1): VF-HF CWs with natural ventilation; Treatment2 (T2): VF-HF CWs with ventilation using an electric air fan blower).

(r = 0.226) for the HF bed. In the case of electric ventilation, linear regressions for BOD were BOD removal (g day^{-1}) = 0.2243 × BOD loading (g day^{-1}) − 36.196 (r = 0.819*, P < 0.05) for the VF bed and BOD removal (g day^{-1}) = −0.0287 × BOD loading (g day^{-1}) + 11.421 (r = 0.871*, P < 0.05) for the HF bed. In the VF bed, the organic loading (BOD) varied between 73 and 588 g day^{-1}, demonstrating mass removal between 9 and 119 g day^{-1} in the VF-HF CW with natural ventilation, whereas variation between 262 and 309 g day^{-1}, with mass removal between 24 and 36 g day^{-1}, was observed with electric ventilation. In the HF bed, the organic loading (BOD) varied between 73 and 588 g day^{-1}, demonstrating mass removal between 1 and 19 g day^{-1} in the VF-HF CW with natural ventilation, whereas it varied between 262 and 309 g day^{-1}, with mass removal between 3 and 4 g day^{-1} in that with electric ventilation.

Linear regressions for SS were SS removal (g day^{-1}) = 0.0714 × SS loading (g day^{-1}) + 12.59 (r = 0.245) for the VF bed and SS removal (g day^{-1}) = 0.0049 × SS loading (g day^{-1}) + 2.7847 (r = 0.248) for the HF bed with natural ventilation. In the case of electric ventilation, linear regressions for SS were SS removal (g day^{-1}) = −0.2533 × SS loading (g day^{-1}) + 97.229 (r = 0.353) for the VF bed and SS removal (g day^{-1}) = 0.089 × SS loading (g day^{-1}) − 16.267 (r = 0.764) for the HF bed. In the VF bed, the SS loading varied between 41 and 416 g day^{-1}, showing mass removal between 4 and 100 g day^{-1} with natural ventilation, and varied between 245 and 273 g day^{-1}, demonstrating mass removal between 24 and 41 g day^{-1} with electric ventilation. In the HF bed, the SS loading varied between 41 and 416 g day^{-1}, presenting mass removal between 1 and 8 g day^{-1} in the VF-HF CW with natural ventilation, whereas variation between 245 and 273 g day^{-1}, demonstrating mass removal between 6 and 9 g day^{-1}, was observed in the case of electric ventilation.

In the VF-HF CW with natural ventilation, linear regressions for TN were TN removal (g day^{-1}) = 0.8408 × TN loading (g day^{-1}) + 1.203 (r = 0.94**, P < 0.01) for the VF bed and TN removal (g day^{-1}) = 0.4213 × TN loading (g day^{-1}) + 8.6059 (r = 0.757**, P < 0.01) for the HF bed. In the case of the electric ventilation, linear regressions for TN were TN removal (g day^{-1}) = 1.1524 × TN loading (g day^{-1}) − 37.96 (r = 0.991**, P < 0.01) for the VF bed and TN removal (g day^{-1}) = 0.509 × TN loading (g day^{-1}) − 6.0137 (r = 0.973**, P < 0.01) for the HF bed. In the VF bed, the TN loading varied between 21.9 and 90.6 g day^{-1}, presenting mass removal between 12.2 and 83.8 g day^{-1} in the naturally ventilated VF-HF CW, and varied between 60.3 and 78.4 g day^{-1}, with mass removal between 30.9 and 52.6 g day^{-1} in the VF-HF CW ventilated with an electric air blower. In the HF bed, the TN loading varied between 21.9 and 90.6 g day^{-1}, demonstrating mass removal between 10.2 and 50.5 g day^{-1} in the VF-HF CW with natural ventilation, whereas it varied between 60.3 and 78.4 g day^{-1}, with mass removal between 23.7 and 33.6 g day^{-1} under electric ventilation.

In the naturally ventilated VF-HF CW, linear regressions for TP were TP removal (g day^{-1}) = 0.4624 × TP loading (g day^{-1}) + 2.07 (r = 0.666**, P < 0.01) for the VF bed and TP removal (g day^{-1}) = 0.1982 × TP loading (g day^{-1}) + 2.0185 (r = 0.427) for the HF bed. In the VF-HF CW with

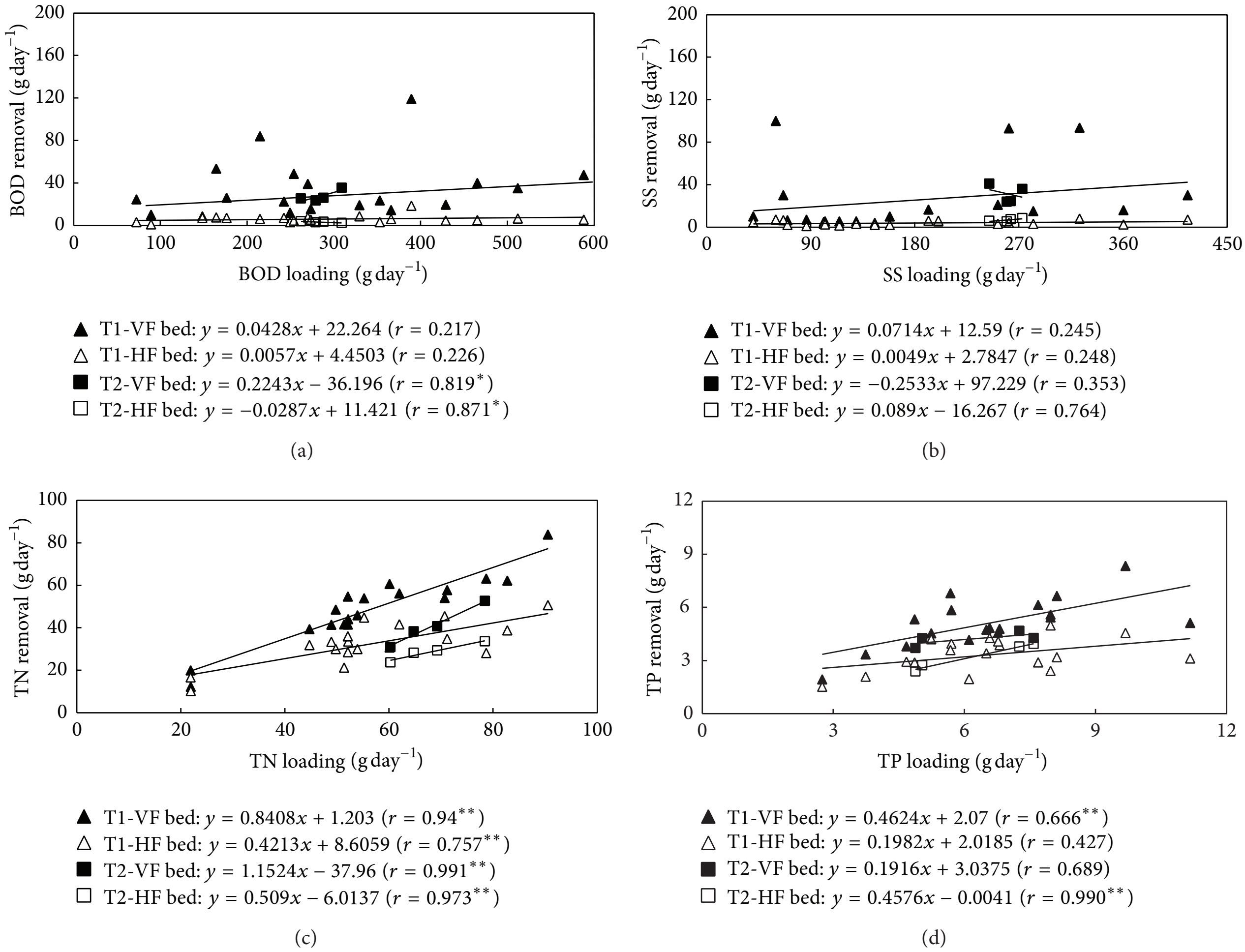

Figure 7: Relationship between BOD, SS, TN, and TP loading and removal in a VF-HF hybrid constructed wetland under different ventilation methods (Treatment1 (T1): VF-HF CWs with natural ventilation; Treatment2 (T2): VF-HF CWs with ventilation using an electric air fan blower).

electrically provided ventilation, linear regressions for TP were TP removal (g day^{-1}) = 0.1916 × TP loading (g day^{-1}) + 3.0375 (r = 0.689) for the VF bed and TP removal (g day^{-1}) = 0.4576 × TP loading (g day^{-1}) − 0.0041 ($r = 0.990^{**}$, $P < 0.01$) for the HF bed. In the VF bed, the TP loading varied between 2.8 and 11.2 g day^{-1}, with mass removal between 1.9 and 8.3 g day^{-1} in the VF-HF CW ventilated naturally, while it varied between 4.9 and 7.6 g day^{-1}, showing mass removal between 3.7 and 4.7 g day^{-1} under electric ventilation. In the HF bed, the TP loading varied between 2.8 and 11.2 g day^{-1}, with mass removal between 1.5 and 5.0 g day^{-1} under natural ventilation, and between 4.9 and 7.6 g day^{-1}, with mass removal between 2.4 and 3.9 g day^{-1} in the VF-HF CW ventilated using an electric air blower. Based on the above results, removal efficiencies of BOD, TN, and TP in the VF-HF CW ventilated using an electric fan air blower were higher than those with natural ventilation.

4. Conclusion

To enhance the performance of organics and nutrient (N and P) removal in VF-HF hybrid CWs, the treatment efficiency of VF-HF hybrid CWs was evaluated during the treatment of domestic sewage from agricultural villages under different ventilation methods. The removal efficiencies of BOD, SS, TN, and TP in the effluent were 95.3–99.0, 88.9–99.1, 19.0–53.3, and 28.8–63.2% in the VF-HF CWs with natural ventilation, whereas they were 98.8–98.9, 97.2–97.5, 57.5–58.6, and 48.1–48.6% in the VF-HF CW with a ventilation pipe and an electric fan air blower, providing air by the renewable energy of solar and wind power, respectively. The removal efficiencies of BOD, TN, and TP in the VF-HF CW with the electric ventilation were higher than those ventilated naturally, excluding only SS. The TN treatment efficiency in the VF-HF CW with electric ventilation was especially higher, increasing by 16.6% in comparison with the VF-HF CW with natural ventilation, since the VF bed provided suitable conditions (aerobic) for nitrification to occur. The treatment performance of the VF-HF CWs under different ventilation methods was assessed. TN in the VF-HF CW with electric ventilation provided by renewable energy was reduced by 57.5–58.6% for inlet TN loading, whereas TN in the VF-HF CW with natural ventilation was reduced by 19.0–53.3% for inlet TN loading. Therefore, to increase the removal of organics and nutrients (N and P) in VF-HF CWs, an improved ventilation system, providing ventilation via an electric fan air blower with the renewable energy of solar and wind power, is recommended.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Authors' Contribution

Dong Jin Lee, Se Won Kang, and Jong Hwan Park contributed equally to this work.

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