



Removal of nutrients from septic tank effluent with baffle subsurface-flow constructed wetlands



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ABSTRACT

Three new baffle flow constructed wetlands (CWs), namely the baffle horizontal flow CW (Z1), baffle vertical flow CW (Z2) and baffle hybrid flow CW (Z3), along with one traditional horizontal subsurface flow CW (Z4) were designed to test the removal efficiency of nitrogen (N) and phosphorus (P) from the septic tank effluent under varying hydraulic retention times (HRTs). Results showed that the optimal HRT was two days for maximal removal of N and P from the septic tank effluent among the four CWs. At this HRT, the Z1, Z2, Z3 and Z4 CWs removed, respectively, 49.93, 58.50, 46.01 and 44.44% of TN as well as 87.82, 93.23, 95.97 and 91.30% of TP. Our study further revealed that the Z3 CW was the best design for overall removal of N and P from the septic tank effluent due to its hybrid flow directions with better oxygen supply inside the CW system.

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1. Introduction

Constructed wetlands (CWs) are increasingly gaining acceptance worldwide for removing contaminants from wastewaters due to their moderate capital cost, low energy consumption, and less maintenance requirement (Vymazal, 2002, 2007). Among several types of CWs, the free water surface, vertical-flow and horizontal subsurface-flow CWs are the most commonly used CWs for wastewater treatments. However, these CWs normally have low nutrient removal efficiency due to their low dissolved oxygen (DO) content in the substrate for nitrification and then denitrification is limited because of insufficient nitrate content (Brix, 1987; Cooper et al., 1996; Cooper and Green, 1995). In recent years, the hybrid CWs have been applied to purify wastewaters in many countries. These CWs combined horizontal and vertical subsurface-flow designs to complement each other for better DO supply in the CW system and are ideal to achieve better nutrient removal efficiency (Vymazal, 2005; Tuncsiper, 2009; Cui et al., 2012). However, the hybrid CWs have some limitations due to their larger land area requirement and lower removal efficiency of P (Zeng et al., 2006). Therefore, the baffle subsurface-flow CWs have been designed in recent years to improve nutrient removal efficiency from

wastewaters.

The baffle subsurface-flow CW is a new type of CW and has a better pollutant removal efficiency as compared to the traditional CWs (Tee et al., 2012; Cui et al., 2013). This CW is based on the traditional CW with increasing baffle through the horizontal and vertical directions to make wastewater repeatedly flow through the CWs. Thus, the pollutant removal efficiency is improved (He et al., 2006; Tee et al., 2012). The advantage of the baffle subsurface-flow CW is the use of up and down flows sequentially for improving the nutrient removal. This design enhances the water twists to prolong water pathway by forcing the wastewater to flow up and down. That is, wastewater was forced to pass through the aerobic zone (upper layer) and the anoxic zone (lower layer), and thereby the nitrification and denitrification can be completed alternatively.

The baffle subsurface-flow CW is commonly filled with graded gravels as the growing medium. This material supports the plant growth, but has a very low P sorption capacity (Vymazal, 2010). In recent years, other materials such as furnace steel slag, coal ash (Zhu et al., 2003), and rice husk (Tee et al., 2009, 2012) are used as the growing media with success. Zhu et al. (2003) reported that using the furnace steel slag as a medium, the removal efficiency is 80–89% for total P (TP), while using the coal ash as a medium, the removal efficiency is 70–85% for TP. Their study showed that furnace steel slag and coal ash are the ideal media for filling the CWs. Although the above studies have provided useful insights into

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the applications of the newly designed baffle subsurface-flow CWs, more studies are still needed to estimate their feasibilities.

The aims of this study were to: (1) investigate the removal of N and P from septic tank effluent by using four types of CWs, namely the baffle horizontal flow, baffle vertical flow, baffle hybrid flow, and horizontal subsurface flow (as a control) CWs. These CWs were filled with furnace steel slag and operated at different hydraulic retention times (HRTs); (2) identify the optimal baffle CWs and their operating parameters for maximal removal of N and P from the septic tank effluent; and (3) estimate the removal rate of N and P from the effluent by the aboveground biomass of canna (*Canna indica* L) plant species.

2. Materials and methods

2.1. Constructed wetland system

A schematic diagram showing a plane view of the four different types of CWs used in this study was shown in Fig. 1. They are horizontal baffle flow (Z1), vertical baffle flow (Z2), hybrid baffle flow (Z3) and horizontal subsurface flow (Z4). The first three cells were further divided into five compartments for different water flow paths. A pool was built into four concrete cells and each cell represents one type of the CW. Each cell was 2 m in length, 1 m in width, and 0.75 m in height and was divided into five compartments (Fig. 1). For the horizontal baffle flow (Z1) CW, the baffles were 0.9 m in length and 0.75 m in height. Therefore, the wastewater can only flow horizontally, but not vertically through the bottom of the compartments due to the baffle separation. For the vertical baffle flow CW (Z2), the first and third baffles were 1 m in length and 0.6 m in height, whereas the second and fourth baffles were 1 m in length and 0.65 m in height. Additionally, there were five holes each with a diameter of 0.05 m along the baffle width at an interval of 0.2 m for the second and fourth baffles. The wastewater entered into the first compartment vertically and overflowed (or spilled) into the second compartment. It then flowed from the second compartment to the third compartment through the baffle holes at the bottom. The wastewater flow path from the third compartment into the fourth compartment was the same as that from the first compartment into the second compartment, while the wastewater flow path from the fourth compartment into the fifth compartment was the same as that from the second compartment into the third compartment. For the hybrid baffle

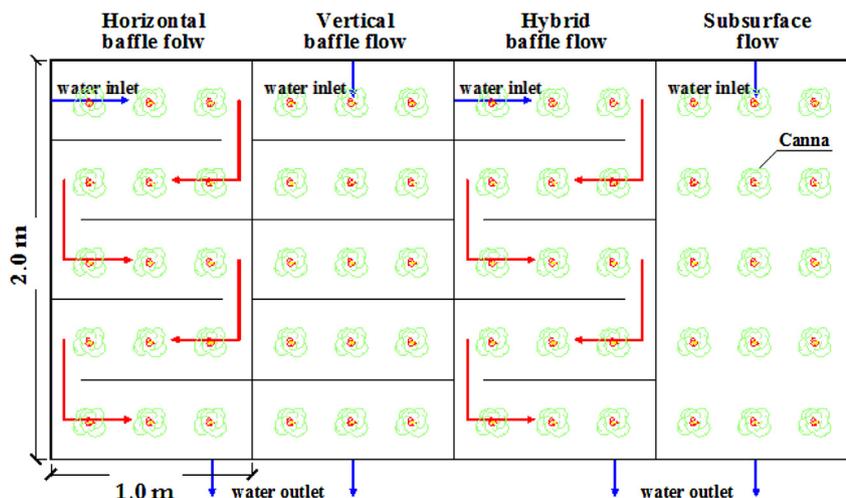


Fig. 1. A schematic diagram showing four different types of constructed wetlands, including horizontal baffle flow (Z1), vertical baffle flow (Z2), hybrid baffle flow (Z3), and subsurface flow (Z4) constructed wetlands.

Table 1

The compositions of wastewater used for the experiment (mg/L).

Index	Variation range	Average
TN	52.46–234.12	145.20 (6.27) ^a
TP	3.31–50.05	12.72 (1.12)
BOD ₅	11.12–214.32	84.78 (7.05)
COD	65.89–793.70	233.59 (18.78)
NH ₄ ⁺ – N	34.65–240.66	137.93 (6.73)
pH	6.64–8.20	7.68 (0.071)

^a Values in the parentheses were standard errors (S.E.).

flow (Z3) CW, it had both the Z1 and Z2 CW designs and the wastewater flow path was a combination of the Z1 and Z2 CWs.

Each cell (or CW) was first filled with 10-cm limestone with a particle diameter of 4 cm at the bottom, and then with 4-cm gravel with a diameter of 1–2 cm as the supporting layer. For the first three baffled subsurface flow CWs (i.e., Z1, Z2, and Z3), the first compartment was filled 25% cinder, 25% rubble, and then 50% blast furnace slag, and the rest of the four compartments for the first three CWs (or cells) were filled with 55 cm thick blast furnace slag above the gravel layer. For the control CW (Z4) (or the conventional horizontal subsurface flow CW), all of the compartments were filled with 55 cm thick blast furnace slag above the gravel layer. Finally, a layer of 3 cm fine sand was spread on the top of the four cells.

The four CWs were planted with yellow flower canna (*C. indica* L), and the average cultivation density of each compartment was three strains. Canna is a perennial herbaceous flower, up to 1 m tall.

2.2. Constructed wetland operation

The four CWs were operated for 24 months from March 2005 to March 2007, with three different hydraulic retention times (HRTs) of 1, 2, and 3d. These HRT schedules made the CWs dried and rewetted. Effluent was added to the CWs at a set rate according to different HRTs. Occasionally, the effluent was discharged at a faster rate when the wetland bed needed for recovery. The plants were harvested each quarter to analyze water, total N (TN), and TP contents. The removal efficiency of TN, TP, and ammonia nitrogen (NH₄⁺ – N) with varying HRTs by the four CWs was estimated to determine the optimum HRTs.

The wastewater (or effluent) was obtained from the septic tank

at Building 5, College of Natural Resources and Environment, South China Agricultural University, Guangzhou, China. This wastewater was analyzed for initial contents of nutrients such as TN, TP, $NH_4^+ - N$, chemical oxygen demand (COD), biochemical oxygen demand at five days (BOD_5), and pH (Table 1). Although the major wastewater components are similar to those of the municipal wastewater, the contents of TN and TP were about three times greater than the latter.

2.3. Chemical and statistical analysis

For water and substrate samples, the COD was determined using the dichromate reduction method, whereas the BOD_5 was analyzed using dilution and inoculation method (APHA, 1998). The $NH_4^+ - N$ was determined with semi-micro Kjeldahl neutralizing acid titration, while the TN was measured with alkaline potassium persulfate oxidation-ultra spectrophotometer. The TP was measured with potassium persulfate oxidation – molybdenum colorimeter (APHA, 1998). For plant issue samples, the TN content was measured with $H_2SO_4-H_2O_2$ – digestion and distillation method, while the TP content was measured with $H_2SO_4-H_2O_2$ – digestion and antimony potassium tartrate, ammonium molybdate – sulphoacid, and then ascorbic acid colorimeter (APHA, 1998). The DRLANGE

CADAS 100 spectrophotometer was used to measure $NH_4^+ - N$, TN and TP contents. Excel 2003 and SAS 8.1 software packages were used for statistical analysis. The multiple comparisons were estimated with the DUNCAN method at $\alpha = 0.05$.

3. Results and discussions

3.1. Removal of $NH_4^+ - N$ and TN

The four CW systems were successively operated at the HRTs of 1, 2, and 3d. Fig. 2 showed the concentrations of $NH_4^+ - N$ in the effluent and its average removal efficiencies from different CWs. At HRT = 1d, the average concentration of $NH_4^+ - N$ in the effluent from the Z1, Z2, Z3, and Z4 CWs was 61.89, 38.51, 63.67, and 68.80 mg/L, respectively; whereas the average removal efficiency of $NH_4^+ - N$ from the Z1, Z2, Z3, and Z4 CWs was 57.55, 72.33, 57.60, and 50.88%, respectively. A large difference in removal efficiency was found between the Z2 and Z4 CWs. This occurred because there were five baffles separated the Z2 CW into four compartments (Fig. 1), which made the wastewater flow vertically in this CW. This vertical flow pattern produced an aerobic-facultative anaerobic–anaerobic condition for nitrification, resulting in reduced the $NH_4^+ - N$ concentration. In contrast, the wastewater flow in Z4 CW

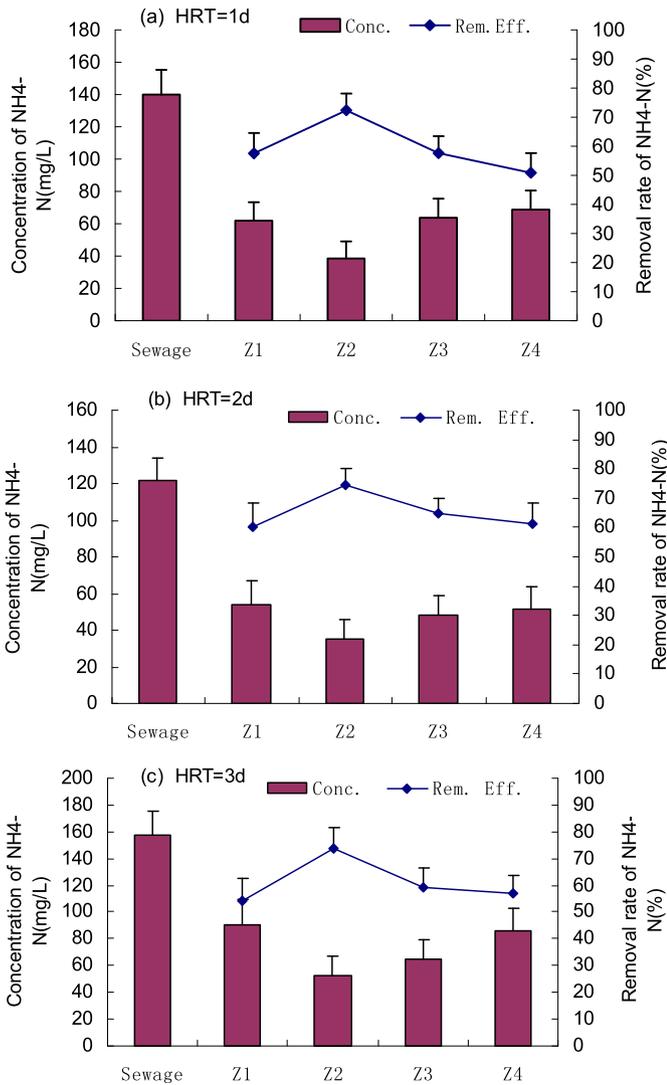


Fig. 2. Removal of $NH_4^+ - N$ at different hydraulic retention times.

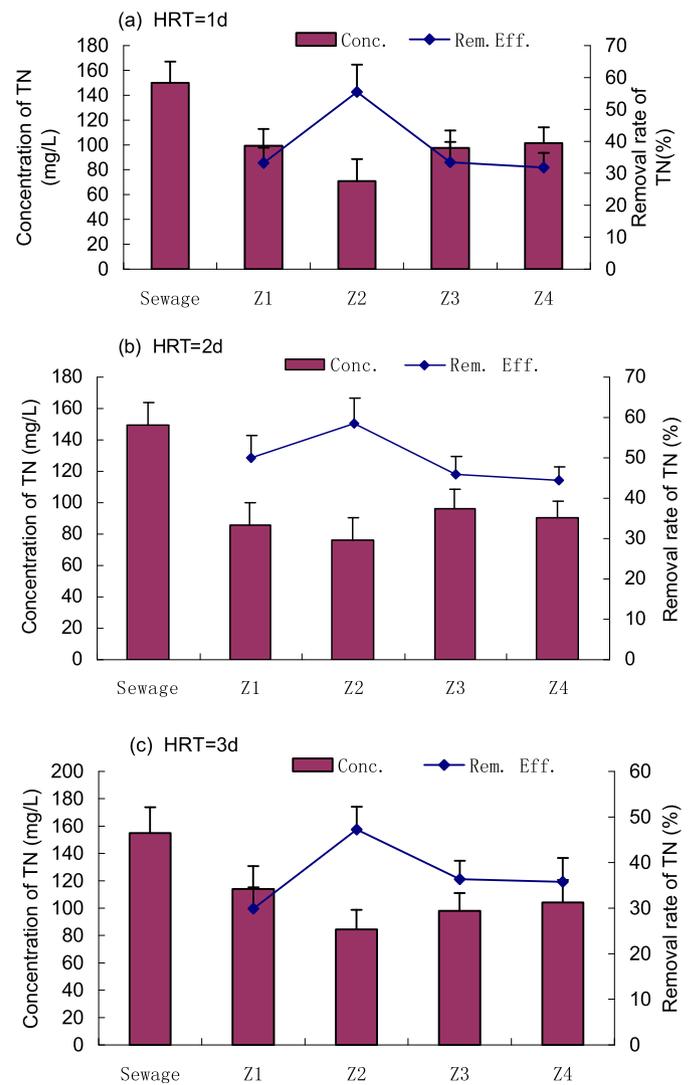


Fig. 3. Removal of TN at different hydraulic retention times.

was primarily in the horizontal direction and the supply of oxygen in this CW was less than that of the Z2 CW (vertical flow). Additionally, the wastewater flow was faster (without baffles) and reduced its contact and reaction times with the substrate in the Z4 CWs. The low oxygen supply and shorter contact and reaction times resulted in low removal of $\text{NH}_4^+ - \text{N}$ in the Z4 CW.

Similar removal efficiencies of $\text{NH}_4^+ - \text{N}$ were found at the HRTs of 2 and 3d. At HRT = 2d, the average concentration of $\text{NH}_4^+ - \text{N}$ in the effluent of the four CWs was 54.14, 35.43, 48.36, and 51.56 mg/L, respectively, and the average removal efficiency of $\text{NH}_4^+ - \text{N}$ was 60.19, 74.50, 64.70, and 61.1%, respectively (Fig. 2b). At HRT = 3d, the average concentration of $\text{NH}_4^+ - \text{N}$ in the effluent of the four CWs was 90.46, 52.55, 64.57, and 86.30 mg/L, respectively, and the average removal efficiency of $\text{NH}_4^+ - \text{N}$ was 54.41, 73.73, 59.42, and 57.04%, respectively (Fig. 2c). It was apparent that the highest removal efficiency of $\text{NH}_4^+ - \text{N}$ was observed in the Z2 CW at the HRTs of 2 and 3d. This occurred due to the same reasons as for the case at HRT = 1d.

Fig. 3 shows the concentration of TN in the effluent and the average removal efficiency of TN at the HRTs of 1, 2, and 3d for the four different CWs. When the HRT was 1d, the average

concentration of TN in the effluent of the Z1, Z2, Z3, and Z4 CWs was, respectively, 99.29, 70.83, 97.61, and 101.39 mg/L, while the average removal efficiency of TN for the Z1, Z2, Z3, and Z4 CWs was, respectively, 33.21, 55.49, 33.5, and 31.85%. Results showed that the Z2 CW was a best design for removal of TN from the wastewater among the four CWs (Fig. 3a) at this HRT. This could occur because there were five vertical baffles in the Z2 CW forcing wastewater continuous to flow between the upper layer and the lower layer of the substrate. The upper layer was aerobic, which is a favorable condition for nitrification; whereas the lower layer was anoxic (even anaerobic), which is a suitable condition for denitrification. As a result, more TN was removed from the Z2 CW.

Similar removal efficient pattern was observed at the HRTs of 2 and 3d. The removal efficiency of TN in the Z1, Z2, and Z3, and Z4 CWs was 49.93, 58.5, 46.01, and 44.44%, respectively, at HRT = 2d (Fig. 3b), while the removal efficiency of TN from the Z1, Z2, and Z3, and Z4 CWs was 29.92, 47.25, 36.34, and 35.75%, respectively, at HRT = 3d (Fig. 3c). These occurred due to the same reasons as for HRT = 1d.

3.2. Removal of TP

Changes in TP concentration trend in the effluent of the four different CWs at the HRTs of 1, 2, and 3d were shown in Fig. 4. The concentrations of TP in the effluent of each CW did not change with varying TP concentrations in the influent, indicating each CW has a buffering capacity for higher concentrations of TP. This could be related to the P adsorption by the substrate such as blast furnace slag (BFS) which was used in the four CWs. The BFS is a high efficient substrate for P adsorption (Korkusuz et al., 2007; Sakadevan and Bavor, 1998). As shown in Fig. 4, the TP concentration in the effluent did not change with HRTs because the adsorption and precipitation of P played a major role in the removal of P from the CWs (Drizo et al., 1999).

Fig. 4 further revealed that the average concentration of TP in the effluent from the Z1, Z2, Z3, and Z4 CWs was 1.82, 0.75, 0.53, and 1.42 mg/L, respectively, and the average removal efficiency of TP in the Z1, Z2, Z3, and Z4 CWs was, respectively, 84.02, 93.74, 96.41, and 88.22% at HRT = 1d. Results indicate that the hybrid

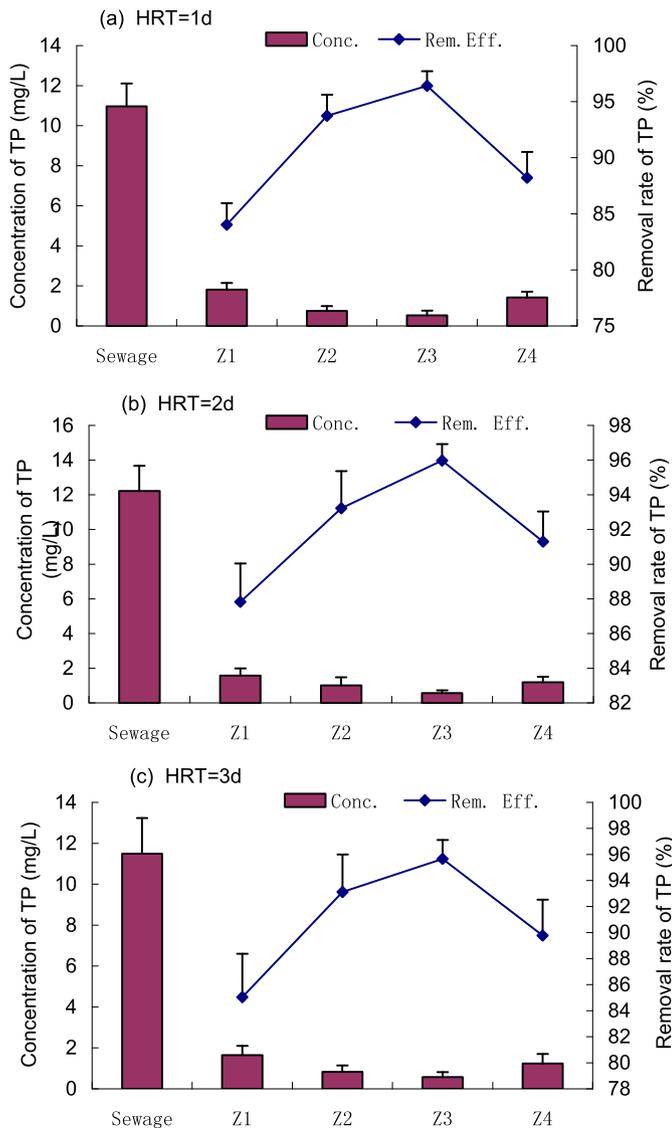


Fig. 4. Removal of TP at different hydraulic retention times.

Table 2
Two-factor variance analysis of four wetland systems.

Pollutants	HRT (d)	Z1 (%)	Z2 (%)	Z3 (%)	Z4 (%)	Comparisons ^a
$\text{NH}_4^+ - \text{N}$	1	57.55	72.33	57.6	50.88	a
	2	60.19	74.50	64.7	61.1	a
	3	54.41	73.73	59.42	57.04	a
	P = 0.0012	B	A	B	B	P = 0.6248
TN	1	33.21	55.49	33.50	31.85	a
	2	49.93	58.50	46.01	44.44	a
	3	27.92	47.25	36.34	35.75	a
	P = 0.0879	B	A	B	B	P = 0.1326
TP	1	84.02	93.74	96.41	88.22	a
	2	87.82	93.23	95.97	91.30	a
	3	85.04	93.11	95.66	89.78	a
	P = <0.0001	D	B	A	C	P = 0.8919
COD	1	61.29	60.27	67.07	58.93	b
	2	74.42	72.45	75.22	65.31	a
	3	70.09	67.85	70.51	70.42	a
	P = 0.6335	A	A	A	A	P = 0.0061
BOD_5	1	49.37	72.11	63.43	55.37	a
	2	71.36	61.76	72.09	73.16	a
	3	63.44	67.36	75.43	56.42	a
	P = 0.5344	A	A	A	A	P = 0.2825

^a Duncan's multiply comparisons are used in this analysis and the same letters for each column mean no statistical difference at $p = 0.05$.

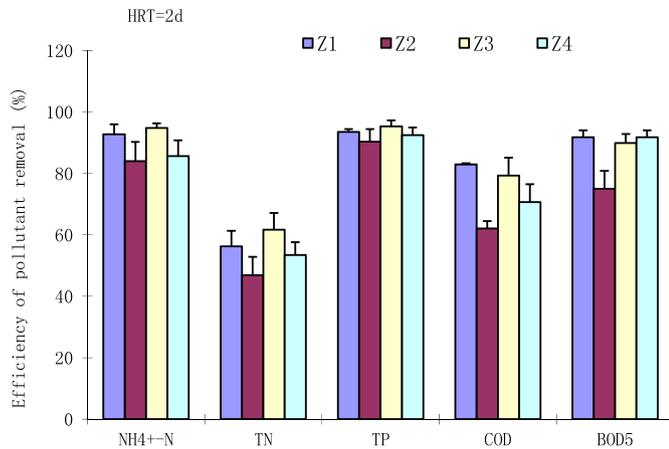


Fig. 5. Efficiency of pollutant removal at hydraulic retention time at 2d.

baffle flow CW (Z3) was the best design CW for removal of TP from the wastewater. A similar result was found at the HRTs of 2 and 3d. For example, at HRT = 2d, the average concentration of TP in the effluent of the Z1, Z2, Z3, and Z4 CWs was, respectively, 1.58, 1.01, 0.56, and 1.19 mg/L, and the average removal efficiency of TP from the Z1, Z2, Z3, and Z4 CWs was, respectively, 87.82, 93.23, 95.97, and 91.30%.

The advantage of the Z3 CW over other CWs for removal of TP from wastewater was determined by its unique flow pattern taken place inside the CW system. Hybrid baffle flow is consisted of both horizontal flow and vertical flow. The flow in the vertical direction can strengthen the filtration of TP, while the flow in the horizontal direction can expedite the settlement of particular P. These combined flow directions could lead to a better removal of TP from wastewater although further investigation of the TP removal mechanisms in this CW is warranted.

3.3. Optimal CW design and best HRT

Under the different HRTs, the removal efficiencies of NH₄⁺ - N, TN, TP, COD, and BOD₅ were highest at HRT = 2d, followed by HRT = 3d, and were lowest at HRT = 1d (Table 2) among the four CWs. Therefore, the optimum HRT for removing these pollutants from the wastewater in the four CWs was two days. Under the same HRT, the removal efficiencies of NH₄⁺ - N and TN were highest for the vertical baffle flow (Z2) CW and followed by the hybrid baffle flow (Z3) CW (Table 2). In contrast, under the same HRTs, the removal efficiency of TP was highest for the hybrid baffle flow (Z3) CW, followed by vertical baffle flow (Z2) CW, and was lowest for the horizontal baffle flow (Z1) CW. Under the same HRTs, the removal efficiencies of COD and BOD₅ were the highest in the hybrid baffle flow (Z3) CW. Therefore, the hybrid baffle flow (Z3) CW was better than the vertical baffle (Z2) CW for COD and BOD₅ removal. Overall,

Table 4
Canna plant fresh weight and its uptake of N and P.

CWs	Harvest fresh weight (kg)	Plant dry weight (kg)	Plant N content (mg/g)	Plant P content (mg/g)	N uptake (g)	P uptake (g)
Z1						
1 time	6.50	0.63	19.43	1.90	12.24	1.20
2 times	4.45	0.43	11.00	1.12	4.73	0.48
3 times	3.80	0.26	2.51	0.24	0.65	0.06
4 times	2.55	0.29	2.13	0.26	0.62	0.08
5 times	3.45	0.22	1.77	0.33	0.39	0.07
Total					18.63	1.89
Z2						
1 time	7.25	0.60	18.66	2.13	11.20	1.28
2 times	7.50	0.69	11.90	1.76	8.21	1.22
3 times	4.55	0.35	2.70	0.26	0.95	0.09
4 times	6.25	0.53	2.35	0.28	1.25	0.15
5 times	7.00	0.53	1.62	0.33	0.86	0.18
Total					22.47	2.92
Z3						
1 time	4.30	0.37	20.92	1.39	7.74	0.52
2 times	4.30	0.39	13.21	1.63	5.15	0.64
3 times	4.30	0.32	2.58	0.26	0.83	0.08
4 times	2.30	0.19	2.17	0.29	0.41	0.06
5 times	1.65	0.14	1.24	0.20	0.17	0.03
Total					14.27	1.33
Z4						
1 time	3.75	0.30	20.11	2.02	6.03	0.61
2 times	3.05	0.29	12.92	1.56	3.75	0.45
3 times	3.05	0.22	2.65	0.27	0.58	0.06
4 times	2.20	0.25	2.42	0.30	0.61	0.08
5 times	3.95	0.26	1.80	0.36	0.47	0.09
Total					11.44	1.29

the Z2 and Z3 CWs were superior to the traditional subsurface flow (Z4) CW for pollutant removal.

The average removal rates of different water quality constituents at HRT = 2d are shown in Fig. 5 and Table 3. It is apparent that the removal rates of NH₄⁺ - N, TN and TP were highest for Z3, followed by Z1, and was lowest for Z2. Fig. 5 further revealed that the COD removal efficiency was the highest for Z1, followed by Z3, and was lowest for Z2. Different results were obtained for BOD₅. That is, the BOD₅ removal rate was the highest for Z1, followed by Z4, and was lowest for Z2.

Table 3 also showed that the average removal rates of NH₄⁺ - N, TN, TP, COD, and BOD₅ were in the following order: Z3 (84.20%) > Z1 (83.43%) > Z4 (78.81%) > Z2 (71.64%). The reason on lowest overall removal efficiency in Z2 CW at HRT = 2 was because the wastewater flowed directly from inlet to outlet in this CW, which reduced its contact time with substrate inside the CW. The average removal rates of NH₄⁺ - N, TN, TP, COD, BOD₅ by the hybrid baffle system at HRT = 2d during the 6-month experiment were, respectively, 77.60, 53.75, 95.88, 83.25, and 83.69% (Table 3), and the average effluent concentrations were, respectively, 26.32, 75.43, 0.53, 57.58, and 20.76 mg/L. As shown in Table 3, the hybrid

Table 3
Comparison of efficiency of pollutants removal by the four CWs at HRT = 2d.

Pollutants	Z1	Z2	Z3	Z4	P value
NH ₃ -N (%)	92.75 (3.25)a	83.99 (6.27)a	94.78 (1.51)a	85.66 (5.11)a	P = 0.2667
TN (%)	56.25 (5.05)a	46.85 (6.02)a	61.67 (5.47)a	53.43 (4.17)a	P = 0.2732
TP (%)	93.52 (0.93)a	90.32 (4.11)a	95.34 (1.95)a	92.49 (2.49)a	P = 0.6026
COD (%)	82.90 (0.42)a	62.05 (2.48)b	79.32 (5.83)a	70.67 (5.85)ab	P = 0.0125
BOD ₅ (%)	91.74 (2.29)a	75.01 (5.83)b	89.87 (2.99)a	91.81 (2.22)a	P = 0.0099
Average	83.43	71.64	84.2	78.81	

(1) Numbers in the table are averaged values followed by standard errors. Six samples for each pollutant species are used for analysis.

(2) Duncan's multiply comparisons are used in this analysis and the same letters for each column mean no statistical difference at $p = 0.05$.

Table 5
Removal of N and P by plant uptake.

Index	CW	Inflow (m ³)	Initial average concentration (mg/L)	Pollutant remove (g)	Plant uptake (g)	Percentage of plant uptake (%)
TN	Z1	23.30	145.33	843.68	18.63	2.21
	Z2	19.36	145.33	989.73	22.47	2.27
	Z3	21.86	145.33	985.29	14.27	1.45
	Z4	25.69	145.33	1164.77	11.44	0.98
TP	Z1	23.30	12.83	252.41	1.89	0.75
	Z2	19.36	12.83	208.00	2.92	1.40
	Z3	21.86	12.83	269.99	1.33	0.49
	Z4	25.69	12.83	299.25	1.29	0.43

Table 6
Comparison of removal efficiency of nutrients between our study and other studies.

Nutrient	Horizontal baffle flow CW		Vertical baffle flow CW		HF-VF baffle hybrid CW		Horizontal subsurface flow CW		
	This study	Saeed et al. (2014) ^a	This study	Saeed et al. (2014) ^a	This study	Tee et al. (2012) ^b	This study	Saeed et al. (2014) ^a	Mburu et al. (2013) ^c
NH ₄ ⁺ – N (%)	92.75	28.9	83.99	50.0	94.78	74	85.66	55	8
TN (%)	56.25	–	46.85	–	61.67	–	53.43	–	–
TP (%)	93.52	63.5	90.32	37.5	95.34	–	92.49	85	26
COD (%)	82.90	55.8	62.05	63.1	79.32	59	70.67	90	86
BOD ₅ (%)	91.74	83.0	75.01	77.3	89.87	–	91.81	–	87

^a CW plant: Macrophytes; CW substrates: saw-dust, coal, pea gravel, small sized gravel, and sylhet sand; feed water: municipal wastewater.

^b CW plant: cattail; CW substrates: rice husk and gravel; feed water: primary-treated domestic wastewater.

^c CW plant: *Cyperus papyrus*; CW substrates: gravel; feed water: university campus' domestic wastewater.

baffle CW (Z3) was the best CW for overall removal of pollutants from wastewater at HRT = 2d.

3.4. N and P removal by plant

The aboveground biomass (fresh weight) and the contents of N and P in the biomass for the four CWs are shown in Table 4. The average fresh weight of the plant from the vertical baffle flow CW (Z2) was highest among the four CWs and they were in the following order: Z2 (6.51 kg) > Z1 (4.15 kg) > Z3 (3.37 kg) > Z4 (3.20 kg). Although the exact reason remains unknown, a possible explanation would be the higher dissolved oxygen content in the Z2 CW, which provided a favorable condition for plant growth.

Uptake of N by plant roots from the Z1, Z2, Z3, and Z4 CWs accounted, respectively, for only 2.21, 2.27, 1.45, and 0.98% of total N removal from wastewater (Table 5). This finding was lower than those reported by Klomjek and Nitorisavut (2005). These authors found that the rates of N uptake by wetland plants such as *Cyperus corymbosus*, *Diceros bicornis*, *Lacuna fusca*, *Brachiaria mutica* and *Spartina patens* were, respectively, about 77.0, 47.5, 31.1, 16.4, and 9.8%. Compared with N removal by microbes through nitrification and denitrification, plant uptake was not an important pathway for N removal in CWs.

Table 5 further showed that the removal efficiency of P through plant uptake in the Z1, Z2, Z3, and Z4 CW accounted, respectively, for 0.75, 1.40, 0.49, and 0.43% of TP removal. This finding was lower than our previous study (average 11.3% of TP removal) in the aboveground biomass by *Cyperus alternifolius* (Cui et al., 2011).

Table 6 compares the removal efficiency of nutrients from wastewaters in CWs between our study and those studies performed by Mburu et al. (2013), Tee et al. (2012), and Saeed et al. (2014). Saeed et al. (2014) study the nutrient removal efficiency of baffled subsurface flow and hybrid surface flow CWs in Bangladesh. Their CW substrate consists of saw-dust, coal, pea gravel, small sized gravel, and sand and the CW plant species is macrophytes. These authors found that the removal efficiency is 83.0% for BOD₅ and 28.9% for NH₄⁺ – N. It is apparent from Table 6 that the removal

efficiency of nutrients from our study was much better than those reported by others. This could occur partially because different CW designs were used and partially because different CW plant species and substrates were employed between our study and other studies.

4. Conclusions

Three newly designed baffle flow CWs (i.e., Z1, Z2, and Z3) were employed to remove pollutants from septic tank wastewater. Results showed that these baffle flow CWs performed much better than the traditional horizontal subsurface flow CW (Z4) in

removing nutrients from the wastewater.

Under the same HRT, the overall removal efficiencies of NH₄⁺ – N and TN from the vertical baffle CW (Z2) were highest among the four CWs, while the overall removal efficiencies of TP, COD, and BOD₅ from the hybrid baffle CW (Z3) was highest among the four CWs.

In general, the removal of pollutants from the wastewater for the four CWs was highest at HRT = 2d. Of which, the hybrid baffle CW (Z3) was the best CW for overall removal of pollutants from wastewater at HRT = 2d.

The vertical baffle flow CW (Z2) produced the highest amount of fresh weight biomass among the four CWs. Uptake of N and P by roots from the CWs accounted for <3% of TN and TP removals from wastewater and was a less important pathway for removing pollutants.

Further study is warranted to conducting experiments to compare different plant species as well as to explore the role of microbes in removal of nutrients from wastewater in the CW systems. Additionally, the effects of environmental factors such as pH, temperature and initial concentrations of TN and TP upon nutrient removal should also be considered.

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