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Original Article

Wastewater treatment performances of horizontal and vertical subsurface flow constructed wetland systems in tropical climate

Suwasa Kantawanichkul* and Suparurk Wannasri

Department of Environmental Engineering, Faculty of Engineering,
Chiang Mai University, Mueang, Chiang Mai, 50200 Thailand.

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Abstract

The study was carried out in 4 concrete beds: two vertical subsurface flow beds (dimension of 1x1.4 x 0.6 m^3) and two horizontal subsurface flow beds (dimension of 0.6 x 2.3x 0.6 m^3) planted with *Cyperus alternifolius L.* Under the average wastewater temperature of 27°C, the hydraulic loading rates (HLR) were varied from 5 to 20 cm/d in order to obtain the optimum operating conditions and compare the removal efficiency. The wastewater was intermittently fed into the vertical subsurface flow beds (5 minutes on and 55 minutes off), and continuously into the horizontal subsurface flow beds. The maximum removal efficiencies were found at the lowest hydraulic loading rate for both systems. The horizontal subsurface flow system had a higher removal rate than the vertical subsurface flow system in terms of COD (the removal rates at 5-20 cm/d were 9.6-33.9 $g/m^2.d$). The vertical subsurface flow system showed higher removal efficiency for TKN and NH_4^+-N, in every hydraulic loading rate and the removal rates for TKN and NH_4^+-N were 0.4-1.1 $g/m^2.d$, respectively. Furthermore, it was found that the uptake of N by plants in the horizontal flow system was higher than in the vertical flow system for every hydraulic loading rate (HLR) but the loss of N via adsorption/denitrification was higher in the vertical flow system than in the horizontal flow system, at 20 cm/d HLR. The removal rate constants in the horizontal subsurface flow system for COD and NH_4^+-N were 0.0166 and 0.0188 m/d and 0.0204 and 0.0287 m/d for the vertical subsurface flow system, respectively.

Keywords: constructed wetland, domestic wastewater, horizontal flow, treatment, vertical flow

1. Introduction

A constructed wetland is an appropriate system for wastewater treatment in tropical countries, especially in rural areas where large areas of land are available and high technology is restricted, due to the lack of expertise in the construction and operation. In Thailand, the use of constructed wetland systems is not widespread but it is expected to be recognized more due to the fact that they are sustainable and energy saving.

So far, study of subsurface flow constructed wetland systems has been extensively conducted in temperate and cold climates but not in the tropics, especially regarding the design parameters, which help the system work properly. It has been proven that a horizontal subsurface flow (HF) constructed wetland can effectively remove organic pollutants such as COD (Chemical Oxygen Demand), BOD (Biochemical Oxygen Demand) and SS (Suspended Solids) but it is 50-60% efficient for nitrogen removal due to the limited oxygen transfer inside the wetland bed. For a vertical subsurface flow (VF) constructed wetland system, the intermittent flow provides a high potential for oxygen transfer rate (Platzer, 1996; Cooper *et al.*,1996) resulting in good nitrification as well as BOD removal, but a lower removal efficiency for suspended solids than HF systems (Vymazal & Kropfelova, 2008).

The objectives of this study were to compare the performances and the treatment efficiencies of HF and VF

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* Corresponding author.
Email address: suwasa@eng.cmu.ac.th

systems under a tropical climate. Three hydraulic loading rates (HLR) were used to find the optimum operation and design criteria.

2. Materials and Methods

The study was conducted at Chiang Mai University, Chiang Mai, Thailand, under an average ambient temperature of 27°C (in the range of 25.7-28.7°C), using 2 concrete VF beds and 2 concrete HF beds. The VF beds (1 x 1.4 m^2) were filled with coarse gravel (3-6 cm) to a depth of 15 cm, topped with 45 cm of small gravel (1 cm) as shown in Figure 1. The HF beds (0.6 x 2.3 m^2) have filled with 20 cm coarse gravel (3-6 cm) at the inlet and outlet zone, and 1.9 m of small gravel (1.0 cm) in the plantation zone. The depth of gravel layer was 60 cm in every bed. For the HF bed, the outlet pipe was raised up to keep the water level within 55 cm of the bed (Figure 2). Umbrella sedge (*Cyperus alternifolius* Linn) was planted at 25 cm intervals. Wastewater from Chiang Mai University treatment plant (Table 1) was used in this study. To acclimatize the plants to the wastewater, the wastewater was diluted and the concentration was gradually increased from 30 to 65 and then 100% within 4 weeks. The influent and the effluent were collected and analyzed every 5 days (during 96 days of the experiment) for COD, BOD, TKN (Total Kjeldahl Nitrogen), NH_4^+-N (Ammonia Nitrogen), NOx-N (Oxidized Nitrogen), SS and TP (Total Phosphorus) (APHA,2005). At the end of the experiment, plants were removed and dry weight was evaluated. N content of plant biomass before and after the experiment was measured to determine N accumulation in plants.

Three HLRs of 5, 10 and 20 cm/d were employed. In the first experiment, hydraulic loading rates of 5 and 10 cm/d were conducted in 2 VF and 2 HF beds from September 2009 to January 2010. The second experiment, with only 1 VF and 1 HF bed operated under 20 cm/d HLR from June to September 2010. In the VF beds, the wastewater was intermittently fed (5 minutes on and 55 minutes off) and in the HF beds it was fed continuously. The reaction rate constants (k) for the COD and NH_4^+-N were analyzed using a first order, plug flow model (Kadlec and Knight, 1996) as follows:

$$k = HLR(\ln C_{in} - \ln C_{out})$$

where k = area-based reaction rate constant, (m/day)
HLR = hydraulic loading rate, (m/day)
C_{in}, C_{out} = concentration in the influent and the effluent, (mg/l)

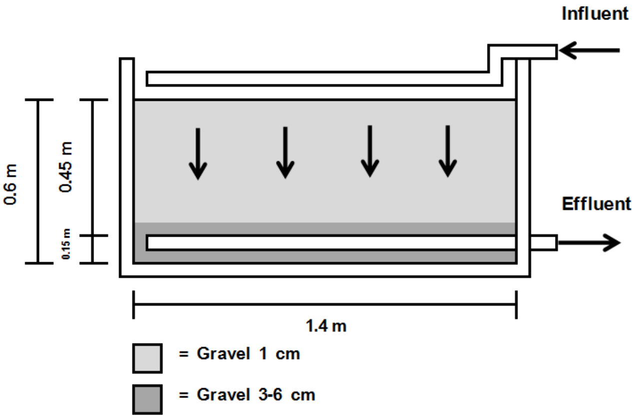


Figure 1. Schematic of VF bed.

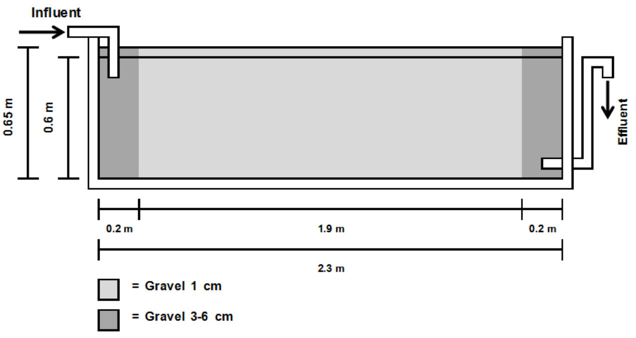


Figure 2. Schematic of HF bed.

Table 1. Characteristics of domestic wastewater used in this study (n = 20)

parameter	unit	values			
		maximum	minimum	average	SD
pH	-	7.2	7.0	7.1	0.1
Temp	ºC	28.7	25.6	27.0	1.0
COD	mg/L	297.6	241.2	267.4	16.4
BOD	mg/L	134.9	108.8	120.9	8.3
TKN	mg/L	17.8	13.7	16.0	1.1
NH_4^+-N	mg/L	11.6	9.9	10.4	0.6
NO_2-N	mg/L	0.02	0.00	0.01	0.0
NO_3-N	mg/L	0.80	0.56	0.6	0.1
SS	mg/L	235.0	184.0	199.8	13.2
TP	mg/L	1.7	1.0	1.3	0.2

3. Results and Discussion

The average temperature and pH of the wastewater were 27°C and 7.1, whereas after being passed through the subsurface constructed wetland beds, the pH was reduced to around 6.8-7.0 and the pH in the effluent from the VF beds was a little lower than in HF beds. Nitrification in the VF beds produced acid resulting in low pH in the effluent (Kadlec and Wallace, 2009).

The void ratio of the gravel bed was 0.41 and calculated HRT (hydraulic retention time) of HF was 4.9,2.4 and 1.2 days at HLR of 5, 10 and 20 cm/d, respectively. The COD and BOD removal rates were reduced with increasing HLR in both the HF and VF beds. The removal efficiencies of COD were 54.8-64.8% in HF beds and 32.9-50.4% in VF beds. Organic particulates were rather high in the raw wastewater, relating to 272.1 mg/L for total COD and 170.8 mg/L soluble COD. Longer contact time between the wastewater and microorganisms, in the HF beds, resulted in higher removal efficiency than in the VF beds. When the removal rate was considered, it was higher in HF beds compared to VF beds as shown in Figure 3 and the removal rates were 9.6-33.9 gCOD/m^2.d in the HF beds and 7.4-20.6 g/m^2.d in the VF beds.

The organic loading rates of COD revealed a positive correlation with the organic removal rates for both HF and VF beds. Besides this, it also showed that the removal efficiencies, in terms of BOD, were higher than those of COD and in the range of 91.2- 94.1 % and 86.5-88.2% for HF and VF beds, respectively. Organic compounds are aerobically and anaerobically degraded by the microorganisms attached to the plant roots and media surface (Vymazal and Kropfelova, 2008). The reduction of SS was slightly higher in HF beds than in the VF beds but they were over 96% (96.8-99.5%) in both systems, at all HLRs, but TP was very low in the influent (1.3 mg/L in average). The removal efficiency of TP was 5.6-16% in VF beds but TP could not be detected in the HF system at 5 and 10 cm/d, yet TP removal efficiency of 47% was found at 20 cm/d HLR.

HF beds have lower ability to oxidize ammonia to nitrate due to their limited oxygen transfer capacity (Vymazal, 2001), and the production of NH_4^+-N by ammonification is known to be faster in a VF bed than in a HF bed as the mineralization rates are faster in the oxygenated zone in a VF bed (Reddy and Patrick,1984). Moreover, intermittent feeding in a VF constructed wetland system has been proved to be very efficient, compared to that in a HF system, due to high oxygen transfer within the bed (Cooper *et al.*,1996). The biological conversion of ammonia to nitrite and nitrate, by chemoautotrophic processes under the aerobic condition is called nitrification. It was found in this study that the removal rates of TKN and NH_4^+-N in VF beds were superior to those in HF beds (Figure 4) and the higher concentration of NO_2-N and NO_3-N supported the efficient nitrification in the VF bed. The concentration of NH_4^+-N in the effluent also increased with increasing HLR (Figure 5), which was due to shorter HRT for nitrification in both the HF and VF beds. Furthermore, TKN and NH_4^+-N loading rates were highly correlated ($p<0.05$) with the removal rates of both VF and HF beds as shown in Figure 6.

There was only 0.5 mg/L of NO_3-N and very little NO_2-N in the influent. The results indicate that nitrification is

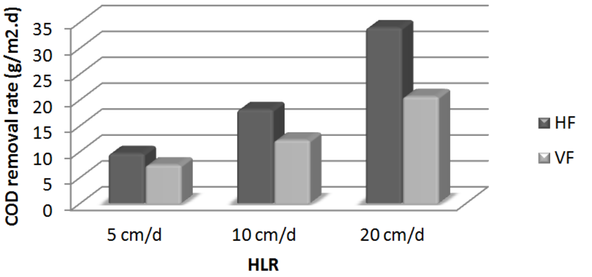


Figure 3. COD removal rates in HF and VF beds

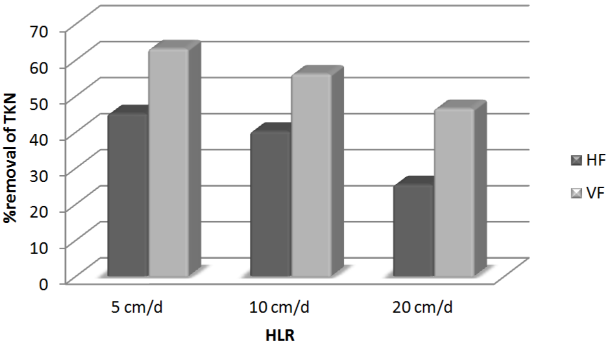


Figure 4. Removal efficiency of TKN in HF and VF beds.

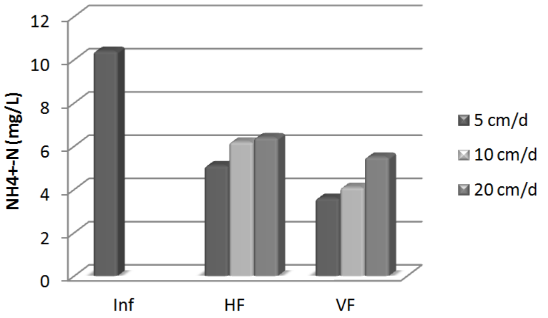


Figure 5. Concentration of NH_4^+-N in the influent and effluent from HF and VF beds.

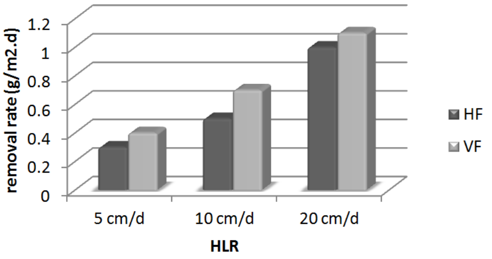


Figure 6. NH_4^+-N removal rate in HF and VF beds.

very limited in HF beds, and denitrification was possible to accelerate the reduction of oxidized nitrogen. It was found that NO_3-N in the effluent of the HF beds of the 3 HLRs were only 0.6-0.8 mg/L compared to 2.8-5 mg/L in VF beds. Nitrification in the 5 cm/d HLR was highest due to sufficient HRT for nitrification; by contrast, nitrification was reduced to 2.8 mg/L in the 20 cm/d HLR.

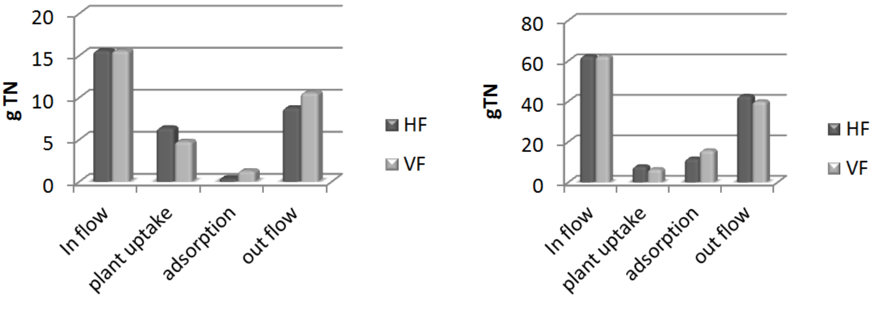
Normally, part of TN in the influent is used by plants and microorganisms and the rest can be lost through adsorption, volatilization and denitrification. Adsorption and volatilization are limited in the constructed wetland systems (Vymazal and Kropfelova,2008) especially in neutral conditions. Furthermore, denitrification can occur in anoxic areas in a VF bed (Cooper *et al*., 2010).

In this study, the nitrogen balance of the systems was analyzed by calculating TN loading in the influent and the effluent of the entire experimental period. The reduction of N caused by plant uptake was measured in the dry plant biomass at the end of the experiment, whereas the rest of N reduction was assumed to have been lost by adsorption, volatilization and/or denitrification. It was found that TN removal efficiency at different HLRs in the HF beds was different from that in the VF bed, and the N balance of both systems at HLR 5 and 20 cm/d is shown in Figure 7. The removal of TN in the HF bed at 5 cm/d HLR was mainly through plant uptake (41%), and in the VF bed at 20 cm/d was mainly by adsorption/denitrification (25.4%).

N uptake by plant was 6.4 gN in HF beds compared to 4.8 gN in VF beds at 5 cm/d HLR or 7.9 and 6.5 gN in HF and VF beds especially at 20 cm/d HLR. The accumulation of N in plant was found to be higher in HF beds as a result of longer contact time between plants and N in the wastewater. The percentage of N uptake by plant was maximum at the lowest HLR (5 cm/d) or 41.0% in HF bed. Nitrogen uptake by plants is not thought to be a major pathway for its removal in a treatment wetland system especially when high loadings are applied. Recently, Kantawanichkul *et al.* (2009) reported the nitrogen uptake of 16.9% by the same plant spp. (*Cyperus alternifolius* L) in a VF system using synthetic wastewater with NH_4^+-N concentration around 300 mg/L and HLR 2 cm/d, Kantawanichkul and Boontakhum (2012) used synthetic wastewater with NH_4^+-N concentration 339 mg/L, HLR 5 cm/d and found nitrogen uptake to be 13.7%. An uptake of 10.05% was reported by Suracoop and Kantawanichkul (2010) using anaerobic digester effluent from pig farm wastewater with NH_4^+-N concentration 153 mg/L and HLR 14 cm/d in VF beds planted with *Cyperus alternifolius* L. Kantawanichkul *et al.* (2003) found only 3-4% nitrogen accumulation in *Scirpus grossus* L. in a combined (HF+VF) system fed with anaerobic digester effluent from pig farm wastewater with NH_4^+-N concentration around 340 mg/L and HLR 6 cm/d. Therefore, the uptake by plant in HF beds was higher than that in VF beds. At low HLR, it is possible that the major pathway of nitrogen removal was by plant uptake due to low N loading compared to other reports above. When TN loading increased according to the increasing of HLR (62.3 gN at HLR of 20 cm/d), plant uptake was reduced to 12.7 and 10.4% of TN loading in VF and HF systems respectively. It can be assumed that N uptake by plant was higher in HF than VF due to longer HRT, which provided better contact time for nutrient adsorption.

The removal rate constants of VF and HF systems were investigated using plug flow, first order reaction as presented by Kadlec and Knight (1996). The $k_{(NH4-N)}$ for HF and VF were 0.018 and 0.0287 m/d, respectively. Kantawanichkul and Somprasert (2005) reported $k_{(NH4-N)}$ of 0.041 and 0.034 m/d for HF and VF for pig farm wastewater using a compact combined system at the same range of temperature. The values of $k_{(COD)}$ were 0.0166 and 0.0204 m/d for HF and VF which was much lower than 0.134 m/d reported by Kantawanichkul *et al.* (2009) under the same environment but using high N concentrations in synthetic wastewater.

However, the k values for both NH_4^+-N and COD in this study were significantly higher in VF system than HF system. The higher oxygen transfer rate in VF supported the aerobic biological degradation and nitrification.



(a) (b)

Figure 7. N balance of HF and VF beds at HLR of (a) 5 cm/d (b) 20 cm/d (adsorption = adsorption+ volatilization and/or denitrification)

4. Conclusions

Both HF and VF systems have high performance for organic carbon and SS removal. Nitrification is superior in a VF system. When N balance was considered, it was found that N uptake by plant in HF was higher than that in VF beds for every HLR but the loss of N via adsorption/denitrification was higher in VF than HF beds at 20 cm/d HLR. However, at the HLR of 20 cm/d, the effluent was still met the national effluent standard of Thailand for domestic wastewater.

The removal rate constants for COD (k_{COD}) and NH_4^+-N (k_{NH4+-N}) were 0.0166 and 0.0188 m/d in HF system and 0.0204 and 0.0287 m/d in VF system, respectively.

Acknowledgement

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