Treatment of agricultural wastewater in two experimental combined constructed wetland systems in a tropical climate

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Abstract Two designs of experimental combined constructed wetland systems were constructed: vegetated (*Scirpus grossus Linn*) subsurface horizontal flow bed followed by a vegetated vertical flow bed and a vegetated vertical flow bed over an unvegetated horizontal flow sand bed. The systems were used to compare the nitrification/denitrification efficiency in a tropical climate which has temperatures above an average of 25°C throughout the year. The effluent from a biogas digester of pig farm wastewater with TKN and COD concentrations of approximately 400 and 1,000 mg/L was fed every 4 hours intermittently. The effluent was recycled to the system with the ratio of 1:1 and the hydraulic loading rate was increased from 3 to 6 and 12 cm/d including recycled water. At higher hydraulic loading rates, nitrogen COD and BOD removal efficiencies were lower. The SS, TP and fecal coliform bacteria removal efficiencies were not clearly affected by the high hydraulic loading or the different layout of the system. Nitrogen uptake by plants was very low in relation to the nitrogen loading of the systems. In general, the removal efficiencies of both types were comparable but the system with a vertical flow over horizontal flow sand bed is more suitable for sites with limited land area, although its construction can be more difficult than the system with horizontal flow followed by a vertical flow bed.

Keywords Combined system; farm wastewater; nitrification/denitrification

Introduction

Water pollution problems have been increasing in Thailand, especially wastewater from agro-industries which have no proper treatment systems. There are many large pig farms currently using anaerobic treatment systems to treat their wastewater but although biogas is produced as a by-product, the effluent from anaerobic systems still exceeds the national effluent standard. Constructed wetlands are an appropriate option for post treatment but the existing surface flow systems are still not effective due to high ammonia concentration in the wastewater. In this study, a combined subsurface flow system was introduced because previous studies have recorded good nitrogen removal by this system design (Vymazal, 2001). Many reports (Cooper and de Maeseneer, 1996; Laber *et al.*, 1999; Urbanc-Bercic and Bulc, 1994) confirmed that subsurface vertical flow is efficient for nitrification and horizontal flow is good for denitrification. Normally, a combined system consists of a horizontal flow bed followed by a vertical flow bed or vice versa. Kantawanichkul *et al.* (2001) reported the high treatment efficiencies of a vertical flow vegetated bed over a horizontal flow sand bed. A comparison of the performance of the two system designs is reported in this paper.

Methodology

The experimental system is composed of two combined constructed wetlands; system A, a vegetated vertical flow bed over an unvegetated horizontal flow sand bed system, and system B, a vegetated subsurface horizontal flow bed followed by a vegetated vertical flow bed. System A is composed of a concrete tank, 2 × 2 × 1.4 m. The tank was separated into two sections by a plastic PVC sheet (0.25 mm). The upper section was filled with gravel (30–60 mm) for 0.15 m depth followed by gravel (10–12 mm) for 0.15 m depth and coarse sand (1–2 mm) for the last 0.3 m from bottom to top. *Scirpus grossus Linn.* were planted at 25 cm intervals. The lower section with 60 cm depth was filled with media from left to right: gravel (30–60 mm) for 0.2 m, coarse sand (1–2 mm) for 1.6 m and gravel (30–60 mm) for the last 0.2 m. Swine wastewater from an anaerobic treatment system was fed intermittently (4 hours on and 4 hours off) to the top of the lower section of the tank. The water infiltrated horizontally and across to the bottom of the tank and collected at the opposite side. The effluent pipe was raised up to saturate the media then fed to the surface of the upper section and the wastewater flowed vertically down to the bottom. The treated wastewater was collected by perforated pipes and recycled to the lower section of the system at a ratio of 1:1 as shown in Figure 1. Recycling of the effluent can enhance the nitrogen removal efficiency and Kantawanichkul and Neamkam (2001) reported the optimum was a 1:1 recycle ratio.

System B is composed of two tanks connected in series. The first tank, 1.5 × 2.5 × 0.6 m, was filled from left to right with gravel (30–60 mm) for 0.2 m, coarse sand (1–2 mm) for 2.1 m and gravel (30–60 mm) for the last 0.2 m. The second tank, 2.0 × 2.0 × 0.6 m, was filled from bottom to top with gravel (30–60 mm) for 0.15 cm, gravel (10–12 mm) for 0.15 m and coarse sand (1–2 mm) for 0.3 m. *Scirpus grossus Linn.* was planted at 25 cm intervals in both tanks. Wastewater was fed to the first tank via perforated PVC pipe and infiltrated horizontally down and across to the bottom of the opposite side. The water level was maintained to saturate the media in the horizontal flow bed and was then collected via a perforated PVC pipe and conveyed to the second tank by the perforated PVC pipes laid on the surface of the media. The water trickled down through the media to the bottom and was collected in a perforated pipe laid on the bottom. The effluent was recycled to the first tank with a ratio of 1:1 as shown in Figure 2.

The height of plants was measured every week. After each run, the plants were randomly harvested to analyze for dry weight and N content. Plants were also cut to the same height (80 cm) before starting the new run.

The wastewater used in the experiment was the effluent from an anaerobic channel digester followed by UASB at Kittiwat pig farm, Chiang Mai. Both systems were fed intermittently (4 hours on and 4 hours off) with hydraulic loading rates of 3, 6 and 12 cm/d including recycled water. The raw wastewater, mixed recycled water and the effluent from vertical and horizontal flow beds were analyzed for total Kjeldahl nitrogen (TKN), ammonia (NH_3-N), oxidized nitrogen (NO_x-N), total nitrogen (TN), chemical oxygen demand

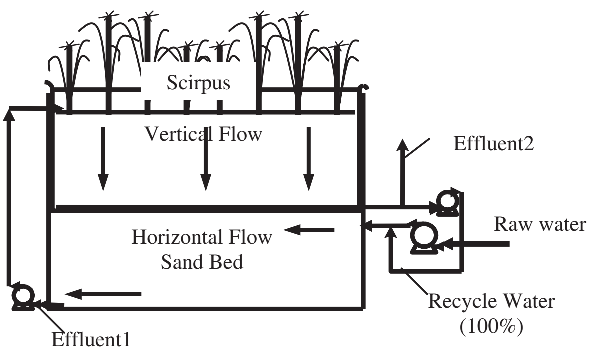

Figure 1 The experimental design of system A

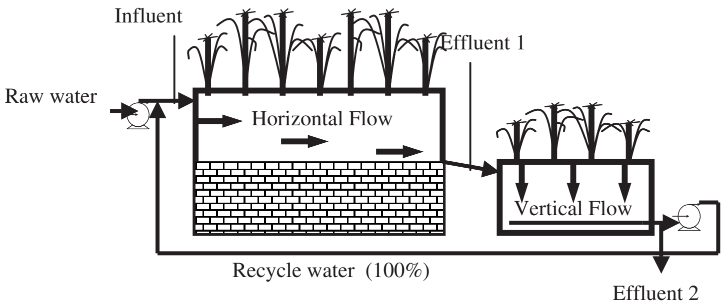

Figure 2 The experimental design of system B

(COD), biochemical oxygen demand (BOD), total phosphorus (TP), suspended solids (SS), alkalinity, pH and fecal coliform bacteria (FC) according to Standard methods for the examination of water and wastewater (1995).

Results and discussions

Hydraulic loading rate of 3 cm/d

During 120 days of the experiment (June to September), the average temperature and pH of wastewater were 29°C and 7.9. The concentration of TKN in the raw wastewater was about 400 mg/L (20.5 g/m^2.d for system A and 27.7 g/m^2.d for system B). After mixing with recycled effluent, the concentration was diluted to 227 mg/L as shown in Table 1. The pattern of nitrogen removal was almost the same for both systems. Nitrification was satisfactory in the vertical flow vegetated bed and denitrification was also clearly noticeable in the horizontal flow bed. Most of the TKN and NH_3-N concentration was reduced by nitrification in the vertical flow vegetated bed resulting in 19.6 gTKN/m^2.d removal rate in the final effluent of system A and 27.6 gTKN/m^2.d in system B. Ammonia volatilization is not a major pathway for nitrogen removal in constructed wetlands. Hunt and Poach (2001) explained that anaerobic ammonia oxidation performed by ammonia-oxidizing bacteria can convert ammonia to dinitrogen gas and requires only half of the O_2 needed in the conventional nitrification/denitrification process. In this experiment, oxidized nitrogen (NO_x-N) was very low (0.7–0.9 mg/L), after mixing with recycled effluent, the concentration increased to 12 and 25 mg/L in systems A and B. Denitrification in the horizontal flow bed reduced NO_x-N to 0.3–0.5 mg/L and it increased again by nitrification in the vertical flow bed to 38 and 73 mg/L in systems A and B respectively.

Most phosphorus was in the form of suspended particles. The removal efficiency of dissolved phosphorus was 97–99% (1.1–1.4 g/m^2.d). The main mechanism for the removal was presumed to be by adsorption and precipitation with iron in the sand media at a concentration of approximately 27.5 ppm. It also appeared that the removal efficiency decreased with time after 300 days due to the saturated adsorption capacity of sand. Hunt and Poach (2001) referred to Szogi *et al*. (1994) who found a rapid decline of P removal efficiency from 99 to 78% in one year for constructed wetlands treated swine wastewater.

The average organic loading rates in terms of COD and BOD in the raw wastewater were 53.6 g/m^2.d and 21.4 g/m^2.d for system A and 82.9 g/m^2.d and 31.5 g/m^2.d for system B, respectively. The ratio of COD:BOD was rather high due to prior digestion in the anaerobic system. The reduction was about 60% in the horizontal flow bed and over 70% in the vertical flow bed and resulted in a 52.2 g/m^2.d removal rate in the final effluent of system A and 82.0 g/m^2.d in system B.

SS and fecal coliform bacteria achieved 98–99% removal efficiency and SS concentrations were lower than 10 mg/L in the final effluent.

Table 1 Performances and removal efficiencies of systems A and B at 3 cm/d (n = 14 except FC and BOD, n = 7)

	System A					System B				
	Raw	Inf.	Eff 1	Eff 2	% removal	Raw	Inf.	Eff 1	Eff 2	% removal
TN,	411	239	218	97	76	416	249	188	77	79
mg/L	*(±52)*	*(±32)*	*(±31)*	*(±20)*		*(±84)*	*(±47)*	*(±53)*	*(±32)*	
TKN,	411	227	218	59	85	415	226	187	8	98
mg/L	*(±52)*	*(±32)*	*(±31)*	*(±28)*		*(±84)*	*(±53)*	*(±53)*	*(±8)*	
NH_3-N,	328	191	186	51	84	346	177	182	7	98
mg/L	*(±48)*	*(±34)*	*(±47)*	*(±25)*		*(±72)*	*(±33)*	*(±47)*	*(±8)*	
NO_x^--N,	0.7	12.5	0.3	38.1		0.9	24.6	0.5	73.7	–
mg/L	*(±0.5)*	*(±6)*	*(±0.2)*	*(±25)*	–	*(±0.9)*	*(±13)*	*(±1)*	*(±30)*	
COD,	1,072	484	186	92	91	1,243	561	205	57	95
mg/L	*(±322)*	*(±123)*	*(±54)*	*(±37)*		*(±270)*	*(±124)*	*(±107)*	*(±40)*	
BOD,	429	84	59	15	96	472	108	40	10	98
mg/L	*(±192)*	*(±42)*	*(±35)*	*(±6)*		*(±250)*	*(±67)*	*(±34)*	*(±7)*	
SS,	547	227	39	4	98	1,023	356	25	3	99
mg/L	*(±232)*	*(±124)*	*(±81)*	*(±4)*		*(±721)*	*(±139)*	*(±13)*	*(±2)*	
TP,	22	18	4	0.6	97	21	21	3	0.3	99
mg/L	*(±6)*	*(±4)*	*(±1)*	*(±0.5)*		*(±5)*	*(±9)*	*(±2)*	*(±0.3)*	
FC,	1×10^8	2×10^6	8×10^4	2×10^2	99	1×10^8	3×10^6	9×10^4	1×10^2	99
MPN/ 100 mL	$(\pm 1 \times 10^8)$	$(\pm 2 \times 10^6)$	$(\pm 8 \times 10^4)$	$(\pm 1 \times 10^2)$		$(\pm 2 \times 10^8)$	$(\pm 6 \times 10^6)$	$(\pm 1 \times 10^5)$	$(\pm 1 \times 10^2)$	

Hydraulic loading rate of 6 cm/d

In this experiment, the hydraulic loading rate of raw wastewater plus recycled effluent was increased to 6 cm/d. During 120 days (November to February) the average temperature of the wastewater was 25°C and pH 7.9. TKN and NH_3-N of raw wastewater were around 414 and 346 mg/L, diluted to about 252 and 218 mg/L after mixing for system A, and 430 and 361 mg/L, diluted to 243 and 199 mg/L after mixing for system B, respectively. The loading rates of TKN for systems A and B were equivalent to 41.4 g/m^2.d and 57.3 g/m^2.d.

In system A, the density of plants was higher than the previous run, resulting in higher nitrogen and carbon from plant debris in the effluent. Therefore, the vertical flow bed was clogged during the last few weeks and anaerobic conditions developed within the bed. During this season the evaporation and evapo-transpiration rates were also high and adversely affected the health of plants in both systems.

The pattern of N removal was similar to the previous run. Therefore, the removal rate of TKN in systems A and B increased to 37.5 g/m^2.d and 55.8 g/m^2.d due to the higher hydraulic loading rate. The change of oxidized nitrogen was satisfactory. NO_{x-}N in the mixed water was 19.3 and 50.5 mg/L in systems A and B, denitrification in the horizontal flow bed reduced NO_x-N to 0.1 and 1.2 mg/L and it increased again to 47.5 and 98.4 mg/L by nitrification in the vertical flow beds of systems A and B, respectively. The removal efficiencies of BOD, TP, SS and FC were 90–99% as shown in Table 2. The adsorption of dissolved TP decreased from 97 and 99% to 93 and 90% in systems A and B.

Hydraulic loading rate of 12 cm/d

Before starting this run, in order to eliminate the clogging problem, the geotextile wrapping around the outlet pipes of the vertical flow bed in system A was removed. Plants were unavoidably taken out and replanted, and therefore the density of plants was lower than in the previous run. The average temperature and pH of the wastewater was 28°C and 7.8. The experiment was performed for 100 days (March to July).

TKN removal rate was increased from 37.5 and 55.8 g/m^2.d in previous runs to 78.5 and 96.0 g/m^2.d in systems A and B, respectively. Other parameters had similar removal

Table 2 Performances and removal efficiencies of systems A and B at 6 cm/d (n = 17 except FC and BOD, n = 7)

	System A					System B				
	Raw	Inf.	Eff 1	Eff 2	% removal	Raw	Inf.	Eff 1	Eff 2	% removal
TN,	415	271	248	175	57	430	294	206	146	64
mg/L	*(±92)*	*(±60)*	*(±46)*	*(±48)*		*(±107)*	*(±74)*	*(±55)*	*(±57)*	
TKN,	414	252	247	128	68	430	243	205	50	88
mg/L	*(±93)*	*(56)*	*(±47)*	*(±18)*		*(±107)*	*(±61)*	*(±55)*	*(±39)*	
NH_3-N,	346	218	234	115	66	361	199	187	49	86
mg/L	*(±68)*	*(±28)*	*(±45)*	*(±26)*		*(±82)*	*(±36)*	*(±52)*	*(±39)*	
NO_x^--N,	0.7	19.3	0.1	47.5	–	0.4	50.5	1.2	98.4	–
mg/L	*(±1.3)*	*(±15)*	*(±0.06)*	*(±35)*		*(±0.6)*	*(±32)*	*(±1)*	*(±41)*	
COD,	1,195	512	198	154	86	1,170	554	213	163	86
mg/L	*(±417)*	*(±143)*	*(±35)*	*(±36)*		*(±353)*	*(±155)*	*(±72)*	*(±86)*	
BOD,	391	163	52	30	92	519	182	55	29	95
mg/L	*(±180)*	*(±87)*	*(±38)*	*(±23)*		*(±151)*	*(±69)*	*(±37)*	*(±18)*	
SS,	1,302	378	8	1	99	1,532	466	10	3	99
mg/L	*(±1,226)*	*(±346)*	*(±5)*	*(±0.9)*		*(±1,345)*	*(±412)*	*(±3)*	*(±2)*	
TP,	26	19	9	2	93	27	23	8	3	90
mg/L	*(±2)*	*(±3)*	*(±2)*	*(±0.5)*		*(±4)*	*(±3)*	*(±5)*	*(±5)*	
FC,	4×10^8	2×10^6	4×10^4	2×10^2	99	8×10^7	1×10^6	2×10^4	9×10^2	99
MPN/ 100 mL	$(\pm 6 \times 10^8)$	$(\pm 2 \times 10^6)$	$(\pm 4 \times 10^4)$	$(\pm 1 \times 10^2)$		$(\pm 1 \times 10^8)$	$(\pm 1 \times 10^6)$	$(\pm 1 \times 10^4)$	$(\pm 8 \times 10^2)$	

performances. The removal efficiency of dissolved TP clearly decreased to 63–64% due to the limited adsorption capacity of sand media as shown in Table 3. During the last few weeks, there was clogging in the vertical flow bed of system B which caused water saturation within the bed. Nitrification, COD and BOD removal efficiencies decreased. However, there was no effect on SS and FC.

Nitrogen uptake by plants

The growth of plants in term of height increment was similar for both systems. The increase in height was rapid during the first 90 days but the dry weather conditions retarded the

Table 3 Performances and removal efficiencies of systems A and B at 12 cm/d (n = 16 except FC and BOD, n = 7)

	System A					System B				
	Raw	Inf.	Eff 1	Eff 2	% removal	Raw	Inf.	Eff 1	Eff 2	% removal
TN,	408	219	160	97	75	369	219	120	96	73
mg/L	*(±99)*	*(±29)*	*(±26)*	*(±22)*		*(±77)*	*(±42)*	*(±41)*	*(±34)*	
TKN,	408	200	157	52	87	367	190	115	40	88
mg/L	*(±99)*	*(±31)*	*(±33)*	*(±22)*		*(±77)*	*(±33)*	*(±41)*	*(±14)*	
NH_3-N,	344	158	141	47	85	302	151	101	32	87
mg/L	*(±82)*	*(±22)*	*(±23)*	*(±20)*		*(±72)*	*(±33)*	*(±47)*	*(±8)*	
NO_x^--N,	0.2	20.0	0.4	44.9	–	0.5	27.9	1.2	55.2	–
mg/L	*(±0.1)*	*(±11)*	*(±0.6)*	*(±23)*		*(±1)*	*(±18)*	*(±50)*	*(±39)*	
COD,	1,143	442	197	143	86	1,229	530	269	224	79
mg/L	*(±560)*	*(±155)*	*(±107)*	*(±74)*		*(±406)*	*(±122)*	*(±196)*	*(±101)*	
BOD,	285	120	52	34	87	328	142	67	58	81
mg/L	*(±143)*	*(±32)*	*(±35)*	*(±15)*		*(±136)*	*(±39)*	*(±29)*	*(±23)*	
SS,	2,418	579	8	2	99	2,268	686	15	2	99
mg/L	*(±1,079)*	*(±320)*	*(±4)*	*(±1)*		*(±1,308)*	*(±356)*	*(±24)*	*(±1)*	
TP,	27	26	17	12	55	29	25	16	10	63
mg/L	*(±4)*	*(±3)*	*(±3)*	*(±3)*		*(±6)*	*(±4)*	*(±2)*	*(±3)*	
FC,	1×10^8	3×10^6	1×10^5	5×10^4	99	2×10^8	1×10^6	2×10^5	6	99
MPN/ 100 mL	$(\pm 1 \times 10^8)$	$(\pm 3 \times 10^6)$	$(\pm 1 \times 10^5)$	$(\pm 7 \times 10^4)$		$(\pm 5 \times 10^9)$	$(\pm 2 \times 10^6)$	$(\pm 3 \times 10^5)$	$(\pm 5 \times 10^3)$	

growth in the second run. Plants were removed and replanted before starting the third run in system A. The height increment of plants in the horizontal flow bed of system B in the third run was very slow due to damage by wind. The growth of *Scirpus* near the inlet part of the horizontal flow bed of system B was also retarded due to the high concentration of NH_3-N.

Nitrogen accumulation in plants was highest in leaves, followed by stems and roots. Nitrogen accumulation and dry weight of plants in system A were maximum in the second run when the density of plants was at a maximum, 0.463, 0.197 and 0.003 $gN/m^2.d$ in leaves, stems and roots, respectively. In system B, the accumulation and dry weight were maximum in the third run 0.18, 0.04 and 0.03 $gN/m^2.d$ in leaves, stems and roots in the horizontal flow bed and 0.25, 0.08 and 0.03 $gN/m^2.d$ in leaves, stems and roots in the vertical flow bed, respectively.

However, N removal by plant uptake was very small compared to other mechanisms. The volatilization, anaerobic ammonia oxidation or N accumulation in bacterial cells were estimated from N input and output as shown in Figures 3 and 4. The maximum N plant uptake was only 4% of N input in system A and 3% in system B when operated at 6 cm/d.

Removal kinetics

Based on the average influent and effluent COD, NH_3-N and hydraulic loading rates, the area-base first order removal constants were estimated by using the following formula (Kadlec and Knight, 1996):

$$C_o / C_i = \exp^{-k/q} \quad (1)$$

Where C_o = effluent concentration (mg/L)
C_i = influent concentration (mg/L)
q = hydraulic loading rate (m/d)

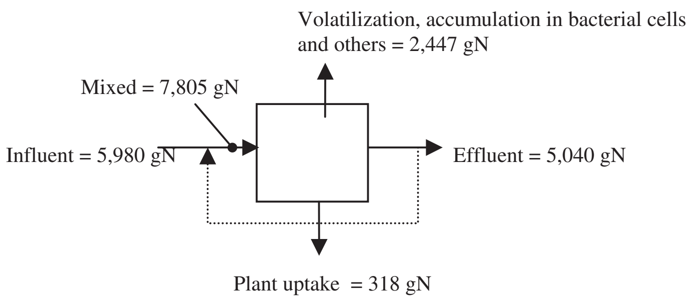

Figure 3 Nitrogen input and output (6 cm/d) of system A

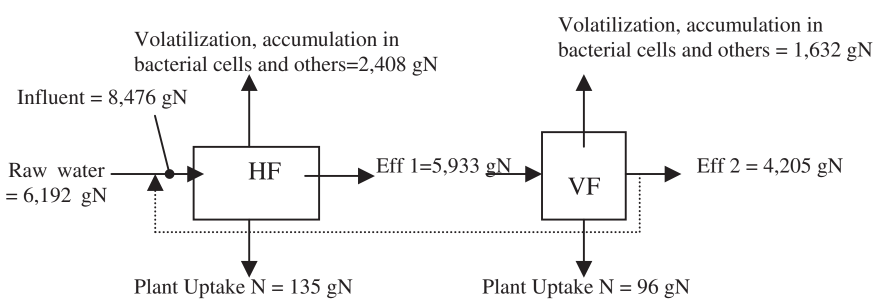

Figure 4 Nitrogen input and output (6 cm/d) of system B

The rate constant of COD, k_{COD}, averaged 0.03 m/d for systems A and B ($R^2 = 0.06$ and –0.11 respectively). The NH_3-N removal rate constant, $k_{NH3\text{-}N}$, was 0.04 m/d ($R^2 = 0.33$) and 0.10 m/d ($R^2 = 0.89$) for systems A and B respectively. The removal of COD and NH_3-N were independently affected by hydraulic loading rates and the low values of R^2 are probably due to first order equations being inappropriate for both systems.

Conclusions

Both systems indicated high efficiency for N, organic carbon, SS and TP removal. Denitrification was promising in the saturated horizontal flow bed and nitrification performance was promising in the vertical flow vegetated bed. The performances of systems A and B did not show clear differences. It was found that the removal rate increased with a higher hydraulic loading rate although at a low hydraulic loading rate (3 cm/d) both systems had higher removal efficiencies than 6 and 12 cm/d, especially in system B. Nitrogen removal by plant uptake was very low compared to other mechanisms. In the dry season, the evapo-transpiration rate was high but rainfall maintained the balance in the system. The area-base first order removal constant $k_{NH3\text{-}N}$ of systems A and B was 0.04 and 0.10 m/d, respectively, and k_{COD} was 0.03 m/d for both systems at 25–27°C. The advantage of system A is that less land area is required but its construction and maintenance are more complex. It is proposed that full scale experimental systems, based on the design of systems A and B, will be constructed on pig farms in Chiang Mai to validate the performance of the pilot scale systems.

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