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Full Length Research Paper

Effects of hydraulic retention time and media of constructed wetland for treatment of domestic wastewater

Suntud Sirianuntapiboon[1]*, Manoch Kongchum[2] and Worawut Jitmaikasem[1]

[1]Department of Environmental Technology, School of Energy and Materials, King Mongkut's University of Technology Thonburi (KMUTT), Bangkok 10140, Thailand.
[2]Department of Agronomyand Environmental Management, Louisiana State University, Botan Rouge, LA 70803, USA.

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A greenhouse experiment was conducted to investigate the effect of varying soil-to-sand ratios of constructed wetland on wastewater treating efficiency. Wetland beds were prepared with locally available plants, specifically cattail (*Typha* sp.). Treatment efficiency was evaluated for parameters such as BOD_5, COD, SS, TKN and TP. The results indicated that the nutrient reduction corresponds to a longer retention time in wetland beds. Under the longest hydraulic retention time (HRT) of 3 days, the system with media containing a soil-to-sand ratio of 75:25 illustrated the highest removal efficiencies of BOD_5, COD, SS, TKN and TP by 92±5, 91±%, 76±9, 90±3 and 95±3%, respectively. The infiltration rate was also decreased after operation, particularly in the treatment with lower sand content. However, the highest growth rate of cattail was found under the shortest HRT (0.75 day) condition.

Key words: Hydraulic retention time (HRT), Media, *Typha* sp., constructed wetland.

INTRODUCTION

Some of the suitable wastewater treatment processes for domestic wastewater include biological treatment processes, such as activated sludge, trickling filter, and rotating biological contractor systems. However, these treatment systems have high operation and investment costs and are difficult to operate and maintain with stable removal efficiencies. Also, the treated wastewater from these types of wastewater treatment plants might require further treatment with a tertiary treatment process, such as a polishing pond, oxidation pond, or constructed wetland (CW), to improve the treated wastewater quality (Metcalf and Eddy, 1998; Amelia, 2001).

The constructed wetland is a natural biological treatment process that is normally used to treat sewage, storm-water, agricultural runoff, landfill leachate, and treated industrial wastewater (Reed et al., 1988; Vrhovsek et al., 1996; Billore et al., 1998; Cooper et al, 1996). The use of CW is now recognized as a widelyaccepted, low-cost eco-technology that is especially beneficial in treating the domestic water of small towns, which cannot afford expensive, conventional treatment systems (Reddy and Gale, 1994; Billore et al., 1998). One type of CW mimics natural systems as the water flows over the bed surface and is filtered through a dense stand of aquatic plants (free water surface, FWS). Another type of CW system promotes subsurface flow (Sundaravadivel and Vigneswaran, 2001) through a shallow, permeable substratum, in which aquatic plants are established (subsurface flow, SF) (Wood, 1995).

There are currently thousands of constructed and natural wetlands worldwide receiving and treating a variety of municipal, industrial, and urban runoff wastewater (Kadlec and Knight, 1996). The attractiveness of the subsurface flow system, when compared to free water surface and overland flow

Corresponding author.E-mail: suntud.sir@kmutt.ac.th.

Abbreviations: BOD5, Biochemical Oxygen demand; COD, chemical oxygen demand; HRT, hydraulic retention time; NH4+, ammonium; NO2-, nitrite; NO3-, nitrate nitrogen; SRT, solids retention time; SS, suspended solids; TKN, total kjeldahl nitrogen; TP, total phosphate; and UFCW, up-flow constructed wetland.

Table 1. Properties and characteristics of soil and sand.

Soil				Sand characteristic	
Properties		Composition			
Type	Silty clay loam	% sand	12.33±0.57	Particle size, mm	0.78±0.27
Source	Ayuthaya, Thailand	% silt	58.14±3.22		
		% clay	29.53±2.67		

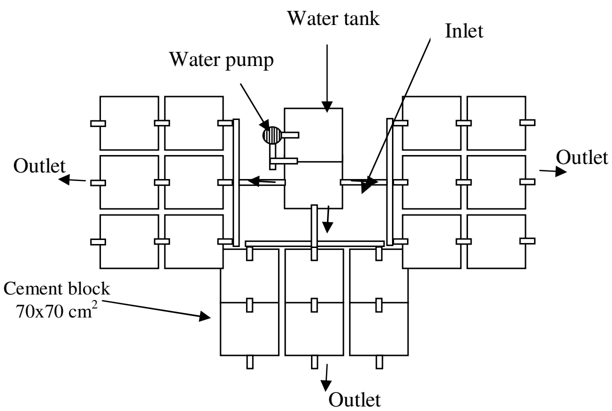

Figure 1. Flow diagram and photograph of the complete set of up-flow constructed wetland (UFCW) system

systems, has been partly due to the perception of a decreased risk of nuisance from flies, mosquitoes, and odor, and greater efficiencies in terms of land usage (Reed et al., 1995). Traditionally, the constructed wetland system has been employed as a terminal treatment component, where it is designed and operated at rather low loads for the purpose of producing effluent that meets various discharge criteria. The typical upper limit for the range of BOD_5 loading rate for this design does not exceed 67.25 kg ha^{-1} d^{-1} for a subsurface flow wetland and 44.84 kg ha^{-1} d^{-1} for free water surface wetlands (Vymazal, 1998).

The objectives of this study were to determine the effects of different mixture of soil-to-sand and hydraulic retention time (HRT) on wastewater treatment by small-scale wetlands. The experiments were carried out in a greenhouse scale constructed wetland with *Typha sp.* under the hydraulic retention times (HRT) of 3, 1.5, and 0.75 day with wastewater from one of the dormitories of King Mongkut's University of Technology Thonburi. Soil and sand were used as the media for the constructed wetland using soil-to-sand ratios of 75:25, 50:50, and 25:75. The quality of effluent, number of bacteria, and the growth rate of *Typha* sp. were investigated.

MATERIALS AND METHODS

Media preparation

Soil used in this study was collected from Ayuthaya province, central plain of Thailand. The soil was air-dried and grinded into a uniform particle size. Sand sample was purchased from the local hardware store. The sand was air-dried and removed gravel and other contaminated materials. The mixtures of soil and sand were prepared by weight basis at the ratio of 75:25, 50:50, and 25:75. Soil sample was analyzed for particle size distribution by pipette method (Walsh and Beaton, 1973). Sand particle was measured by sieving method (Metcalf and Eddy, 1991). Soil and sand properties are shown in Table 1.

Wetland bed preparation

Constructed wetland beds were made by cement blocks (Figure 2). The size of each constructed wetland bed was 0.7 x 0.7 x 0.7 m. The coarse rock (2-2.5 cm in diameter) was packed in the inlet and outlet area of the bed (Figure 2). Then the media was filled in the middle of the bed. Nine sets of constructed wetland systems were set up as shown in Figure 1. Each constructed wetland set consisted of 2 joined beds to complete a system (Figure 1). PVC pipes (1.91 cm in diameter) were used as the wastewater inlet. A 1,000 liter wastewater tank (0.7 x 0.7 x 1.10 m) was used to supply the wastewater to the nine sets of constructed wetland system (Figure 1).

Microbial determination

The number of aerobic bacteria on the media was determined by the standard methods of water and wastewater determination (APHA, 1992). The media of the systems were collected before and after operation to determine the number of aerobic bacteria.

One gram of dry basic sample (media) was suspended in 9 ml of sterile distilled water (the dilution was 1:10 weight by volume) and

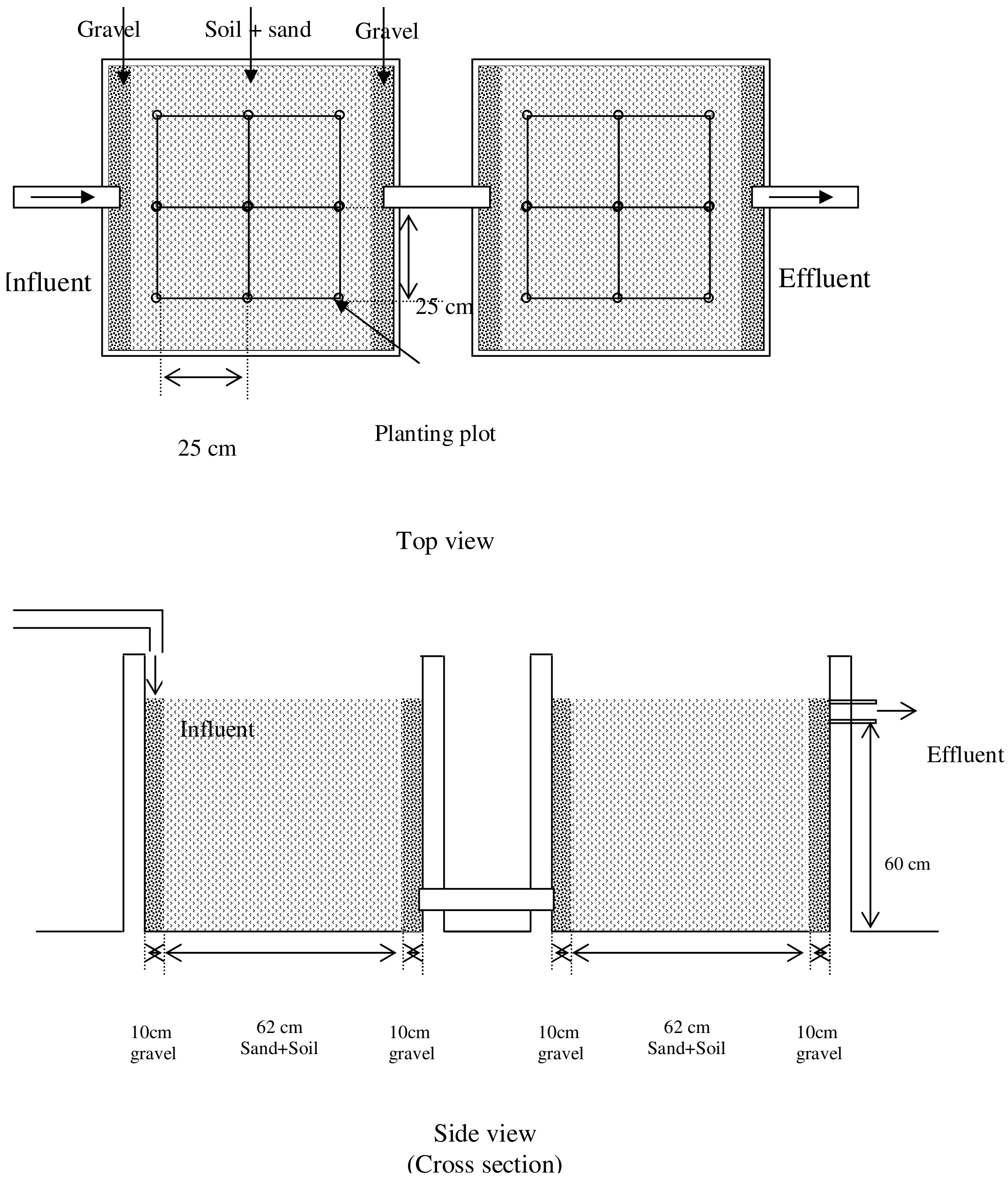

Figure 2. Show the unit of laboratory scale of up-flow wetland (UFCW) system.

the solution was diluted up to 10^{-12}-10^{-20}. The 0.1 ml diluted sample solutions were used as the inoculum on nutrient agar plates (Difco laboratory, 1967) using the pour plate technique (APHA, 1992). Then the agar plate was incubated at 30°C for 48 h. The aerobic bacterial colonies on the agar plate were counted after incubation.

Chemical analysis

Chemical measurements were made weekly on the influent and every 3 days on the effluent from each of the wetland bed from July 2003 through June 2004. Influent and effluents samples were collected in sterile 500-mL Nalgene bottles and stored on ice for transport to laboratory. Then the samples were transferred to a refrigerator for storage at 4 °C until processing. Samples were analyzed for total suspended solids (TSS), biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), ammonium (NH_4^+), nitrite (NO_2^-), nitrate (NO_3^-), total Kjeldahl nitrogen (TKN) and total phosphate (TP) (Tables 2) following standard methods (APHA, 1992).

Hydraulic retention time schedule

Wetland beds were initially filled with deionized water. Cattails were transplanted at the rate of nine plants per bed. Wastewater was collected from the student dormitory of King Mongkut's University of Technology Thonburi in Bangkok, Thailand and was introduced into the bed in July, 2003. Retention times were set at 0.75, 1.5, and 3.0 days (Tables 3). Each wetland bed received 150 liters of domestic

Table 3. Operating parameters of UFCW system with media containing various soil: sand ratio with domestic wastewater under various HRT of 0.75, 1.5 and 3.0 days.

Operating Parameter	HRT operation of UFCW systems		
	3.0 Days	1.5 Days	0.75 Days
Flow rate (l/d)	50.16	100.32	200.64
Surface hydraulic loading (m^3/m^2-d)	0.05	0.10	0.20
Organic (BOD_5) loading (g/d)	5.92±0.51	11.84±1.02	23.68±2.04
Surface organic loading (g/m^2-d)	6.04±0.60	12.08±1.20	24.16±2.4
Nitrogen loading (g/d)	1.93±0.11	3.85±0.22	7.70±0.44
Surface nitrogen loading (g/m^2-d)	1.97±0.12	3.94±0.24	7.88±0.48
Phosphorus loading (g/d)	0.60±0.12	1.20±0.23	2.40±0.45
Surface phosphorus loading (g/m^2-d)	0.64±0.12	1.28±0.23	2.56±0.46

Table 2. Properties of domestic wastewater of Student Dormitory in King Mongkut's University of Technology Thonburi.

Properties	Concentration
COD (mg/l)	173±27
BOD_5 (mg/l)	118±14
TKN (mg/l)	38.4±4.2
TP (mg/l)	12.0±1.9
pH	7.1±0.3
Temperature (°C)	29.3±0.6

wastewater per a retention time treatment. The influents and effluents of the systems were collected once a day for chemical analysis.

Plant biomass

The cultivated plants (*Typha* sp.) of the UFCW systems were analyzed before and after 12 weeks cultivation to determine net biomass (APHA, 1992). The cattail was harvested before and after operation to determine biomass and relative growth rate (RGR). The harvested plants were chopped and dried at 103°C for 24 h before determining the quantity of dry biomass. The relative growth rate (RGR) of the plant was calculated using the following equation (Beadle, 1982):

$$RGR = \frac{\ln W_2 - \ln W_1}{t_2 - t_1}$$

Where, W1 and W2 are the dry biomass values before (t1) and after 12 weeks cultivation (t2), respectively.

Statistical analysis

The experiment was repeated at least 3 times. All of the data was subjected to two-way analysis of variance (ANOVA) using SAS Windows Version 6.12 (SAS Institute, 1996). Statistical significance was tested using least significant difference (LSD) at the $p < 0.05$ level. The results are shown as the mean ± standard deviation.

RESULTS

Effects of media and HRT on the infiltration rate

The effects of soil-to-sand ratio on the infiltration rate of UFCW system are shown in Table 4. No difference in infiltration rates was observed between the three types of media in the wetland systems before planting at any controlling for hydraulic retention time (HRT). The infiltration rates of the systems increased with a decrease in HRT. The infiltration rates of the systems under an HRT of 3 days were about 4 times higher than those under an HRT of 0.75 days. However, the infiltration rates of all systems decreased approximately 10- 40% after 12 weeks of operation (Table 4). Additionally, the infiltration rate of the system increased by increasing HRT, especially in the UFCW system with media containing a soil-to-sand ratio of 50:50. The infiltration rate of the system under an HRT of 0.75 days decreased by 35.9±16.2% after 12 weeks of operation, while it only decreased by 7.9±1.1% under an HRT of 3 days.

Effects of soil: sand ratio on the efficiency and performance of UFCW systems

The effects of soil-to-sand ratio on the efficiencies and performance of UFCW systems are shown in Table 5 and Figures 3-5. Under the longest HRT operation of 3.0 days, all types of the UFCW system could be operated at nearly stable and high removal efficiency (Table 5). The effluent quality of the systems was quite stable during operation even though the influent quality fluctuated (Figures 3-5). Also, the removal efficiencies were fairly constant for all three types of UFCW systems, but the composition of media (soil-to-sand ratio) did have an effect on the efficiency of the UFCW system when the system was operated under short HRTs of 0.75-1.5 days. The COD and BOD_5 removal efficiencies of the UFCW system with media containing a soil-to-sand ratio of 75:25 under an HRT of 0.75 days were 84±5% and 88±6%, respectively, while they were only 71±7% and 83±5% for

Table 4. Infiltration rate of wastewater in UFCW with various type of media under HRT of 3.0, 1.5, 0.75 days.

Infiltration rate	Type of media in UFCW (Soil: sand ratio of media)								
	75:25			50:50			25:75		
	HRT, days								
	3.0	1.5	0.75	3.0	1.5	0.75	3.0	1.5	0.75
Before cultivation	50.2±4.5	100.3±7.6	200.6±11.1	50.2±4.5	100.3±7.6	200.6±11.1	50.2±4.5	100.3±7.6	200.6±11.1
3rd weeks cultivation	44.9±0.7	90.2±4.8	191.4±9.6	48.0±1.3	63.1±6.2	147.4±16.5	48.0±1.3	99.7±10.7	189.5±11.2
6th weeks cultivation	43.2±0.9	84.4±5.0	181.9±10.0	45.8±1.3	63.2±5.9	136.2±15.8	46.5±1.4	79.0±10.6	170.3±11.0
9th weeks cultivation	44.1±0.9	80.9±4.8	174.9±10.0	46.1±1.3	52.9±6.1	119.9±15.9	46.8±1.6	78.8±10.1	168.2±11.1
12th weeks cultivation	43.8±1.0	79.3±4.9	169.1±9.4	44.9±1.0	51.8±6.2	110.6±16.0	45.9±1.1	77.2±10.1	164.6±11.1
%Reduction	12.3±1.0	16.6±5.1	10.6±8.1	7.9±1.1	42.5±6.3	35.9±16.2	6.2±1.4	16.6±10.4	13.7±10.9

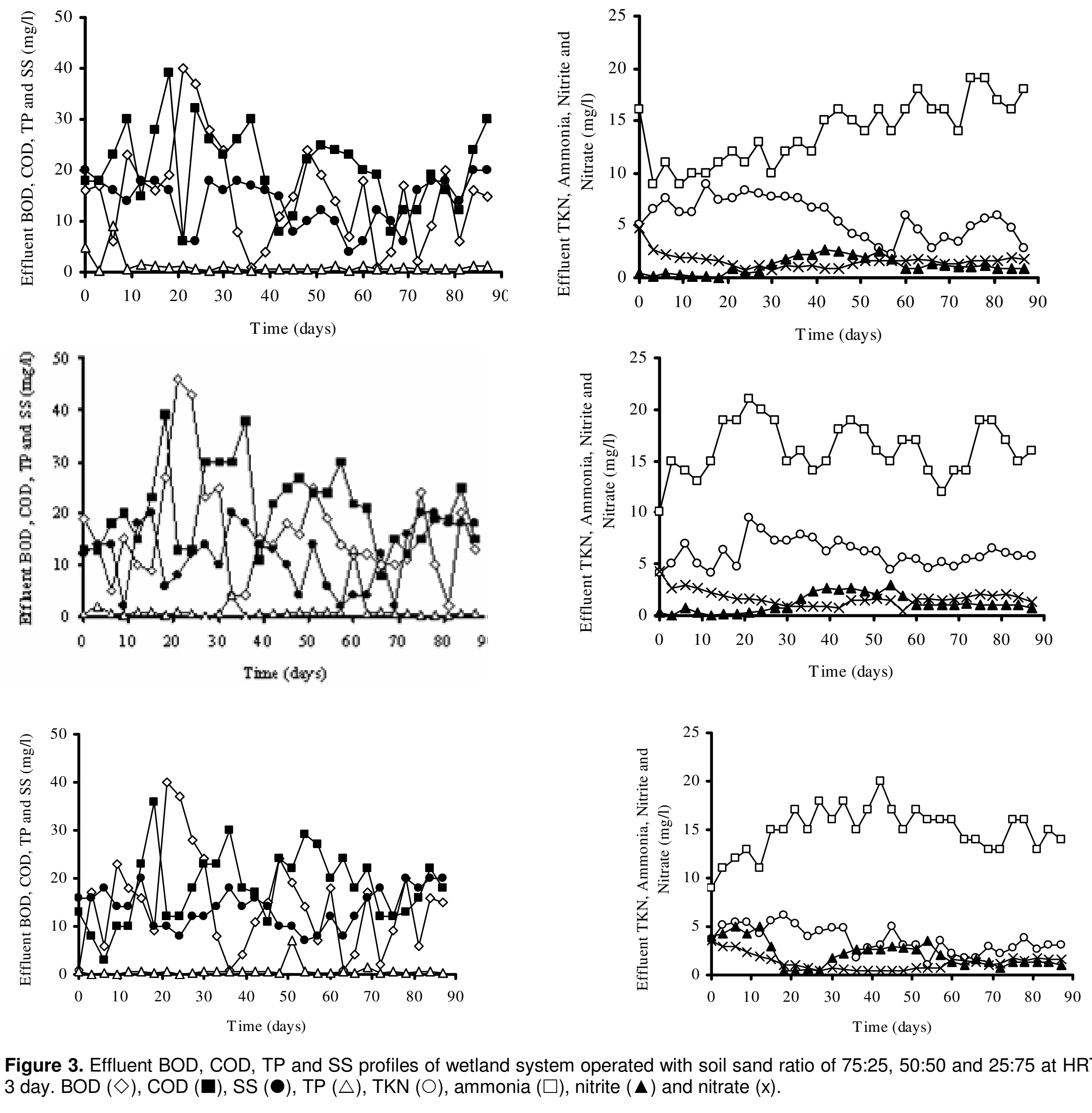

Figure 3. Effluent BOD, COD, TP and SS profiles of wetland system operated with soil sand ratio of 75:25, 50:50 and 25:75 at HRT of 3 day. BOD (◇), COD (■), SS (●), TP (△), TKN (○), ammonia (□), nitrite (▲) and nitrate (x).

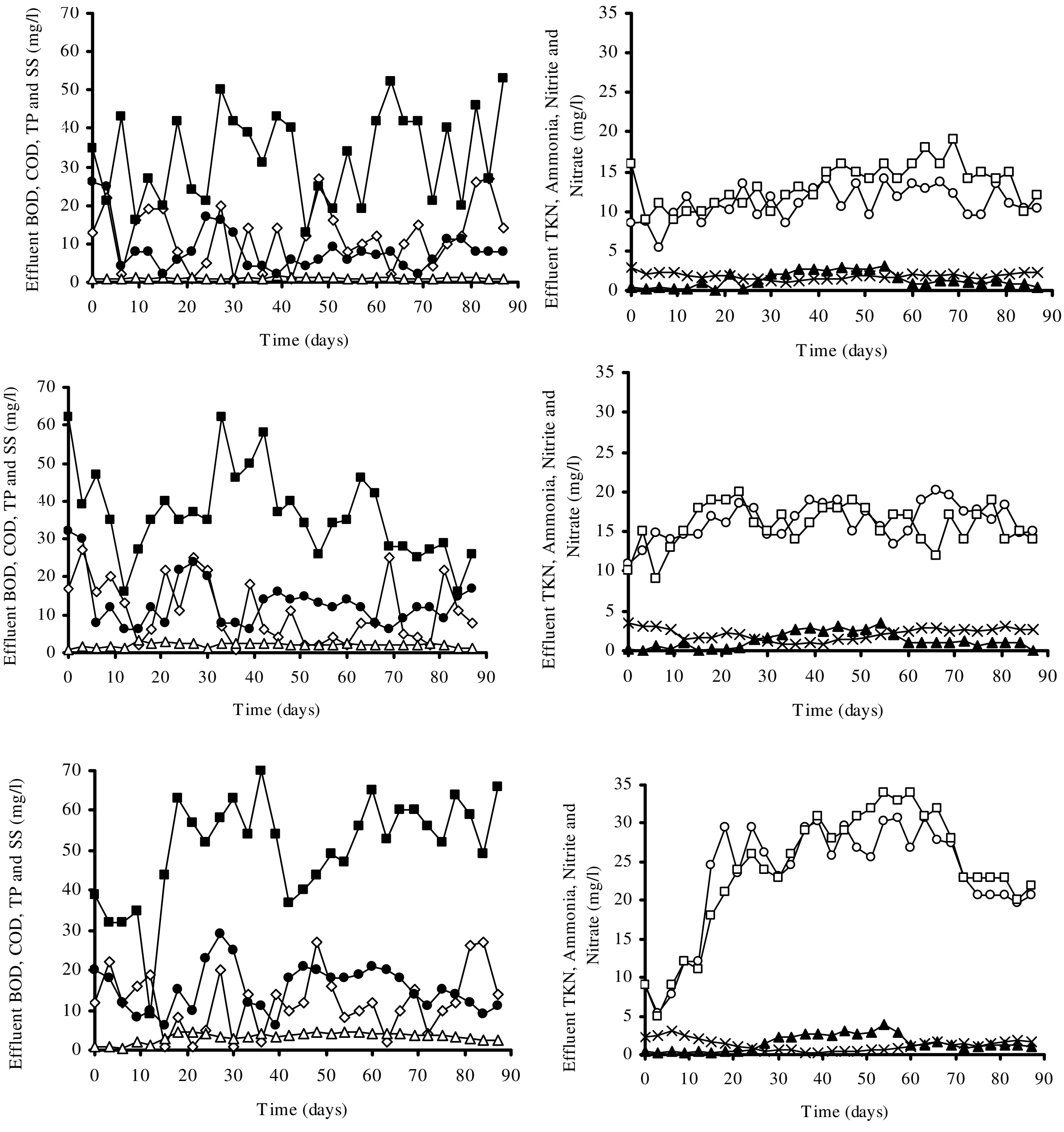

Figure 4. Effluent BOD, COD, TP and SS profiles of wetland system operated with soil sand ratio of 75:25, 50:50 and 25:75 at HRT of 1.5 day. BOD (◇), COD (■), SS (●), TP (△), TKN (○), ammonia (□), nitrite (▲) and nitrate (x).

the UFCW system with media containing a soil-to-sand ratio of 25:75. The TKN removal efficiency of the system under an HRT of 3.0 days increased with an increase in the percentage of sand in the media. The TKN removal efficiency of the UFCW system with media containing a soil-to-sand ratio of 75:25 under an HRT of 3 days was 84±5%, while it was only 90±3% for the UFCW system with media containing a soil-to-sand ratio of 25:75. For the effluent NO_3^-, it was found that the nitrate of the wastewater increased after treatment by all types of

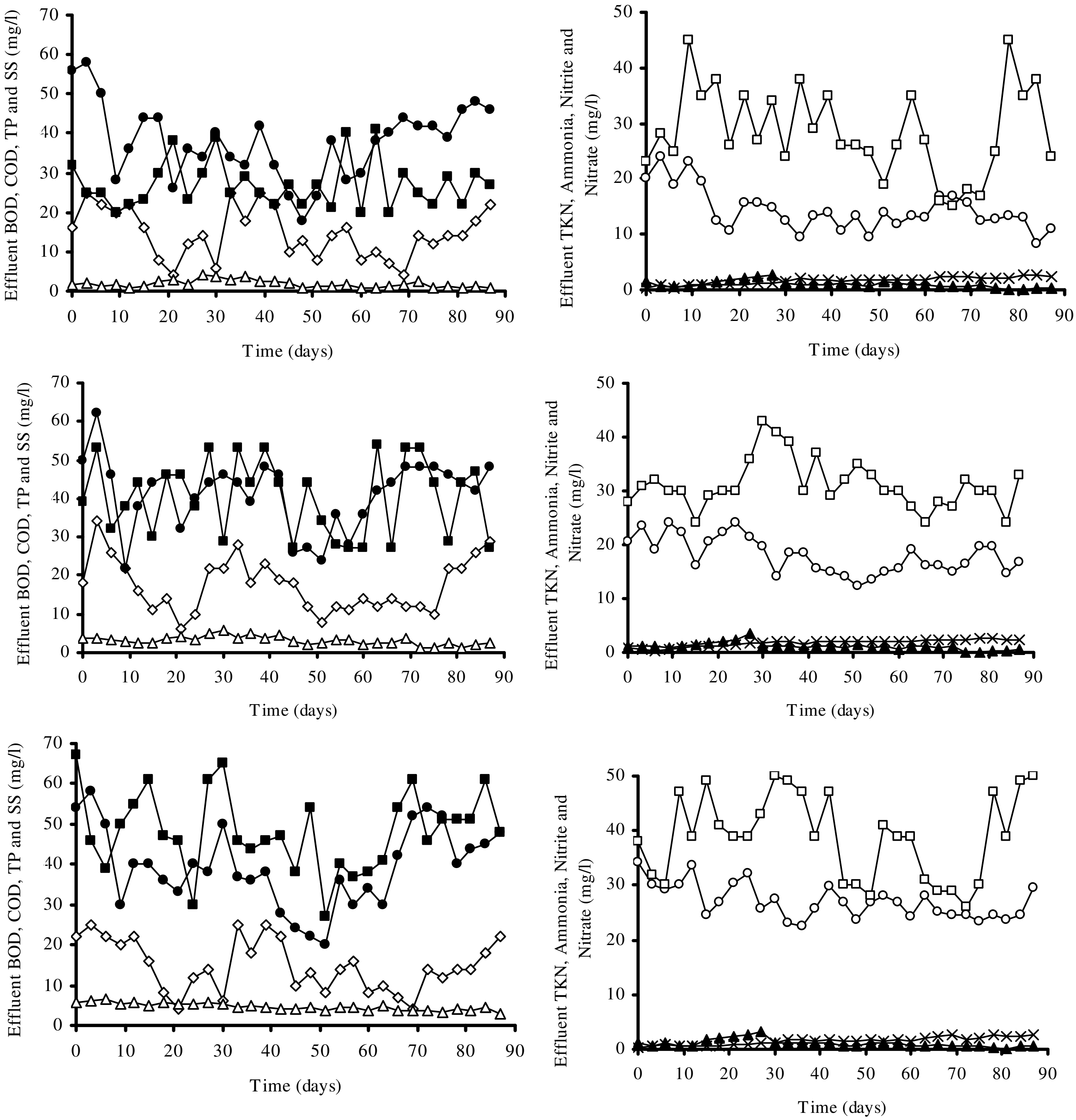

Figure 5. Effluent BOD, COD, TP and SS profiles of wetland system operated with soil sand ratio of 75:25, 50:50 and 25:75 at HRT of 0.75 day. BOD (◇), COD (■), SS (●), TP (△), TKN (○), ammonia (□), nitrite (▲) and nitrate (x).

UFCW system. The effluent NO_3^- of the UFCW system increased as the percentage of sand in the media decreased. Also, the phosphorus removal efficiency of UFCW system decreased as the percentage of sand percentage in the media increased. The SS removal efficiency of the system increased with the increase of the soil percentage of the media. The effluent SS of the system also increased with the increase of sand percentage in the media. However, the effluent SS of the systems were lower than 30 mg/l in all experiments.

Table 5. Efficiencies of Up-flow constructed wetland system with various types of media (soil: sand ratio of 75:25, 50:50 and 25:75) under HRT of 3.0, 1.5 and 0.75 days.

Parameters	Soil: sand ratio					
	75:25		50:50		25:75	
	Effluent	% Removal	Effluent	% Removal	Effluent	% Removal
HRT of 3.0 days						
COD	21±8	90 ± 4	21±8	90 ± 4	18±7	91 ± 5
BOD	15±10	91± 5	16±1	91 ± 5	15±10	92± 5
SS	14±5	76± 10	13± 6	78 ± 12	14±6	76 ± 9
TP	0.8±0.3	93 ± 3	0.6±0.3	9.3± 3	0.5±0.3	95 ± 3
TKN	5.7±1.9	84± 5	6.1±1.3	83 ± 4	3.6±1.4	90± 3
Ammonia	14.0±3.0	62± 3	16.0±2.8	57 ± 3	15±2..9	59± 3
Nitrate*	1.7±0.7	-	1.7±0.7	-	1.3±0.9	-
Nitrite	1.2±0.8	25 ± 1	1.2±0.9	25 ± 1	1.4±.0.1	13 ± 0.9
HRT of 1.5 days						
COD	33±12	82 ± 7	37±11	80 ± 6	51±13	73.± 7
BOD	13±7	91 ± 5	11±8	91 ± 7	18±6	90± 6
SS	8±6	84± 11	13±7	74 ± 11	15±6	71 ± 9
TP	1.0±0.3	89 ± 3	2.1±0.5	78 ± 7	3.2±1.1	66 ± 14
TKN	11.0±2.1	67 ± 6	16.4±2.4	51 ± 8	23.1±7.2	32.7 ± 19.2
Ammonia	3.0±0.8	64 ± 3	3.4±0.4	56 ± 3	2.7±0.5	33.3 ± 8.2
Nitrate*	1.8±0.4	-	2.1±0.7	-	1.3±0.7	-
Nitrite	1.3±1.0	19 ± 1	1.31.0	19 ± 1	1.5±1.0	6.3± 1.2
HRT of 0.75 days						
COD	27±6	84 ± 5	40±10	76 ± 7	48±10	71± 9
BOD	15±6	88 ± 6	17±7	86 ± 6	23±6	83± 5
SS	38±9	30±12	41±9	24 ± 11	39±10	28 ± 13
TP	1.9±0.8	84 ± 6	3.1±1.1	73 ± 9	4.7±0.9	60 ± 11
TKN	14.3±3.8	63 ± 8	18.0±3.4	53± 7	27.1±3.2	29 ± 7
Ammonia	2.6±0.9	28 ± 3	2.4±0.9	23 ± 3	2.6±0.9	-
Nitrate*	1.0±0.6	-	1.8±0.7	-	1.5±0.7	-
Nitrite	1.7±0.7	9 ± 1	1.1±0.7	9 ± 1	1.1±0.7	9 ± 1

*Effluent nitrate was higher than influent nitrate.

Effects of soil-to-sand ratio on aerobic bacteria

The effects of soil-to-sand ratio on growth of aerobic bacteria are shown in Table 6. The percentage of sand in the media affected the growth of the aerobic bacteria. The population of the bacteria (aerobic bacteria) in the media of the UFCW system with media containing a soil-to-sand ratio of 75:25 under an HRT of 0.75 days increased up to $1.53x10^{23}$ after 12 weeks cultivation, while it was only $1.1x10^{23}$ by UFCW with media containing a soil-to-sand ratio of 25:75.

Effects of soil: sand ratio on the growth of *Typha* sp.

The effects of soil-to-sand ratio on the growth of *Typha* sp. are shown in Table 7. The growth rate of *Typha sp.* increased with the increase of sand percentage in the media under the shortest HRT of 0.75 days. The UFCW with media containing a soil-to-sand ratio of 75:25 showed the highest growth rate of *Typha* sp. as 5.38 d^{-1} under the shortest HRT of 0.75 days.

Effects of HRT on the efficiencies and performance of UFCW system

The effects of HRT on the efficiencies of UFCW system are shown in Table 5 and Figures 3-5. The efficiency of the system increased with the increase of HRT for all types of UFCW system. The COD and BOD_5 removal efficiencies of the UFCW system with media containing soil-to-sand ratio of 72: 25 under an HRT of 0.75 days were 88±6% and 84±5%, respectively, while they were 91±5% and 90±4%, respectively, under an HRT of 3.0 days. TKN removal efficiencies of the UFCW systems decreased with the decrease in HRT. The TKN removal efficiency of the UFCW system with media containing a

Table 6. Population of bacterial cells (cells/g of media) in various types of UFCW under HRT of 3.0, 1.5 and 0.75 days.

Hydraulic retention time of the systems, Days	Number of bacteria in media of UFCW (cells/g of media)					
	75:25 (soil: sand)		50:50 (soil: sand)		25:75 (soil: sand)	
	Before cultivation	After 12 weeks cultivation	Before cultivation	After 12 weeks cultivation	Before cultivation	After 12 weeks cultivation
3.0	3.00×10^{14}	7.00×10^{14}	1.20×10^{14}	7.00×10^{14}	0.70×10^{14}	3.30×10^{14}
1.5	3.00×10^{14}	2.34×10^{16}	1.20×10^{14}	1.95×10^{16}	0.70×10^{14}	1.80×10^{16}
0.75	3.00×10^{14}	1.53×10^{23}	1.20×10^{14}	1.35×10^{23}	0.70×10^{14}	1.10×10^{23}

Table 7. The growth rate of *Typa sp.* in various types of UFCW under HRT of 3.0, 1.5, 0.75 days.

Parameters	Types of media in UFCW (soil: sand ratio)								
	75:25			50:50			25:75		
HRT, days	0.75	1.5	3.0	0.75	1.5	3.0	0.75	1.5	3.0
Before cultivation (Kg/m^2)	1.44	1.43	1.47	1.44	1.47	1.43	1.43	1.47	1.44
12 weeks cultivation Kg/m^2)	4.99	4.62	4.53	4.25	4.16	4.01	3.61	3.61	3.33
Relative growth rate (d^{-1})	5.38	4.72	4.44	3.62	3.47	3.10	1.45	1.33	0.93

soil-to-sand ratio of 75:25 under an HRT of 3.0 days was 84±5%, while it was only 63±8% under an HRT of 0.75 days. Interesting results were obtained regarding effluent NO_3^- of the systems. The effluent NO_3^- increased with the increase of HRT. The effluent NO_3^- of the UFCW system with media containing soil-to-sand ratio of 75: 25 increased from 1.0±0.6 mg/l to 1.7±0.7 mg/l when the HRT of the system increased from 0.75 days to 3.0 days. Similarly, all types of UFCW systems showed the highest phosphorus removal efficiencies under the longest HRT of 3.0 days, and these efficiencies decreased with the decrease of HRT.

Effects of HRT on the growth of aerobic bacteria in the media

The effects of HRT on the growth of aerobic bacteria are shown in Table 6. The number of aerobic bacteria increased as HRT decreased. The population of aerobic bacteria in the UFCW system increased up to 1.1-1.53×10^{23} cells/g of media under an HRT of 0.75 days.

Effects of HRT on the growth of *Typha* sp.

The effects of HRT on the growth of *Typha* sp. are shown in Table 6. It could be concluded that the growth rate of Typha sp. decreased with the increase of HRT in all types of media in the UFCW system. The growth rate of *Typha* sp. in the UFCW system with media containing a soil-to-sand ratio of 25:75 under an HRT of 0.75 days was 3.62 d^{-1}, while it was only 1.12 d^{-1} under an HRT of 3 days.

DISCUSSION

For the determination of the infiltration rates of the UFCW systems, it was found that the infiltration rate increased with the increase of HRT due to the increased flow rate of the wastewater into the system (Kadlec and Knight, 1996; Metcalf and Eddy, 1993). However, the infiltration rate of the systems decreased after operation due to the growth of aerobic bacteria and the packing of the media, which occurred as a result of the pressure from the wastewater during feeding (Metcalfand Eddy, 1993; Brix, 1993).

Also, the systems under the shortest HRT of 0.75 days were more effective in reducing infiltration rate than the systems under the longer HRTs of 1.5-3.0 days. For example, the infiltration rate of the UFCW system with media containing a soil-to-sand ratio of 50:50 under HRT of 3.0 days was reduced to 7.9±1.1% after 12 weeks cultivation. It was 42.5±6.3% under HRT of 1.5 days due to the high growth rate of the aerobic bacteria on the media with shorter HRT operation, which was the result of high BOD_5 loading (Metcalf and Eddy, 1993; Tanner et al, 1995).

However, the infiltration rate of the systems could be recovered by increasing the sand percentage of the media because sand could increase the porosity of the media (Ronald, 1994). The number of aerobic bacteria on the media of the UFCW system with media containing a soil-to-sand ratio of 75:25 under an HRT of 0.75 days increased up to 1.53x10^{23} cells g^{-1} of media, while it was only 7.00x10^{14}cells g^{-1} of media under an HRT of 3.0 days. However, the infiltration rate of the system under an HRT of 1.5 days after 12 weeks cultivation was lower than that of the system under an HRT of 0.75 days. This might be due to the high flow rate of the wastewater under the shortest HRT of 0.75 days, which may help to recover the infiltration rate.

The concentration of sand in the media also had an effect on the growth of both *Typha sp*. and aerobic bacteria on the media. The number of aerobic bacteria on the media of the UFCW systems increased as the sand percentage in the media increased when the UFCW systems were operated under HRTs of up to 1.5 days. The number of aerobic bacteria of the UFCW system with media containing a soil-to-sand ratio of 25:75 was about 2 times higher than that of the system with media containing a soil-to-sand of 75:25. This could be due to the increased porosity of the media that has a soil-to-sand ratio of 25:75, which provides better aerobic conditions for the aerobic bacteria (Ronald, 1994; Hammer, 1992). However, after 12 weeks cultivation, the number of aerobic bacteria was increased up to the maximum in all types of UFCW systems.

In the analysis of UFCW system efficiencies and effluent quality, it was found that the designed UFCW systems showed high removal efficiency and good effluent qualities, especially for organic matter, nitrogenous compounds, and phosphorus compounds. The systems under the longest HRT operation of 3 days did not show any significant difference in removal efficiency, which might be explained by the low organic loading of these systems (Metcalf and Eddy, 1993; Stottmeister et al., 2003). However, under the HRT 0.75 and 1.5 days, the efficiency of the system varied according to the type of media. This variation in system efficiency may be due to the percentage of sand in the media (Ronald, 1994; Metcalf and Eddy, 1993; Tanner et al., 1995; Drizo et al., 1997; Lei, 2001). The removal efficiency decreased as the percentage of sand in the media increased. The growth rate of both *Typha sp* and aerobic bacteria increased with the increase of soil percentage in the media because the soil component provides good conditions for growth of both *Typha sp.* and aerobic bacteria (Stottmeister et al., 2003). There are also some other growth factors, such as minerals, present in the soil component for both *Typha sp.* and aerobic bacteria (Lei, 2001; Stottmeister et al., 2003). The effluent NO_3^- of the system increased with the increase of sand percentage due to the activity of nitrification bacteria that is stimulated by aerobic conditions in the media (Mecalf and Eddy, 1993; Polprasert, 1997; Julie, 1996; Huang, 2000). Media with a high percentage of sand has a high porosity, which increases the dissolved oxygen concentration in the media, and this affects the system in the aforementioned ways. Phosphorus removal efficiency was increased with the increase of soil percentage in the media. Increasing the soil percentage in the media also increases the phosphorus adsorption yield due to the increase in clay percentage in the media (Lei, 2001; Drizo, 1997).

For application, the UFCW system with media containing a soil-to-sand ratio of 75:25 under an HRT of 3.0 days was the most suitable system for treating domestic wastewater. This system had the highest removal efficiency and had low growth rates for both aerobic bacteria and *Typha sp*. The other advantage of this system was the decreased harvesting times during operation due to the low growth rate of *Typha sp.*

In conclusion, the study showed that the UFCW system with media a containing soil-to-sand ratio of 25:75 was effective in treating raw domestic wastewater under an HRT of 3 days and had the highest BOD_5, COD, SS, TKN and TP efficiencies of 92±5%, 91±5%, 76±9%, 90±3% and 95±3%, respectively, and the lowest *Typha sp.* growth rate of 0.93 d^{-1}. The low growth rate of *Typha sp.* in this system resulted in decreased harvesting times during operation. The infiltration rate of the system was decreased after operation, but the infiltration rate of the system could be recovered or increased by increasing the percentage of sand in the media or by decreasing HRT. The removal efficiency of the system was dependent on the growth and activity of both *Typha* sp. and aerobic bacteria.

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