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Performance of experimental horizontal subsurface-flow-constructed wetlands treating river water: effect of substrate, configuration, hydraulic retention time, temperature and external carbon source

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ABSTRACT

The water quality of Yapu River flowing into Lake Taihu was monitored for one year and the effects of substrate, configuration, hydraulic retention time (HRT) and temperature on nitrogen removal were evaluated in five pilot-scale horizontal subsurface-flow-constructed wetlands (CWs). Additionally, the impact of adding external carbon on nitrogen removal was investigated. Yapu River was shown to be eutrophic, with a low C/N ratio (COD/TN ≤ 1.5) and the main pollutant was total nitrogen (TN ≥ 2 mg/L). CWs with substrates of combined gravel-zeolite and gravel-ceramsite showed higher ammonium nitrogen (NH_4^+-N) and chemical oxygen demand (COD) removal efficiencies than the CWs with gravel substrates. Trapezoidal CWs showed improved dissolved oxygen in the front when compared with the rectangular CWs, enabling complete nitrification. A longer HRT (four days) improved the removal efficiencies of organics, nitrogen, and phosphorus. CWs performed better during the warm period. Moreover, addition of 400 g cattail litter during winter led to increased influent of COD. The average removal efficiencies of NO_3^--N and TN were increasing up to 90.5 and 85.3%, respectively.

Keywords: Constructed wetlands; Substrates; Hydraulic retention time; Temperatures; External plant carbon source; Removal efficiency

1. Introduction

Lake Taihu (a national key protected lake in China) has been reported to be eutrophic due to nitrogen pollution [1,2]. Almost 80% of nutrients in the lake originate from river effluent and surface runoff [3,4].

Constructed wetlands (CWs) for the biological treatment of wastewater were initially developed in Germany, in early 1950s and then throughout the Europe and the USA [5,6]. CWs are now used to treat many other types of wastewater, including industrial and agricultural wastewater, landfill leachate and storm water runoff [7,8]. However, a few studies have investigated the effects of CWs which are used to treat eutrophic river waters in the developing countries. Denitrification is widely accepted as the dominant

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process that removes nitrate from the water in CWs [8]. However, many factors are known to influence denitrification rates in CWs, including substrate, configuration, hydraulic retention time (HRT), season and pH [7,9,10]. Among them, substrates provide the necessary environmental conditions for the growth of plants as well as the places for microbes that degrade pollutants [11]. Indeed, the surface of substrates may be adhered by a large number of biological membranes that have a direct effect on nitrification or denitrification [12].

In recent studies, nitrogen removal from eutrophic rivers using CWs was mainly restricted by carbon sources, because the rivers had a low C/N ratio [13,14]. Among various external carbon sources, plant biomass materials could be widely applicable to enhance denitrification in organic carbon-limited wetlands because of their low costs, renewable biomass and wide availability [2,15]. However, the majority of studies conducted till date were based on synthetic water media. Additionally, until recently, there has been a lack of knowledge regarding denitrification and nitrate removal efficiency in response to the addition of plant litter to CWs.

Therefore, this study was conducted to investigate the effect of different substrates, configurations, HRTs and temperatures on CWs during the treatment of eutrophic river water in the estuary of Yapu River flowing into Lake Taihu. The effect of using cattail litter as an external carbon source during the cold period to improve denitrification in CWs was also evaluated.

2. Materials and methods

2.1. Experimental setup

Five horizontal subsurface-flow CWs (HW1, HW2, HW3, HW4, and HW5) were placed next to the estuary of Yapu River, Changzhou, China (N 31.78˚, E 119.95˚). All the five CWs were made of PVC. Four of them including HW1, HW2, HW3, and HW5 were rectangular tanks, with dimensions of 1.7 m long, 0.4 m wide and 0.8 m deep. Only HW5 was trapezoid and had the same length and depth as that of the other CWs. The long edge of HW5 was used as the water inlet with a width of 0.5 m, while the short one whose length was 0.3 m was naturally the water outlet. Along the length from the inlet to the outlet, each CW was separated into four parts by three perforated plates, including a water distribution area (0.15 m), carbon resource area (0.20 m), porous media area (1.20 m) and catchment area (0.15 m) (Fig. 1). The water distribution area and catchment area were filled with gravel (diameter, 20–30 mm; porosity, 0.6). Additionally, three different substrates were used in the porous media of various microcosms (Table 1). The porous media were placed in each tank at a thickness of 60 cm. River water was distributed through a perforated PVC pipe, which is placed across the entire width at the upstream side of the water distribution area of the tank. The outlet structure of the units was an orifice, at the bottom of the downstream end of the unit which is connected to a U-pipe. The elevation of the downstream end of this pipe, from where the water spilled over, controlled the downstream water surface elevation in the tank at the upper surface of the porous medium at about 60 cm. In addition, two sampling tubes were placed between the second-perforated plate and the third-perforated plate which was below the surface media of 0.3 m. Due to their small scale and excellent distribution condition, there is no obvious fall of water table found along the length of CWs. Moreover, each microcosm contained plants (*Phragmites australis*) at approximately 24 plants/m^2.

2.2. Operation of CWs

The CWs were fed with eutrophic water from the Yapu River. The amount of inlet wastewater was controlled by pumps (BT100–2J, Longer, Baoding, China) which were operated constantly throughout the experiment. The operation programme of the CWs is shown in Table 2. HRT was calculated with Eq. (1), while hydraulic loading rate (HLR) was calculated with Eq. (2).

$$\mathrm{HRT} = \frac{A \times d \times \varepsilon}{Q} \quad (1)$$

$$\mathrm{HLR} = \frac{Q}{A} \quad (2)$$

where A = surface area of the CW (m^2), d = water table (m), ε = porosity of the CW media, and Q = flow (m^3/d).

2.3. Using plants as a carbon source

In this study, cattail litter (*Typha latifolia*) was used as an external carbon source according to previous studies [2,15]. The cattail litter was collected near the CWs in February of the first year. After collection, some of the cattail litter was cleaned, cut into pieces between 1 and 2 cm and air-dried to a constant mass

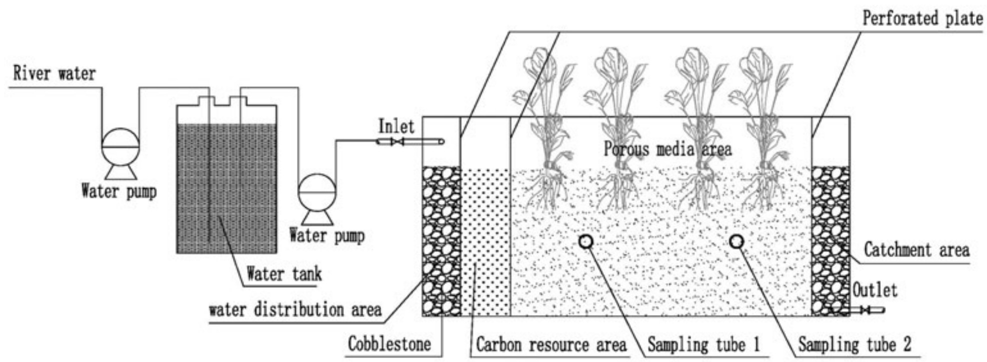

Fig. 1. Schematic diagram of the microcosm wetland system.

Table 1
Details of packed bed (length 120 cm) in each CW from the inlet to the outlet

	0–30 cm			30–120 cm
CWs	Media[a]	Diameter (mm)	Porosity	Support media[b]
HW1	Gravel	10–15	0.5	Gravel
HW2	Zeolite	7–10	0.4	Gravel
HW3	Ceramsite	8–14	0.4	Gravel
HW4	Ceramsite	8–14	0.4	Gravel
HW5	Gravel	10–15	0.5	Gravel

[a]The media ware bought from the local market.
[b]Diameter = 10–15 mm, porosity = 0.5.

Table 2
Operation programme of CWs

	Operation time									
	May in the first year		June in the first year		July in the first year		August in the first year		September in the first year–July in the second year	
CWs	HRT (d)	HLR (m^3/m^2 d)	HRT (d)	HLR (m^3/m^2 d)	HRT (d)	HLR (m^3/m^2 d)	HRT (d)	HLR (m^3/m^2 d)	HRT (d)	HLR (m^3/m^2 d)
HW1	8	2.0	4	1.0	4	1.0	4	1.0	4	1.0
HW2	8	1.6	4	0.8	4	0.8	4	0.8	4	0.8
HW3	8	1.6	4	0.8	4	0.8	4	0.8	4	0.8
HW4	8	1.6	4	0.8	4	0.8	4	0.8	4	0.8
HW5	8	2.0	4	1.0	2	0.5	1	0.25	4	1.0

before being stored in a container free from moisture and stored at room temperature (20℃). On 28 February, the one trial cattail litter weighing 400 g was added to the carbon resource area of HW5, which is equally based on our previous study of adding aquatic plant biomass to improve C/N effectively [16]. Plastic nets with dense gaps were also set up approximately 5 cm below the water surface to ensure that the cattail litter was in full contact with the water.

2.4. Water and data analysis

Water samples of Yapu River were collected every 15 d, while influent and effluent of the five CWs were collected for almost every three days. The influent and effluent samples of each CW were taken from the influent and effluent ports separately. Besides, water samples from the two sampling tubes were collected after the performance of CWs and was stable under each operating condition. In addition, a repeat sample was set for every sample. NO_3^--N (225 and 275 nm), NO_2^--N (538 nm) and NH_4^+-N (420 nm) were analysed using an ultraviolet spectrophotometer (UV-2401 PC, Shimadzu, Japan). TN was measured by alkaline potassium persulphate oxidation—ultra spectrophotometry and TP was measured by potassium persulphate oxidation—molybdenum colorimetry. Chemical oxygen demand (COD) was represented by the potassium permanganate index. The following parameters were also analysed according to standard methods [17]: pH, electric conductivity (EC), chlorophyll a (Chla), transparency and dissolved oxygen (DO). Statistical analyses were conducted using SPSS version 16.0, which was used to calculate the mean and the standard deviation of datum.

3. Results and discussion

3.1. Monitoring the water quality of Yapu River

Yapu River is located at Yapu Village in Changzhou. The river is a branch of rivers around Wujin Port that flows into Lake Taihu. Owing to the subtropical monsoon climate, the average temperature in the study area is 4°C in winter and 27.5°C in summer.

River water samples were collected 0.5 km from the estuary of Yapu River, from December to next November (Fig. 2). The COD, TP, TN, and NO_3^--N of the wastewater are shown in Table 3. The COD was not high during the cold period (November–April); however, the TN was quite high, the majority of which was NO_3^--N. During the warm period (May–October), the COD varied greatly and remained at a high level. The TN concentration showed a downward tendency, decreasing from 14.2 to 2.3 mg/L. Moreover, the TP varied from 0.06 to 0.75 mg/L throughout the period. The likely reason for the high TN in the river water was low water temperature, which led to poor microbial activities.

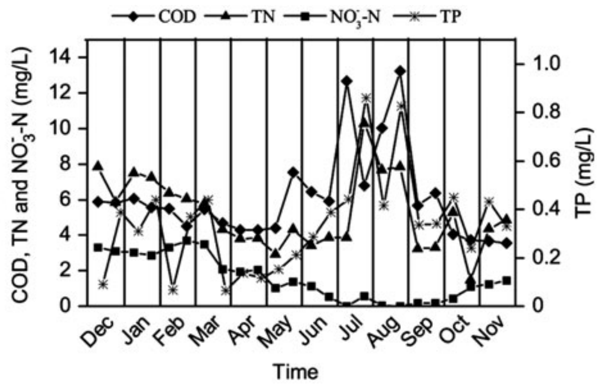

Fig. 2. River water quality during the whole monitoring year.

Table 3
Quality of the river water in Yapu River feeding the CWs

Parameter	Data			
	Cold period		Warm period	
	Range	Mean	Range	Mean
Temperature (°C)	2.3–10.2	5.4	20.4–35.8	26.5
Transparence (cm)	10–30	19	6–28	14
DO (mg/L)	2.7–7.6	5.1	5.2–8.6	6.9
pH	6.7–8.8	7.7	7.3–7.8	7.6
EC (μS/cm)	429–727	577	503–971	758
Chla (μg/L)	0.4–4.2	1.4	1.2–12.5	6.4
COD (mg/L)	3.6–9.1	5.5	3.9–20.5	10.0
TP (mg/L)	0.06–0.75	0.26	0.05–2.83	0.41
TN (mg/L)	2.3–14.2	6.8	1.5–8.8	6.7
NO_3^--N (mg/L)	0.5–5.3	2.9	0.1–2.4	0.9
NO_2^--N (mg/L)	0.1–0.3	0.2	0.1–0.5	0.2
NH_4^+-N (mg/L)	0.9–4.1	2.9	0.5–5.0	2.4

3.2. Impact of substrates

Considering the important role of the substrates for the CW, different substrates were used in HW1, HW2, and HW3 in order to compare their pollutant removal efficiency (Fig. 3(A)).

The removal efficiency of COD in HW2 (zeolite–gravel) was highest (47.90%), which may have been due to a better oxygen environment provided by zeolite for microbes [12]. As shown in Fig. 3(A), the NH_4^+-N removal efficiencies occurred in the order HW2 (zeolite–gravel) >HW3 (ceramsite–gravel) > HW1 (gravel). The adsorption of zeolite played an important role in the removal of NH_4^+-N by CWs, which was consistent with the results of studies conducted by Bruch et al. [12] and Jayaweera and Mikkelsen [18]. According to Li [19], both zeolite and ceramsite contained greater than 50% SiO_2. Since Si facilitates the absorption of NH_4^+-N, the absorption abilities of zeolite and ceramsite were better than that of gravel. The average removal efficiency of NO_3^--N in HW3 (over 90%) was much better than that in HW2 (72.27%). Since the majority of TN was NO_3^--N, the TN removal efficiency was as follows:

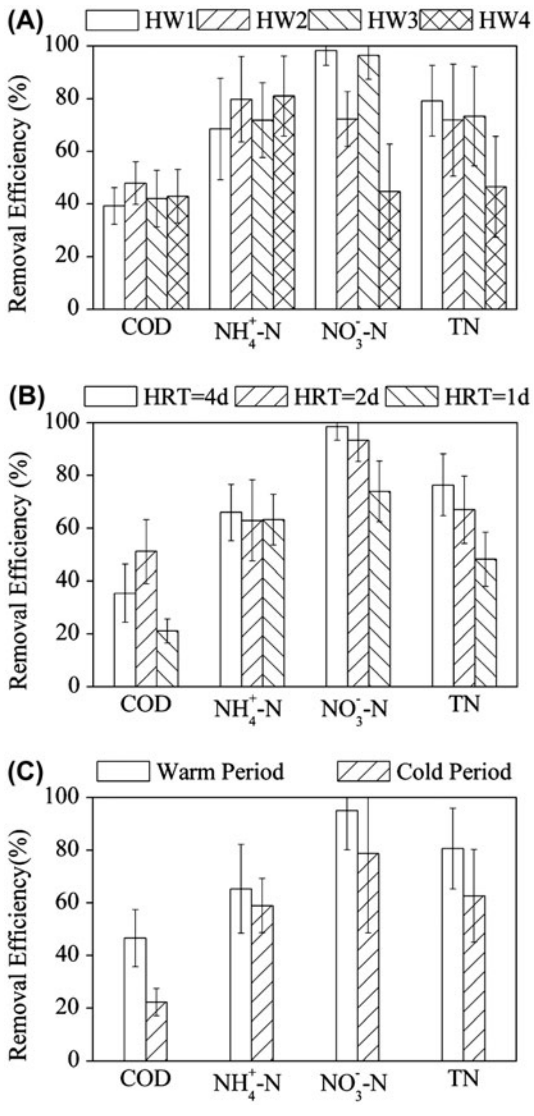

Fig. 3. Removal efficiencies of pollutants with different substrates and different configurations (A), different HRTs by HW5 during the warming period (B), and different seasons by HW1 (C). Values were the average plus/minus one standard deviation ($n > 3$).

HW1 > HW3 > HW2. Based on these findings, the use of gravel substrate is an effective method for the removal of nitrogen from river water with low carbon and high nitrogen levels.

3.3. Impact of configurations

This study examined the use of an irregular trapezoidal CW (HW4) for the treatment of nutrient-rich river water. As shown in Fig. 3(A), the removal efficiency for COD was nearly equal between HW3 and HW4, while the removal efficiency of NH_4^+-N (81.02%) in HW4 was 10% higher than that in HW3. However, the NO_3^--N removal efficiency (44.65%) was only 46.37% than that of HW3. For both CWs, the front of the tank had a high DO concentration than the end. DO (dissolve oxygen) of sampling tube 1 in HW3 was 2.8 ± 0.1 mg/L, while that of sampling tube 2 was 0.3 ± 0.1 mg/L. For HW4, DO values of sampling tubes 1 and 2 ware 3.1 ± 0.1 and 0.1 ± 0.1 mg/L, respectively. Thus, it can be concluded that the shape has an effect on the distribution of DO, which could have an impact on nitrogen removal. Carbon was limited in the end of HW4, which could not ensure complete denitrification, because the organic matter was primarily removed by aerobic metabolism and was retained by sediments [20]. Consequently, a sufficient carbon source must be ensured when trapezoidal CWs are used to improve the DO concentration in the front of the system [21].

3.4. Impact of HRT

HRT is related to water flow, wetland shape and porosity, which have a close relationship with the effect of the CW treatment [7]. Accordingly, it was identified as one of the important parameters for CW management systems [22]. A suitable HRT will improve the removal efficiency [7].

The removal efficiencies of COD, NH_4^+-N, NO_3^--N and TN in HW5 for various HRTs (1, 2 and 4 days) are presented in Fig. 3(B). When HRT was longest (4 d), the removal efficiencies of NH_4^+-N, NO_3^--N and TN were highest in HW5. The removal efficiency of TN was 79.23% and the level of TN in the effluent dropped to 0.99 mg/L. While for an HRT of 2 d, the removal efficiency of TN declined to 74.04% and the concentration was 1.58 mg/L. These findings indicate that with a longer residence time, nitrification and denitrification react more completely and nitrogen removal efficiency is higher [7].

3.5. Impact of temperatures

Many previous studies have shown that the effect of CWs was significantly influenced by temperature [21,23]. Akratos [7] demonstrated that the removal efficiencies of pollutants were improved by an increase in temperature. As shown in Fig. 3(C), COD and TN were removed significantly by HW1 during the warm period; however, the removal was not as great during the cold period. This difference may have been in response to the reduced bacterial activity owing to the low temperature and lack of carbon [9]. The difference in the average COD removal efficiency during the warm and cold period was 24.31% and NO_3^--N removal efficiency during the cold period was low and fluctuant.

3.6. Impact of external carbon sources

Based on the analysis above, denitrification in HW1 was relatively weak during the cold period. A study conducted by Lu et al. [9] revealed increased denitrification rates when external carbon was added. Wen et al. [15] and Hume et al. [24] also demonstrated the feasibility of using cattail litter as an organic carbon source for the elimination of nitrate in CWs. However, the present study was the first to investigate the effects of adding cattail litter as a carbon source on denitrification in CWs with the influence of eutrophic river water.

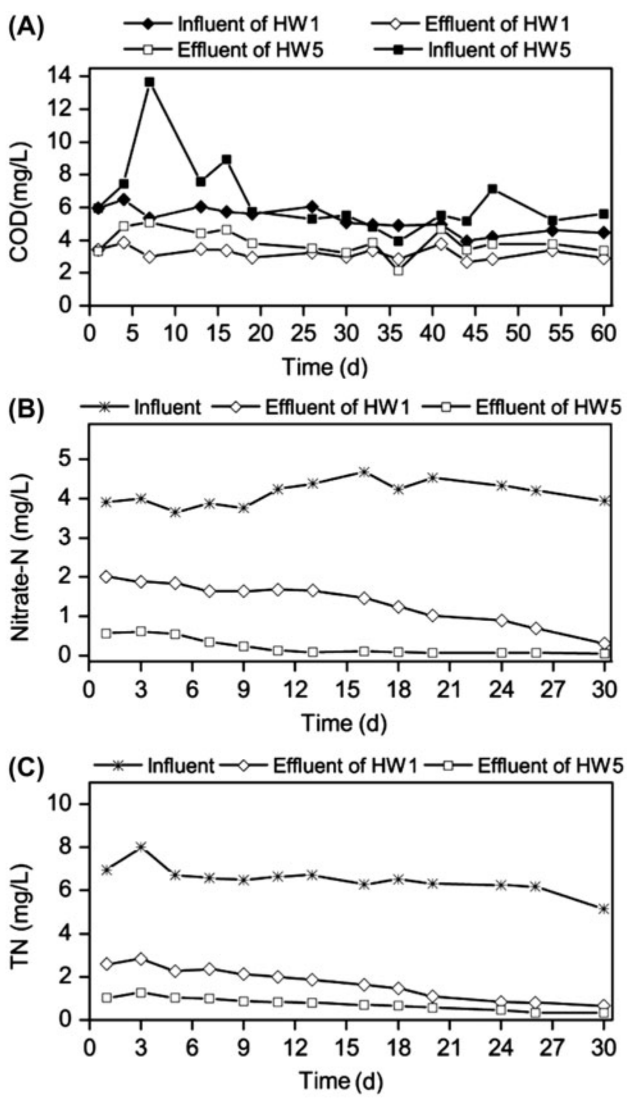

Fig. 4. COD, NO_3^--N and TN concentrations of the influent and effluent of HW1 and HW5 from 1 March to 2 July in the first operation year (after the addition of carbon to HW5).

Changes in the COD concentration of influent and effluent in HW1 and HW5 are shown in Fig. 4(A). COD in HW5 was higher than that in HW1 and increased greatly in the former period, but then stabilized. After adding 400 g of cattail litter for 7 d, the COD of influent in HW5 reached its highest level of 13.66 mg/L, which was 2.56 times higher than that of HW1. This may have been due to the biodegradable portion of the cattail litter being utilized by microbes, thereby leading to a rapid increase in COD. The COD of effluent also increased, but the growth was not high. The highest COD (5.06 mg/L) appeared at the same time as the influent, which was 70.87% greater than that in HW1. After 20 d, COD in HW5 was slightly higher than that in HW1, and the difference gradually became smaller.

The nitrogen removal is presented in Fig. 4(B) and (C). The NO_3^--N concentration in HW5 decreased significantly, and the effect was so high on the second day that the NO_3^--N and TN of effluent in HW5 were 27.91 and 38.98% of that in HW1, respectively. After adding cattail litter to HW5 for 20 d, the NO_3^--N and TN in HW1 and HW5 gradually became similar, indicating that the advantages of HW5 were reduced. Wen [15] found that adding cattail litter (1.4 kg/m^2) caused the TN removal efficiency of a CW to be 2.6 times greater than that of a CW that did not receive cattail litter. Similarly, the TN removal efficiency in HW5, which received added carbon, was higher than that of HW1, which did not receive external carbon. These findings indicate that adding plant carbon can enhance the removal ability of nitrogen, which is also an effective way to improve the low removal efficiency during the cold period.

4. Conclusions

In this study, CWs with substrates of zeolite–gravel or ceramsite–gravel were found to effectively eliminate COD and NH_4^+-N. The trapezoidal CW improved the DO concentration in the front part to provide complete nitrification. Organics, nitrogen and phosphorus could be removed more effectively with a longer HRT. The CWs performed better during the warm period. Adding plant litter as a carbon source improved the removal efficiency of nitrogen, indicating that this technology can be applied in CWs to enhance denitrification during the cold period.

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References

[1] Q. Yan, M. Zhao, H. Miao, W. Ruan, R. Song, Coupling of the hydrogen and polyhydroxyalkanoates (PHA) production through anaerobic digestion from Taihu blue algae, Bioresour. Technol. 101 (2010) 4508–4512.

[2] Y. Chen, Y. Wen, J. Cheng, C. Xue, D. Yang, Q. Zhou, Effects of dissolved oxygen on extracellular enzymes activities and transformation of carbon sources from plant biomass: Implications for denitrification in constructed wetlands, Bioresour. Technol. 102 (2011) 2433–2440.

[3] L. Hu, W. Hu, S. Zhai, H. Wu, Effects on water quality following water transfer in Lake Taihu, China, Ecol. Eng. 36 (2010) 471–481.

[4] F.E. Wang, P. Tian, J. Yu, G.M. Lao, T.C. Shi, Variations in pollutant fluxes of rivers surrounding Taihu Lake in Zhejiang Province in 2008, Phys. Chem. Earth, Parts A/B/C. 36 (2011) 366–371.

[5] J. Vymazal, Horizontal sub-surface flow and hybrid constructed wetlands systems for wastewater treatment, Ecol. Eng. 25 (2005) 478–490.

[6] J. Vymazal, Constructed wetlands for wastewater treatment, Water 2 (2010) 530–549.

[7] C.S. Akratos, V.A. Tsihrintzis, Effect of temperature, HRT, vegetation and porous media on removal efficiency of pilot-scale horizontal subsurface flow constructed wetlands, Ecol. Eng. 29 (2007) 173–191.

[8] V. Tsihrintzis, G. Gikas, Constructed wetlands for wastewater and activated sludge treatment in north Greece: A review, Water Sci. Technol. 61 (2010) 2653–2672.

[9] S. Lu, H. Hu, Y. Sun, J. Yang, Effect of carbon source on the denitrification in constructed wetlands, J. Environ. Sci. 21 (2009) 1036–1043.

[10] X. Wei, X. Wang, B. Dong, X. Li, A.K. Plappally, Z. Mao, L.C. Brown, Simplified residence time prediction models for constructed wetland water recycling systems, Desalin. Water Treat. 51 (2013) 1494–1502.

[11] D. Giraldi, R. Iannelli, Measurements of water content distribution in vertical subsurface flow constructed wetlands using a capacitance probe: Benefits and limitations, Desalination 243 (2009) 182–194.

[12] I. Bruch, J. Fritsche, D. Bänninger, U. Alewell, M. Sendelov, H. Hürlimann, R. Hasselbach, C. Alewell, Improving the treatment efficiency of constructed wetlands with zeolite-containing filter sands, Bioresour. Technol. 102 (2011) 937–941.

[13] Y.-F. Lin, S.-R. Jing, T.-W. Wang, D.-Y. Lee, Effects of macrophytes and external carbon sources on nitrate removal from groundwater in constructed wetlands, Environ. Pollut. 119 (2002) 413–420.

[14] Ş. Aslan, A. Türkman, Combined biological removal of nitrate and pesticides using wheat straw as substrates, Process Biochem. 40 (2005) 935–943.

[15] Y. Wen, Y. Chen, N. Zheng, D. Yang, Q. Zhou, Effects of plant biomass on nitrate removal and transformation of carbon sources in subsurface-flow constructed wetlands, Bioresour. Technol. 101 (2010) 7286–7292.

[16] X.-F. Huang, X. Liu, J.-J. Shang, Y. Feng, J. Liu, L.-J. Lu, Pretreatment methods for aquatic plant biomass as carbon sources for potential use in treating eutrophic water in subsurface-flow constructed wetlands, Water Sci. Technol. 66 (2012) 2328–2335.

[17] American Public Health Association, Standard Methods for the Examination of Water and Wastewater, American Public Health Association, Washington DC, 1998.

[18] G.R. Jayaweera, D.S. Mikkelsen, Assessment of ammonia volatilization from flooded soil systems, Adv. Agron. 45 (1991) 303–356.

[19] Z. Li, Use of surfactant-modified zeolite as fertilizer carriers to control nitrate release, Microporous Mesoporous Mater. 61 (2003) 181–188.

[20] T. Saeed, R. Afrin, A.A. Muyeed, G. Sun, Treatment of tannery wastewater in a pilot-scale hybrid constructed wetland system in Bangladesh, Chemosphere 88 (2012) 1065–1073.

[21] I.P. Kotti, G.D. Gikas, V.A. Tsihrintzis, Effect of operational and design parameters on removal efficiency of pilot-scale FWS constructed wetlands and comparison with HSF systems, Ecol. Eng. 36 (2010) 862–875.

[22] J. Yu, K. Park, Y. Kim, A characteristic study on the particles in a constructed stormwater wetland during dry days, Desalin. Water Treat. 38 (2012) 238–247.

[23] S. Lee, M.C. Maniquiz, J. Choi, J.-H. Kang, S. Jeong, L.-H. Kim, Seasonal treatment efficiency of surface flow constructed wetland receiving high nitrogen content wastewater, Desalin. Water Treat. 48 (2012) 9–16.

[24] N.P. Hume, M.S. Fleming, A.J. Horne, Plant carbohydrate limitation on nitrate reduction in wetland microcosms, Water Res. 36 (2002) 577–584.