Environment Protection Engineering

Vol. 42 2016 No. 4

DOI: 10.5277/epe160409

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PERFORMANCE ANALYSIS OF THE HORIZONTAL SUBSURFACE FLOW CONSTRUCTED WETLAND UNDER DIFFERENT HYDRAULIC LOADING RATES FOR RURAL DOMESTIC WASTEWATER TREATMENT

The performance of horizontal subsurface flow constructed wetland (HFCW) for rural domestic sewage treatment has been evaluated. The system was built as a tertiary treatment after the biological processes to improve the effluent wastewater quality. The HFCW was operated in three phases under different hydraulic loading rates (HLRs), and with three kinds of aquatic plants i.e., water spinach, Chinese celery and cress. The vegetation growth parameters such as plant height, fresh and dry weights were monitored and analyzed. The influent and effluent concentrations of the chemical oxygen demand (COD), ammonium nitrogen (NH_4^+-N), total nitrogen (TN) and total phosphorus (TP) were measured. The average removal efficiencies at the first phase were 52.9%, 64.7%, 58.2% and 72.8%, and it reduced to 48.6%, 52.2%, 44.04% and 64.4% in the second phase for COD, NH_4^+-N, TN and TP, respectively. In the third phase, the HFCW system showed the following mean removal efficiencies: 51.2%, 74.2%, 58.5% and 80.9%. The results revealed that the removal efficiencies increased with decrease in the HLR and increased temperatures. The findings confirmed that the horizontal flow constructed wetland is more convenient for the rural wastewater treatment with efficient nutrient removal.

1. INTRODUCTION

Rural domestic wastewater is one of the main water pollution sources in China. Only <1% of wastewater in rural areas are being treated, and most of rural populations have no access to sanitation services [1]. Rural wastewater contain high concentrations of nutrients. Therefore, the constructed wetlands (CWs) are considered one of the most common schemes used for nutrient removal from the domestic sewage of small communities in rural areas according to their advantages. The CWs have become widely

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used for various wastewater treatments around the world. In recent years, the CWs are increasingly being used in China to accomplish secondary and tertiary treatment of the domestic, municipal, and industrial wastewaters [2]. CWs offer an attractive option to wastewater treatment with efficient and less energy intensive, low operation costs and maintenance requirements and are more aesthetically pleasing compared with conventional wastewater treatment systems [3, 4]. Furthermore, CWs are considered attached growth biological reactors, which offer higher pollutant removal efficiency through physical, chemical, and biological mechanisms. Many of the contaminants such as organic material, nutrient, total coliforms, and heavy metals can be removed from the wastewater with constructed wetlands through sedimentation, coagulation, adsorption, filtration, plant uptake, and microbial transformation [5].

In a horizontal subsurface flow constructed wetland (HFCW), organic matter and nutrient are removed by aerobic bacteria attached to the porous media and the plant roots. Therefore, wetland plants have great influence on the purification capacity of wastewater [6]. Besides that, it is also assist on control the ventilation and microbial conditions in the HFCW bed. The nitrogen removal is achieved through nitrification/denitrification, volatilization of ammonia (NH_3) storage in detritus and sediment, and uptake by wetland plants and storage in plant biomass [7]. The wetland plants transport O_2 to the rhizosphere, thereby creating aerobic conditions at the sites near the roots and rhizomes, where the ammonium ions will be oxidized to nitrites and then to nitrates by nitrifying bacteria [8]. Water spinach (*Ipomoea aquatic*), Chinese celery (*Oenanthe javanica*) and cress (*Lepidium sativum*), which are widely used for water pollution control are planted into HFCW at different seasonal conditions to evaluate their influence on the treatment efficiency [9].

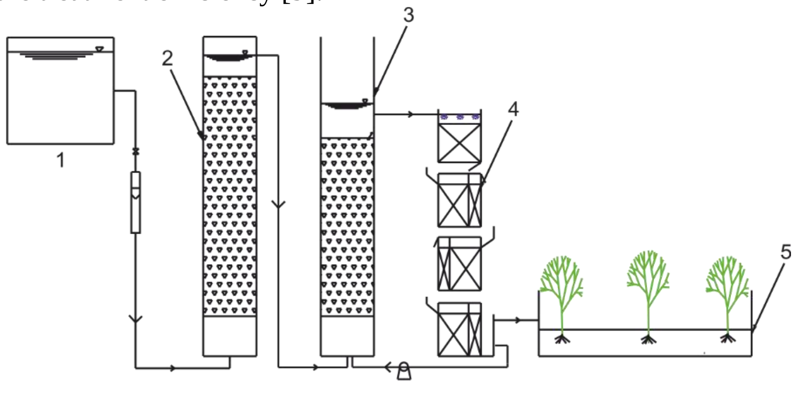

Fig. 1. Integrated biological constructed wetland system: 1 – influent tank, 2 – anaerobic filter, 3 – anoxic filter, 4 – waterfall aeration biofilm reactor, 5 – constructed wetland

In this study, the HFCW as a tertiary wastewater treatment was applied to increase the removal efficiency of the organic material and nutrients. The wastewater that feeds the HFCW was pumped directly from a waterfall aeration bio-reactor of the biological processes (A^2O: anaerobic – anoxic – oxic). The HFCW performance efficiencies under different HLRs, and three of aquatic vegetation types planted in varied climatic conditions were evaluated. The schematic diagram of the integrated system is shown in Fig. 1.

2. EXPERIMENTAL

2.1. RAW WASTEWATER CHARACTERISTICS

The HFCW was installed after the biological treatment processes in order to improve the quality of the wastewater effluent. Raw wastewater from a campus main manhole was pumped into a storage tank for sedimentation, and then pumped to the biological processed. The effluent wastewater from the waterfall aeration biofilm reactor with low organic material and high nutrient was used as influent of HFCW system. The HFCW treatment performance was evaluated by collecting wastewater samples and analyzed during the experimental operations. The wastewater characteristics used in this study as influent of HFCW are shown in Table 1. The table presents the minimum, maximum and the average values with standard deviations of the wastewater pollutant concentrations during the experimental operations.

Table 1

Parameters of the wastewater
in the influent of constructed wetland [mg/dm^3]

Parameter	Minimal	Maximal	Mean±SD
COD	51.5	145.8	88.9621.16
TN	13.4	28.3	21.44±4.09
NH_4^+-N	8.5	23.0	13.51±2.69
TP	0.52	3.0	1.81±0.73
DO	3.8	7.2	5.07±0.91
pH	7.2	8.1	7.55±0.63

2.2. CONSTRUCTED WETLAND SETUP AND TEST PROCEDURES

The study was conducted in Southeast University campus of Taihu lake environmental research center in Wuxi City, China; approximately ten months ranged from July to May. The HFCW was operated and their performance efficiency was investigated. The HFCW was made of polyvinyl chloride as a rectangular basin 2.3 m long, 0.6 m wide, 0.4 m deep. The longitudinal bottom slope is 0.5%. The HFCW basin was filled with two matrix layers to support plants growth: the 20 cm layer of coarse gravel (5–25 mm), followed by a 10 cm sand layer with various diameters (0.5–2 mm), and some clay was also added to the reactor. The HFCW was operated in three phases; the water spinach was planted in the first phase which started on 15th of July; the Chinese celery was planted in the second phase which started on 15th of October and the cress was cultivated in the third phase which started on 15th of March. The temperatures in the study area during the experimental operation ranged from 16.4 to 33.5 °C in the first phase (summer–autumn), from 4 to 17.8 °C in the second phase (autumn–winter), and in the third phase (spring–summer) it ranged between 11 and 26.3 °C.

The seedlings of these aquatic plants were collected from the research garden of our university in Yixing village and planted into the constructed wetland during experimental operations. These plants were cultivated during different climatic conditions such as warm season (July–October), the wet season (October–January) and moderate season (March–May) in the first, second and third phase system operations, respectively. Figure 2 illustrates the schematic of the constructed wetland used in this study.

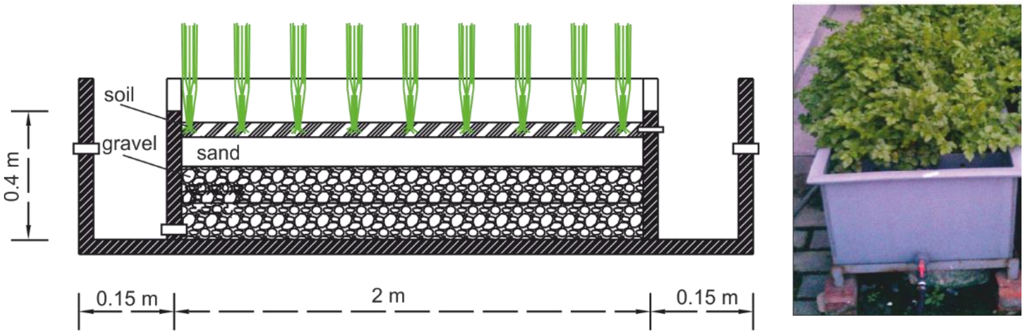

Fig. 2. Schematic chart of constructed wetland and photograph of HFCW wetland

The samples of influent and effluent wastewater were collected in plastic bottles and analyzed for the chemical pollutant concentrations. The chemical oxygen demand (COD), ammonium nitrogen (NH_4^+-N), total nitrogen (TN) and total phosphorus (TP) were measured according to the standard methods recommended by US Environmental Protection Agency [10]. However, the plant growth parameters such as fresh and dry weights were measured by the method proposed by Leto et al. [11], and the plant height was measured using a measuring tape.

3. RESULTS AND DISCUSSION

3.1. PLANT GROWTH PARAMETERS

The average temperatures during the experimental operations are presented in Table 2. The average temperature during the first phase was 25.2 °C, during the second phase – 12.3 °C and during the third phase – 20.1 °C. Water spinach showed good growth with green leaves during the experimental operations.

Table 2

Means of monthly temperature during the experiment [°C]

Month	Mean temperature
July	31.2
August	28.4
September	22.3
October	19.0
November	15.4
December	11.3
January	4.4
March	16.2
April	20.3
May	24.1

At the harvested time, the average height of the plant was 56 cm and the fresh and dry weights were 123 g, and 22.6 g, respectively (Table 3). In the second phase of the system operation, Chinese celery exhibited good growth. However, in this phase results revealed slight reduction in the plant growth, especially in January and showed some green-yellow leaves caused by low temperature at this time. At the end of the second phase, the Chinese celery average height was 48.4 cm with 102 g and 17.9 g for fresh and dry weights, respectively. In contrast, the cress cultivated in third phase also showed good growth with the plant height of 53 cm, dry weight was 19.2 g, and the fresh weight was 105 g on average at the harvesting time. It seems that the three plant species showed good growth and can be used for nutrient removal.

Table 3

Growth parameters of the plants during the experiment

HLR [m/day]	Time	Water spinach			Chinese celery			Cress		
		Weight [g]		Plant height [cm]	Weight [g]		Plant height [cm]	Weight [g]		Plant height [cm]
		Fresh	Dry		Fresh	Dry		Fresh	Dry	
	Cultivating time	20	4.1	14	15	3.5	8	16.4	6.5	17.3
0.150	First month	76.2	8.8	33.6	58.7	7.4	25	52.0	9.7	24.8
0.222	Second month	102.2	17.2	45.2	86.9	11.2	39	91.1	15.1	48.8
0.3	Third month	123	22.6	56	102	17.9	48.4	105	19.2	53.0

3.2. ORGANIC MATTER REMOVAL EFFICIENCY

Organic matter is reduced in CWs by the bacteria, other aerobic and anaerobic microbes, and the plants and substrate have a positive effect on the treatment performance [12]. Leto et al. [11] stated that the planted constructed wetland systems had significant influence on the organic matter removal, and demonstrated better COD decomposition than unplanted systems. The influent COD concentrations during the experimental operations ranged between 51.5 and 145.8 mg/dm^3, and the average effluent was almost settled below 50 mg/dm^3.

Figures 3–5 present the COD removal efficiencies during the entire three phases of the experiments. The average influent, effluent concentrations and the average COD removal efficiency ratios under different HLR and vegetation types are shown in Table 4.

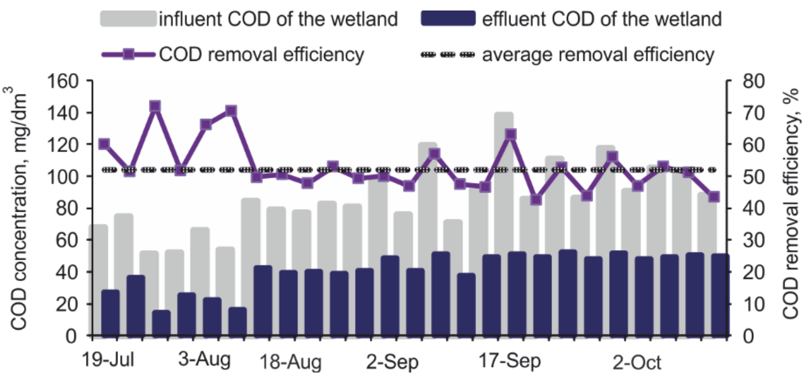

Fig. 3. COD removal efficiency of the constructed wetland in the first phase (water spinach)

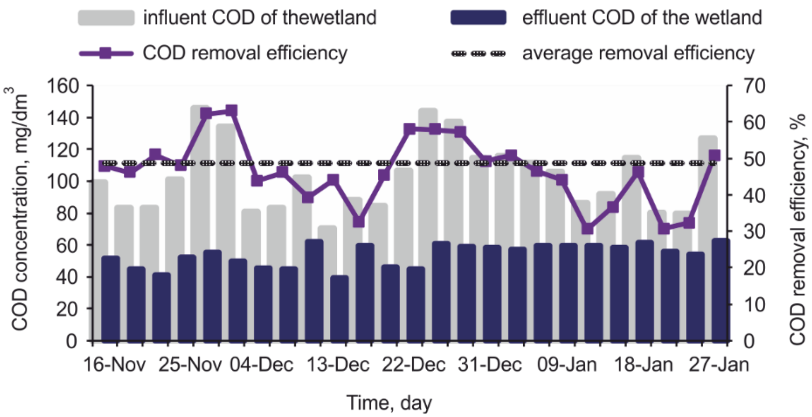

Fig. 4. COD removal efficiency of the constructed wetland in the second phase (Chinese celery)

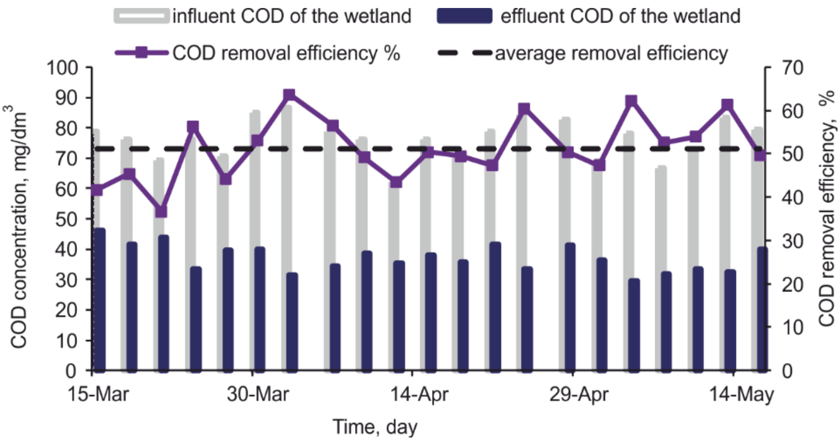

Fig. 5. COD removal efficiency of the constructed wetland in the third phase (cress)

Table 4

Average removal efficiency of COD in the constructed wetland

HLR [m/day]	Influent COD [mg/dm^3]	Effluent COD [mg/dm^3]	Removal efficiency [%]
Water spinach			
0.15	67.26	29.2	56.6
0.222	94.55	44.6	52.8
0.3	98.24	49.8	49.3
Chinese celery			
0.15	103.86	49.1	52.7
0.222	104.56	52.9	49.4
0.3	101.84	57.2	43.8
Cress			
0.15	76	34.9	53.9
0.222	75.3	36.6	50.9
0.3	77.5	39.4	48.7

The average COD removal efficiency in the first phase was 56.6%, 52.8% and 49.3% with the average effluent concentration of 29.2, 44.6, 49.8 mg/dm^3 at 0.15, 0.222 and 0.3 m/day of HLR, respectively. In the second phase, the average COD removal was 52.7%, 49.4% and 43.8% with the final effluent concentration of 49.1, 52.9 and 57.2 mg/dm^3 under the HLR of 0.15, 0.222, and 0.3 m/day, respectively. The average COD removal obtained in the third phase of operations were 53.9, 50.9, 48.7 mg/dm^3 at 0.15, 0.222 and 0.3 m/day, respectively. The HFCW revealed that the total average COD removal through the entire experimental operations was about 51%. The water spinach and cress wetland system showed the average COD removal of 52.9% and 51.1%, little higher than that for the wetland planted with Chinese celery (48.6%).

HLR is the major operational control factor for improving the treatment efficiency of CWs [13, 14]. The COD removal increased with decrease in the HLR. The removal efficiency obtained was quite similar to that determined in the study conducted by Me et al. [15], who observed a positive effect of hydraulic retention time HRT on COD removal efficiency in HFCW. Sun et al. [16] observed a decrease in organic matter removal efficiency with the increase in HLR in a horizontal subsurface flow constructed wetland system at more than 0.3 m/day of hydraulic load. Ghosh et al. [17] studied HFCWs applied for municipal wastewater treatment and the removal rates of COD were 46% and 71.8% at 0.15 and 0.1 m/day of HLR.

3.3. REMOVAL EFFICIENCY OF THE TOTAL NITROGEN AND AMMONIUM NITROGEN

The HFCW performance efficiencies based on the TN and NH_4^+-N removal under different HLR, and aquatic vegetation are presented in Figs. 6–11 and in Table 5. The HFCW treatment system showed the average removal of TN of 63.6%, 58.3%, and 52.6% in the first phase, and 47.2%, 44.3%, and 40.5% in the second, while in the third phase, it was 63.4%, 62.1% and 49.7% at the 0.15, 0.222, 0.3 m/day of HLR, respectively. The total nitrogen reduced with the increase in temperature and decrease in HLR. These results were in agreement with the study conducted by Akratos et al. [18]. Spieles et al. [19], found that the decreasing TN removal rate during the winter season justified that the decrement of nitrifying activity was associated with lower temperatures.

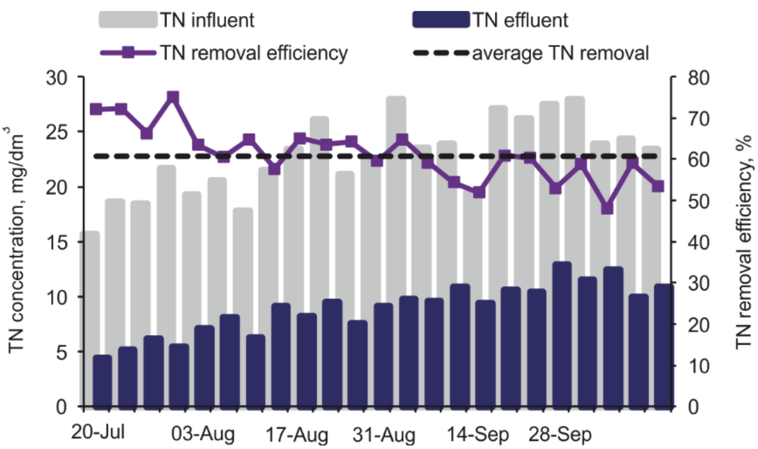

Fig. 6. Removal efficiency of total nitrogen in the first phase (water spinach)

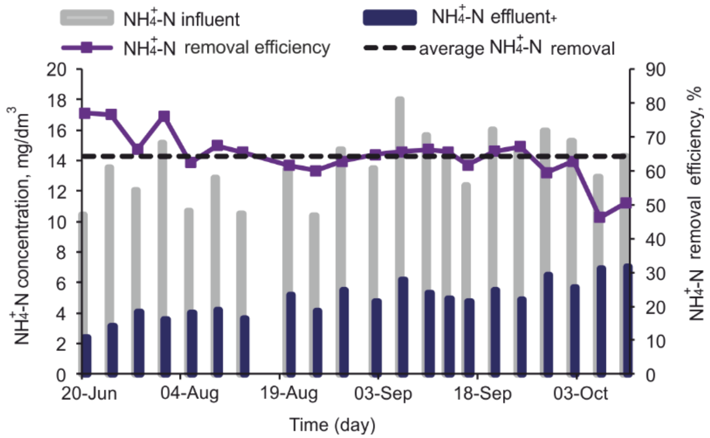

Fig. 7. Removal efficiency of ammonium nitrogen in the first phase (water spinach)

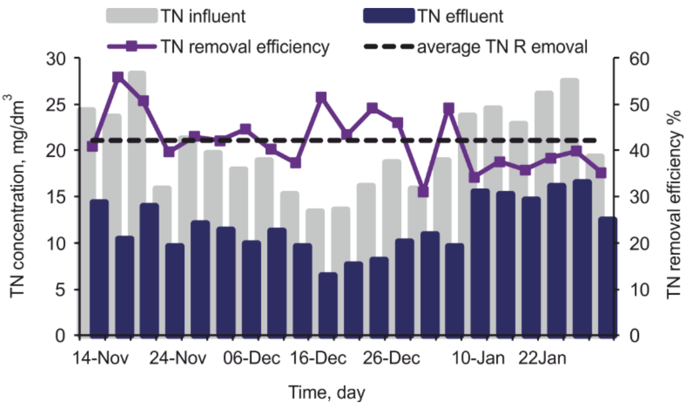

Fig. 8. Removal efficiency of total nitrogen in the second phase (Chinese celery)

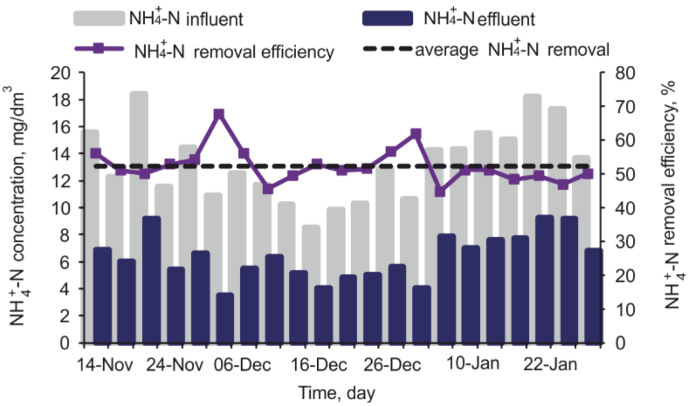

Fig. 9. Removal efficiency of ammonium nitrogen in the second phase (Chinese celery)

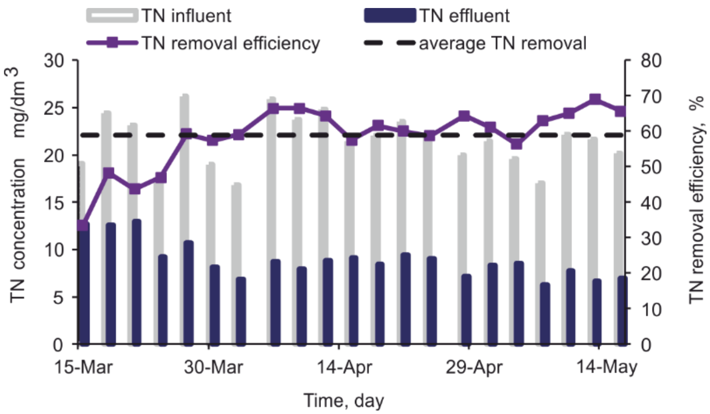

Fig. 10. Removal efficiency of total nitrogen in the third phase (cress)

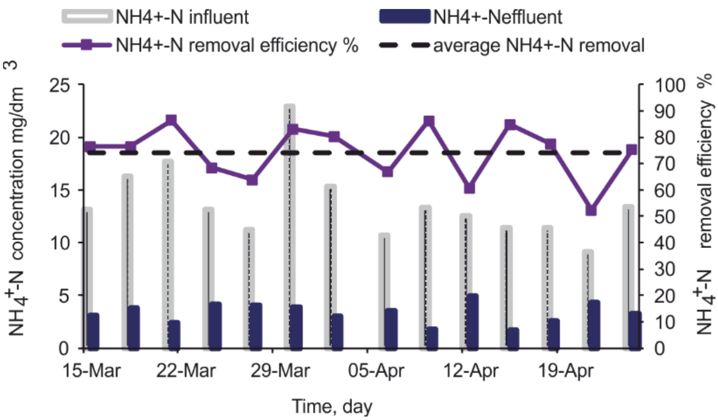

Fig. 11. Removal efficiency of ammonium nitrogen in the third phase (cress)

The average removal of NH_4^+-N and TN were 64.7%, 58.2%, 52.2%, 44.04% and 74.2%, 58.5% in the first, second and third phases, respectively. Furthermore, the total average removal rates of NH_4^+-N and TN during entire experimental operations were 62.3% and 54.03% with average final effluent concentrations of 5.04 and 9.82 mg/dm^3, respectively. Jamieson et al. [20] concluded that the improvement in ammonia removal was due to increased nitrification activity. Similar results were demonstrated by Abou--Elelaa et al. [21], who tested the treatment performance of HFCW, and found that the average efficiency of total Kjeldahl nitrogen removal (TKN) was 60%, while the average removal efficiency of NH_4^+-N was 57.1%. These values are higher than those obtained by Zurita et al. [22], who reported only 45.8% removal of TKN in the horizontal flow constructed wetland. Kuschk et al. [23] stated in their literature review that the nitrogen removal in HFCW systems is about 30–40% in general, and average values of 30% NH_4^+-N and 39.6% of TN were reported for 268 European constructed wetlands.

Table 5

Average removal efficiency of total nitrogen
in the constructed wetland

HLR [m/day]	Influent COD [mg/dm^3]	Effluent COD [mg/dm^3]	Removal efficiency [%]
Water spinach			
0.15	19.2	6.99	63.6
0.222	23.5	9.8	59.8
0.3	25.8	12.2	52.14
Chinese celery			
0.15	21.5	11.36	47.2
0.222	15.98	8.9	44.3
0.3	23.2	13.8	40.5
Cress			
0.15	20.27	7.38	63.4
0.222	23.3	8.77	62.1
0.3	20.84	10.44	49.7

3.4. REMOVAL EFFICIENCY OF TOTAL PHOSPHORUS

The influent, effluent concentrations and the removal efficiencies of the total phosphorus (TP) during the experimental operations are shown in Figs. 12–14, respectively. The average influent of TP was 1.81 mg/dm^3, the average effluent was 0.46 mg/dm^3, and the total average removal efficiency during experimental operations was 74.8% (Table 6). As is seen, the HLR has a significant effect on the removal efficiency of phosphorus and the HFCW was effective for the total phosphorus removal at high temperatures. The average removal efficiency for the phosphorus decreased from 77.3% to 67.9% during the first phase when the HLR increased from 0.15 to 0.3 m/day. The average removal during the second phase decreased from 70% to 58.9% under 0.15 and 0.3 m/day of HLR. During the third phase, the TP removal efficiency reached 89.5% at 0.15 m/day of HLR and it reduced to 66.7% at 0.3 m/day of HLR.

Kaoru et al. [9] stated that the TP removal efficiency was considerably influenced by the phosphorus absorption capacity of the plants. Akratos et al. [18] and Noor et al. [24], pointed out that the high phosphorus removal was due to the plants and microorganisms attachment in substrate, and in contrast, the phosphorus removal was mainly dependent on vegetation, porous media (type and size) and temperature. The results revealed that the HFCW was more efficient in the total phosphorus removal at the warm and moderate season. The temperature fluctuation and the Chinese celery growth in the constructed wetland withered steadily during the winter season. In order to improve the phosphorus removal in cold season, the scraped plaster was added into the inlet of the constructed wetland which can react with orthophosphate and increases the phosphorus removal.

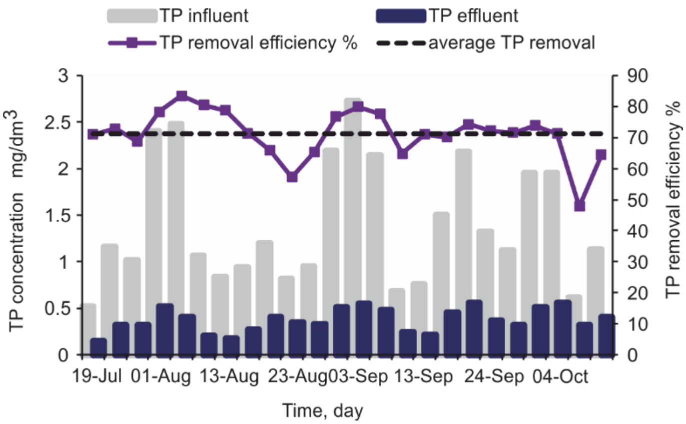

Fig. 12. Removal efficiency of total phosphorus (water spinach)

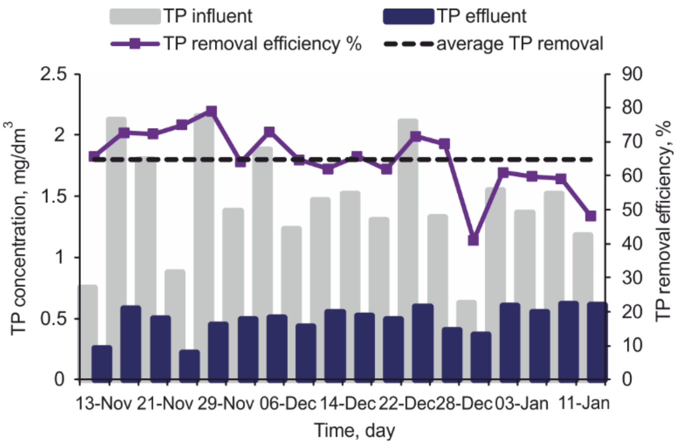

Fig. 13. Removal efficiency of total phosphorus (Chinese celery)

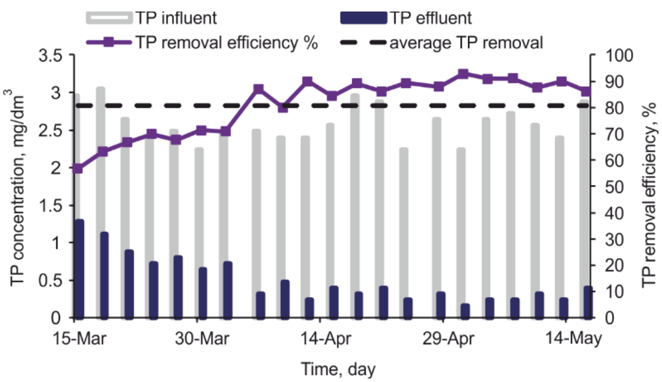

Fig. 14. Removal efficiency of total phosphorus (cress)

Table 6

Average removal efficiency of total phosphorus in the constructed wetland

HLR [m/day]	Influent COD [mg/dm^3]	Effluent COD [mg/dm^3]	Removal efficiency [%]
Water spinach			
0.15	1.30	0.29	77.3
0.222	1.43	0.39	73.1
0.3	1.47	0.47	67.9
Chinese celery			
0.15	1.57	0.46	70
0.222	1.37	0.49	64.1
0.3	1.40	0.57	58.9
Cress			
0.15	2.58	0.27	89.5
0.222	2.56	0.34	86.5
0.3	2.61	0.88	66.7

4. CONCLUSIONS

The horizontal subsurface flow constructed wetland for the rural domestic wastewater treatment has been evaluated under different hydraulic loading rates and aquatic vegetation plants. The results obtained during the entire experimental operations demonstrated that the constructed wetland system exhibited good performance for the nutrient and organic matter removal. The reduction in the HLR and the higher temperature leads to increase of the removal efficiency. For the water spinach HFCW system, the average removal efficiencies of COD, ammonium nitrogen, total nitrogen and total phosphorus were 52.9%, 64.7%, 58.2 and 72.8% in the first phase, decreasing to 48.6%, 52.2%, 44.04% and 64.4% respectively with Chinese celery HFCW system. The third phase with cress HFCW system showed good removal efficiency of the pollutant with an average COD, NH_4^+-N, TN and TP of 51.1%, 58.5%, 74.2% and 80.9%, respectively.

The HFCW showed the higher pollutant removal efficiencies at the lower HLR, and the cress wetland system presented highest nutrient removal compared with the other plant species. The three plant species showed good growth, and assist to obtain high efficiency for nutrient removal from the rural domestic wastewater. These results demonstrated that the HFCW systems are more suitable and efficient as a tertiary treatment for the rural domestic wastewater.

ACKNOWLEDGEMENTS

This research was funded by the National Natural Science Foundation of China under the project No. 51078074.

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