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Effect of feeding rate and frequency on organics and nitrogen removal in VFCWs with a novel reoxygenation corridor

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ABSTRACT

Subsurface oxygen transfer rate is considered one of the main rate-limiting factors for removal of organic and nitrogenous compounds in subsurface flow wetlands used for domestic wastewater treatment. In this paper, a novel reoxygenation corridor was set up in vertical flow subsurface constructed wetlands (VFCWs) to improve the subsurface oxygen transfer and pollutants removal. The experiment results indicated that the existence of corridor can improve the internal oxygen environment of VFCWs and the removal efficiency of chemical oxygen demand (COD) and ammonium nitrogen (NH_4^+–N). The feeding rate experiment results showed that the best removal of COD, NH_4^+–N and total nitrogen (TN) were 89.6%, 71.0% and 57.4%, respectively. Moreover, in feeding frequency experiments, the best removal efficiency of COD, NH_4^+–N and TN were 86.9%, and 77.8% and 58.4%, respectively. Finally, the 180 L/h feeding rate and 12 times/d feeding frequency were selected as optimal operation conditions. These findings can give useful guidance for the design and operation of VFCWs with a reoxygenation corridor.

Keywords: Vertical-flow constructed wetlands; Reoxygenation corridor; Oxygen transfer; Feeding rate; Feeding frequency

1. Introduction

Constructed wetlands have been widely used and demonstrated to be a low-cost and reliable technology for wastewater treatment [1–4].

Constructed wetlands for wastewater treatment are typically classified into two types according to the wetland hydrology: free water surface (FWS) CWs and subsurface flow (SSF) CWs. SSF CWs could be further divided into horizontal flow (HFCWs) and vertical flow (VFCWs) [5]. VFCWs can successfully remove ammonium, but the presence of very low denitrification rates means that they often do not remove sufficient quantities of nitrate. In contrast, HFCWs provide conditions that are more conducive to denitrification but are less effective at nitrifying ammonium [6, 7]. Oxygen transfer tends to be one of the main rate-limiting parameters in SSF CWs.

The domestic and overseas study of improving the subsurface constructed wetlands' oxygen transfer is mainly focused on the following three aspects[8]: (1) developing new substrates for the constructed wetland [9, 10]; (2) selecting more adaptive plant and bacteria species for the wetland [11–13]; and (3) optimizing the operating mode of wetland [14, 15].

The prominent pathways of oxygen transfer in subsurface flow treatment wetlands are atmospheric diffusion, plant-mediated oxygen transfer, and convective flow of air within the pore space of the substrate [16]. Some design advances have been proposed to improve oxygen availability by artificial aeration to increase pollutant removal efficiency [17–20]. Although continuous aeration increases both organics removal efficiency and conversion rate of ammonium nitrogen (NH_4^+–N) into nitrate (NO_3^-–N) [18, 21], its application is greatly limited due to the significantly increased operation and maintenance cost. Moreover,

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continuous oxygen supply results in the faster depletion of influent carbon source and the lack of effective anoxic zone; both of them inhibit the subsequent denitrification step, which is an anoxic and heterotrophic microbial process and is believed to account for more than half of the nitrogen removal in CWs [22].

A reoxygenation corridor and intermittent feeding mode were employed in this study to enhance oxygen transfer rate and improve oxygen environment inside the wetlands. And the performance of main pollutants' (COD, NH_4^+–N, and Total nitrogen, TN) removal was analyzed. Finally, the optimal feeding rate and frequency were determined to facilitate the design in the practical projects.

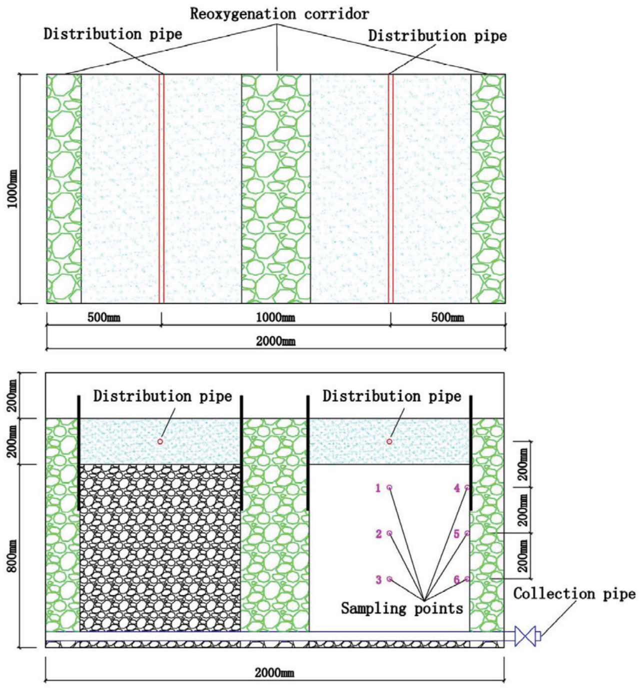

Fig. 1. Schematic diagram of the pilot-scale VFCWs reactors.

2. Materials and methods

2.1. VFCWs reactors

Four identical simulating VFCWs reactors are employed in this study. The dimensions of the reactors are 2.0 m (L) × 1.0 m (W) × 1.2 m (H). Wastewater distribution systems are installed at 10 cm below the surface level, and wastewater collection systems laid at 0.5 cm above the reactor bottoms. Wastewater distribution and collection systems are made of serrated PVC pipes of 16 mm in diameter with holes for wastewater distribution/collection every 20 cm along the pipes. Each reactor has six sampling points at 20 cm, 40 cm and 60 cm below the wastewater distribution systems (Fig. 1).

VFCWs reactor substrates are 5~14 mm pebbles (0.8 m height), and sand (0.2 m height over the pebbles), and the void ratio of pebbles is 33%. The substrate filled in the corridor is gravel, 10~20 mm in size; and the void ratio is 45%.

2.2. Experiment conditions

2.2.1. Feeding rate experiments

The hydraulic loading of this experiment is 0.3 $m^3/m^2 \cdot d$, using intermittent feeding mode. The grit chamber effluent of a sewage treatment plant in Shanghai was used as feeding water for the VFCWs reactors in this study. The water quality parameters were shown in Table 1, and the experiment conditions were list in Table 2.

2.2.2. Feeding frequency experiments

The hydraulic loading and feeding water of this experiment are same with feeding rate experiments. The water quality parameters were shown in Table 3, and the experiment setting conditions were list in Table 4.

2.3. Sampling and analysis

The experiments were conducted from May to October 2014. The reactors run one month to stable status before wastewater and gas samples were taken. Wastewater

Table 1
Water quality for feeding rate experiments

	COD_{Cr} (mg/L)	NH_4^+–N (mg/L)	TN (mg/L)	T (°C)	DO (mg/L)
Range	122.85~336.49	15.74~32.96	20.71~44.97	26.5~30.1	0.02~0.05
Average	210.02	25.75	34.85	28.6	0.03
N	63	63	63	63	63

Table 2
Experiment setting conditions

VFCWs reactors	Corridor width	Substrates	Hydraulic loading	Feeding rate	Feeding frequency	Time (min)	Depth of saturation region
1#	30 cm	10~20 mm gravel	0.3 $m^3/m^2 \cdot d$	180 L/h	12	8 min	30 cm
2#	30 cm	10~20 mm gravel	0.3 $m^3/m^2 \cdot d$	100 L/h	12	15 min	30 cm
3#	30 cm	10~20 mm gravel	0.3 $m^3/m^2 \cdot d$	50 L/h	12	30 min	30 cm
4#	30 cm	10~20 mm gravel	0.3 $m^3/m^2 \cdot d$	25 L/h	12	60 min	30 cm

Table 3
Water quality for feeding frequency experiments

	COD_{Cr} (mg/L)	NH_4^+–N (mg/L)	TN (mg/L)	T (◦C)	DO (mg/L)
Range	181.85~538.98	24.79~46.61	30.2~59.96	20.4~22.1	0.03~0.10
Average	276.34	34.02	43.56	21.3	0.05
N	63	63	63	63	63

Table 4
Experimental setting conditions

VFCWs reactors	Corridor width	Substrates	Hydraulic loading	Feeding rate	Feeding frequency	Time (min)	Depth of saturation region
1#	30 cm	10~20 mm gravel	0.3 $m^3/m^2·d$	180 L/h	16	6 min	30 cm
2#	30 cm	10~20 mm gravel	0.3 $m^3/m^2·d$	180 L/h	12	8 min	30 cm
3#	30 cm	10~20 mm gravel	0.3 $m^3/m^2·d$	180 L/h	8	12 min	30 cm
4#	30 cm	10~20 mm gravel	0.3 $m^3/m^2·d$	180 L/h	6	16 min	30 cm

samples were collected via vacuumed hoses connected to wastewater sampling points. Gas samples were taken at each sampling points by using portable vacuum pump, which connected to an Oxyman OM-25MP20 Oxygen meter. The water quality parameters included dissolved oxygen (DO), pH, COD, NH_4^+–N, and TN were analyzed immediately in the lab, according to applicable Chinese National Standards [23].

2.4. Statistical analysis

All experimental data were expressed as means of triplicates with standard deviation. Data analysis was performed using SPSS 17.0 software (SPSS Inc., Chicago, USA) to investigate the difference and interaction in treatment performance of four VFCWs reactors.

3. Results and discussion

3.1. Feeding rate experiment results

3.1.1. Pollutants removal

It can be seen from Fig. 2(a) and (b) that the COD removal efficiency increased with the feeding rate decreasing (from 1# to 4# VFCWs reactors). The low flow rate can provide more contact time between organic matters and microorganisms. The best removal efficiency was in 4# wetland and the average COD concentrations in all wetlands effluent were less than 60 mg/L, this can meet the discharge standard of pollutants for municipal wastewater treatment plant at class B of first standard level. The ANOVA analysis results of COD removal showed that there is a significant difference (p = 0.009) between 4# wetland and other three wetlands. This indicated that the low feeding rate can improve the organic matters removal efficiency.

As shown in Fig. 2 (c) and (d), the removal of NH_4^+–N in each wetlands decreased at first and then increased, with feeding rate decreasing. The NH_4^+–N removal rate was 70.8% in 1# wetland, meanwhile NH_4^+–N removal rates of 2#, 3# and 4# wetlands were 66.5%, 61.2% and 71.0%, respectively, NH_4^+–N average concentration in 4# wetlands was under 8 mg/L. The ANOVA analysis results of NH_4^+–N removal efficiency for each wetland indicated that there is significant difference (p = 0.00) between each wetlands, and 3# wetland was significant difference from the other three wetlands, with a lowest NH_4^+–N removal rate (61.2%).

It can be seen from Fig. 2(e) and (f) that the TN removal rates are appropriately 50%–60%, and the average TN concentrations in effluent can meet the discharge standard of pollutants for municipal wastewater treatment plant at class B of first standard level, especially in 1# wetland can reach class A of first standard level. The 30-cm saturation region at the bottom of VFCWs reactors can improve the TN removal efficiency. The ANOVA analysis results of TN removal efficiency for each wetland indicated that there is no significant difference between each wetland.

3.1.2. Oxygen variation

It described the oxygen variation before and after feeding at four sampling points within the wetlands (Fig. 3). It can be concluded that the oxygen contents were significantly different between the sampling points that under water distribution pipes and and points besides the corridor in 1# and 4# wetlands. As for the oxygen contents in 2# and 3# wetlands, there is no obvious difference between the sampling points that under water distribution pipes and and sampling points besides the corridor. The oxygen contents at 1# and 4# sampling points were slightly higher than at 2# and 5# sampling points. This indicated that the areas that 20–40 cm under distribution pipes were saturated with wastewater.

3.1.3. Selection of optimal feeding rate

As for pollutants removal, the effluent COD of four wetlands can reach the discharge standard of pollutants for municipal wastewater treatment plant at class B of first standard level, and the treatment capacity sequence is 4# > 3# > 2# > 1#. And the effluent ammonia concentration in 1# and

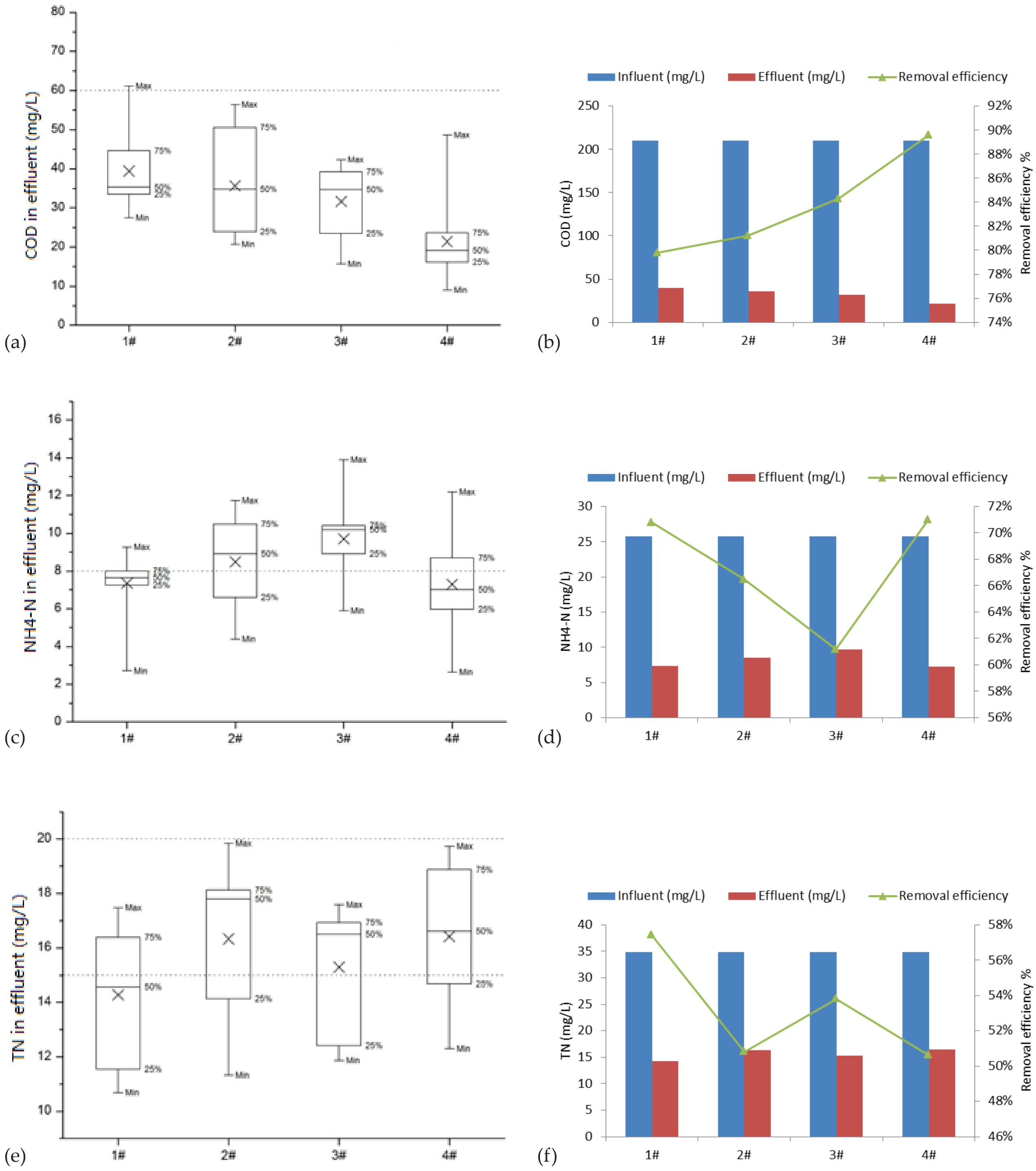

Fig. 2. Effect of feeding rate on pollutants removal.

4# wetlands can meet the class B standard, and the removal capacity was at the same level, but the 1# wetland has a more stable capacity. As for TN, the effluent of 1# wetlands can meet class A standard, and the remaining three wetlands effluent can reach class B standard. To sum up, 180 L/h was selected as the best feeding rate, the instantaneous optimal hydraulic loading 4.32 $m^3/m^2 \cdot d$.

3.2. Feeding frequency experiment results

3.2.1. Pollutants removal

As shown in Fig. 4(a) and (b), the average COD removal rate of each wetlands can meet the discharge standard of pollutants for municipal wastewater treatment plant at class B of first standard level. The COD removal

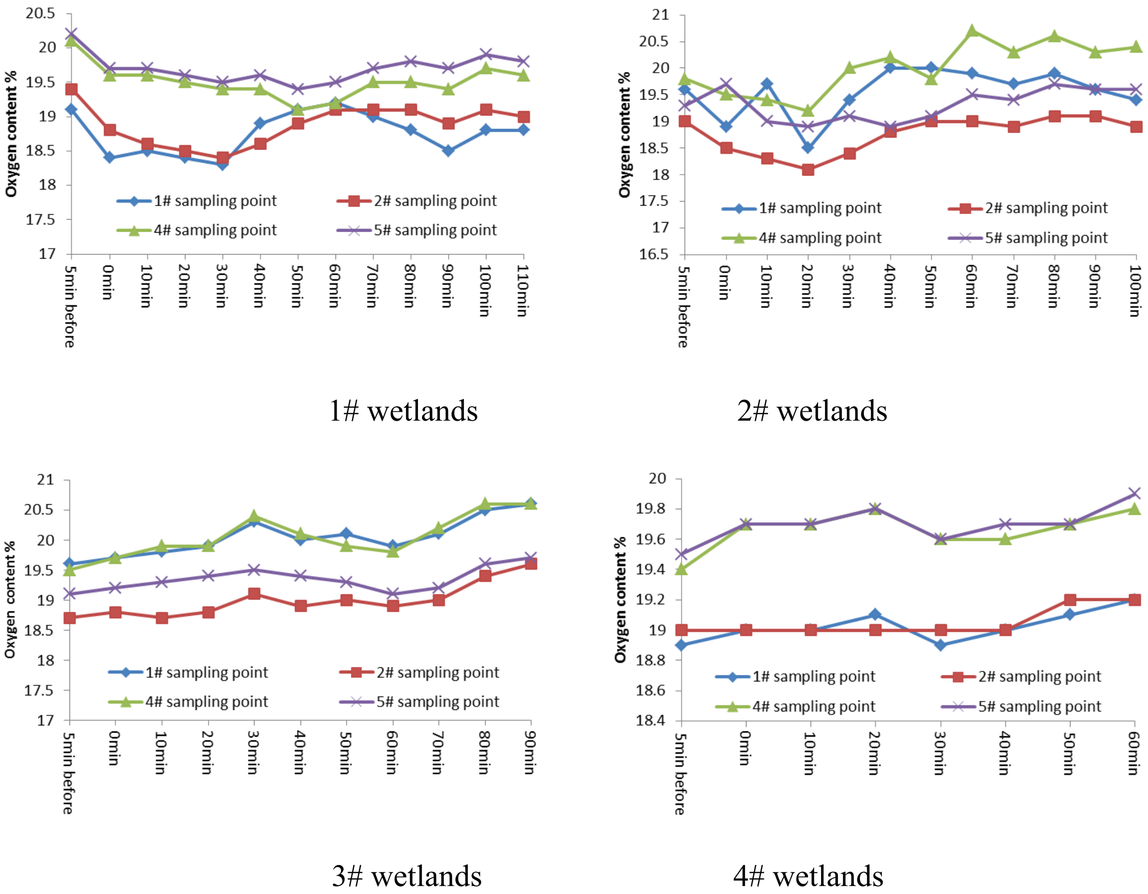

Fig. 3. Oxygen variation with time in wetlands.

efficiency of four wetlands was 82.9%, 86.9%, 82.2% and 83.6%, respectively. The maximum removal was occurred in 2# wetland with feeding frequency at 12 times/d. The ANOVA analysis results of COD removal efficiency indicated that there is no significant difference between each wetlands (p = 0.370).

As shown in Fig. 4(c) and (d), it can be seen that only 2# wetland can meet the discharge standard of pollutants for municipal wastewater treatment plant at class B of first standard level for NH_4^+–N removal. The NH_4^+–N removal efficiency was increasing at first and then decreased with the feeding frequency decreased. The ANOVA analysis results of NH_4^+–N removal efficiency for each wetland showed that there is a significant difference between 2# wetlands and other three wetlands, indicating that the feeding frequency of 2# wetland can significantly improve the wetland's capacity of NH_4^+–N removal.

It can be concluded from Fig. 4(e) and (f) that the average TN removal rates of each wetland can meet the discharge standard of pollutants for municipal wastewater treatment plant at class B of first standard level. The sequence of four wetlands for TN removal capacity is 3# > 1# > 2# > 4#. The ANOVA analysis results of TN removal efficiency for each wetland indicated that there is no significant difference between each wetland.

3.2.2. Oxygen variation

The internal oxygen content was measured during the different feeding frequencies experiment, and the results are shown in Table 5. It can be seen from the results that the oxygen content increased when the feeding frequency decreased. The lower the feeding frequency, the higher wastewater feeding rate, resulting in more oxygen flow into the wetland substrates. Therefore, the reoxygenation capacity was improved. Meanwhile, a large amount of single feeding brings higher degree of turbulence. And this not only facilitated oxygen transfer from the air to liquid, but also can improve the dissolved oxygen level. Moreover, the higher dissolved oxygen level is benefit for nitrification.

3.2.3. Selection of best feeding frequency

High feeding frequency and little single feeding rate facilitated the wastewater and microbes in contact longer conductively to the removal of pollutants. Low feeding frequency and large single feeding rate brings higher degree of turbulence. And this not only facilitated oxygen transfer from the air to liquid, but also can improve the dissolved oxygen level. The pollutants removal experiment results indicated that the COD, ammonia nitrogen and total nitrogen exhibited better removal efficiency at 12 times/d feeding frequencies.

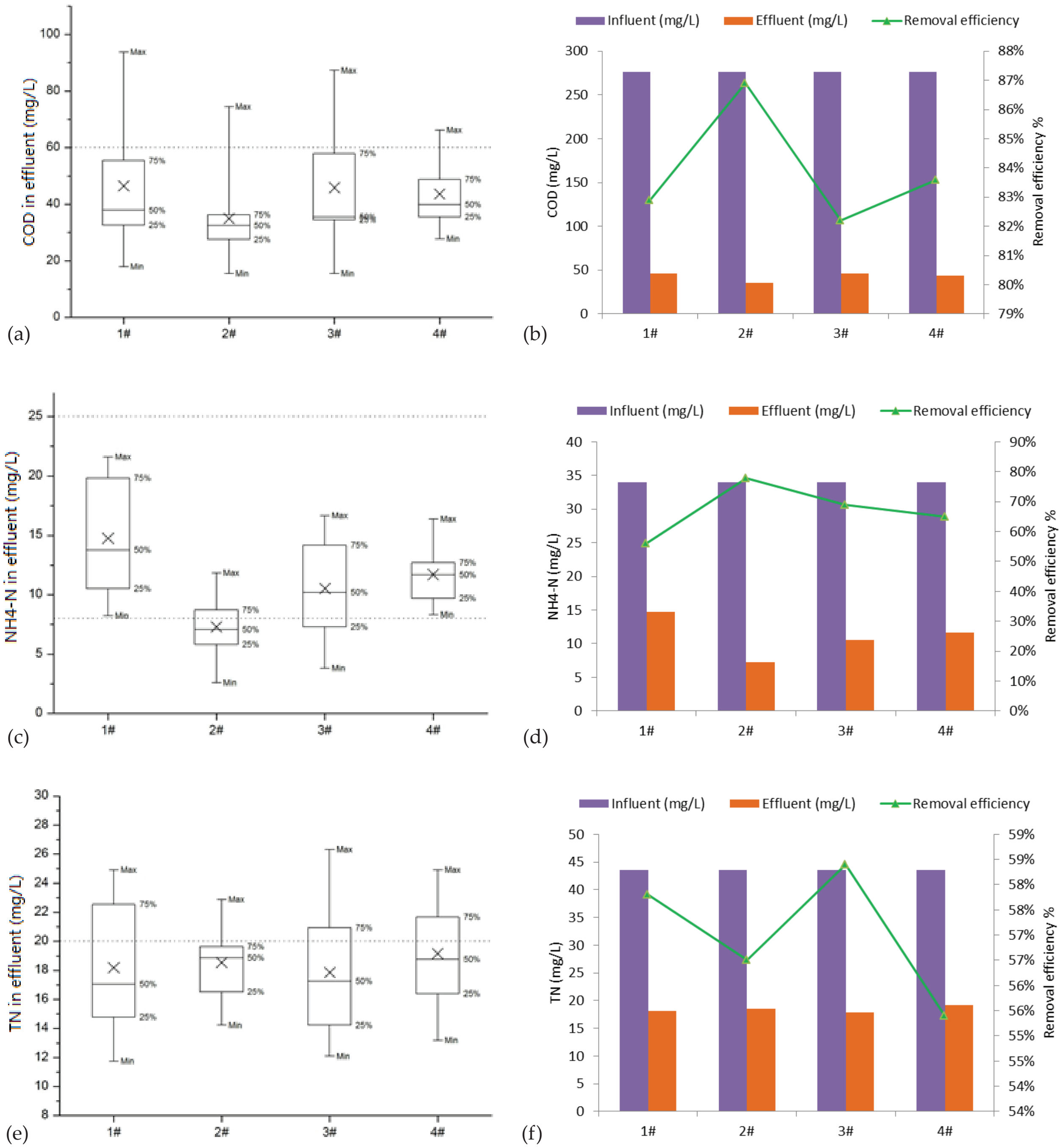

Fig. 4. Effect of feeding frequency on pollutants removal.

Table 5
The internal oxygen content in different operation phases (%)

Oxygen content %	Sampling depth	1#		2#		3#		4#	
		Under distribution pipe	Aside corridor	Under distribution pipe	Aside corridor	Under distribution pipe	Aside corridor	Under distribution pipe	Aside corridor
20.9	20 cm	18.8	19.4	19.3	20.0	19.6	20.2	20.2	20.6
	40 cm	18.3	18.8	18.8	18.7	19.0	20.0	19.8	20.4

Therefore, feeding frequency of 12 times/d was selected as the best water feeding frequency.

3.3. Discussion

The removal of organic matter in CWs was influenced by various factors including both aerobic and anoxic microbial processes as well as sedimentation and filtration [24]. But the aerobic condition was considered as the predominant factor influencing organic matter removal efficiency. Compared with FWS treatment wetlands, the actual surface area of the air-water interface in SSF wetlands is reduced by at least 60% due to the presence of the sand or gravel substrates. Mechanisms such as wave action and wind-induced mixing that contribute to surface reaeration in FWS wetlands are not operable in SSF wetlands; therefore, atmospheric diffusion is the primary means of oxygen transfer. Tanner and Kadlec estimate that atmospheric diffusion of oxygen into a subsurface flow wetland system is on the order of 0.11 g/m^2 d, which for domestic wastewater treatment wetlands is an order of magnitude smaller than the oxygen demand of the incoming wastewater [15]. The present experiment results indicated that the corridor can improve the oxygen transmission within the pores between substrate particles.

Nitrogen transformation and removal mechanisms in CWs include mineralization (ammonification), ammonia volatilization, nitrification, denitrification, plant and microbial uptake, nitrogen fixation, nitrate reduction, anaerobic ammonia oxidation (ANAMMOX), adsorption, desorption, burial, and leaching [13]. But nitrification and denitrification is generally the dominant N removal process in mature SSF CWs [12, 25]. It was reported that significantly greater oxygen transport capacity provides much better conditions for nitrification [26, 27]. However, the process of denitrification is strictly anoxic process and is sensitive to the oxygen levels presented in CWs. Denitrification is affected by many other factors including temperature, nitrate concentration, organic carbon source [28].

Given the same configurations in this experiments, it could be ignored that the effect of differences between chemical adsorption and precipitation on NH_4^+–N removal. The existence of corridor significantly enhances NH_4^+–N removal. The variation of NH_4^+–N concentration can be expressed with Eq. (1); the variation amount of nitrate nitrogen concentration can be calculated using Eq. (2); the variation amount of total nitrogen concentration can be calculated using Eq. (3); the assimilation of ammonia nitrogen can be calculated using Eq. (4). The results are shown in Table 6.

Table 6
Fate of nitrogen in wetlands

VFCWs	1#	2#	3#	4#
ΔNH_4^+–N (mg/L)	18.4	17.27	16.04	18.46
ΔNO_3^-–N (mg/L)	3.98	6.32	4.76	8.42
ΔTN (mg/L)	20.58	18.52	19.56	18.44
Assimilation (mg/L)	5.68	5.81	5.94	6.28
Nitrification (mg/L)	18.88	19.03	18.38	20.58
Denitrification (mg/L)	14.90	12.71	13.62	12.16
$N_{denitrification}/N_{nitrification}$	78.9%	66.8%	74.1%	59.1%

$$\Delta NH_3 - N = N_{assimilation} + N_{nitrification} - N_{ammonification} \tag{1}$$

$$\Delta NO_3 - N = N_{nitrification} - N_{denitrification} \tag{2}$$

$$\Delta TN = N_{assimilation} + N_{denitrification} \tag{3}$$

$$N_{assimilation} = 0.074 \times BOD_5 \tag{4}$$

As shown in Table 6, Comparing the N amount of denitrification and nitrification effect in wetlands, it can be concluded that the nitrification is greater than denitrification in 2# and 4# wetlands, indicating that the internal environment of the wetlands are more suitable for nitrification reaction. It can be seen from the COD removal that there is a strongest COD removal capability in 4# wetlands, its lowest COD concentration in saturation region, can be used as carbon source for denitrification. And the COD removal capacity of 1# wetland was minimum, it can provide abundant carbon source for denitrification.

4. Conclusion

The main conclusions are as follows:

(1) There is a 30-cm depth saturation area at the bottom of wetlands, to provide denitrification conditions and places, which greatly improved the total nitrogen removal, and the removal rate remained above 50%. The average TN can meet the discharge standard of pollutants for municipal wastewater treatment plant at class B of first standard level. Meanwhile, part of organic matter can be used as carbon source for denitrification microorganisms; therefore, COD removal efficiency can be further improved in denitrification process.

(2) The COD removal efficiency increased with the feeding rate decreasing. The high feeding rate can improve distribution uniformity and increase wetlands idle time, which will help make full use of wetlands volume and strengthen reoxygenation. The total nitrogen removal was affected by anaerobic environment, nitrate nitrogen concentration, organic matter concentration and other factors. There is good TN removal at 180 L/h of single tube flow, because of its good water distribution uniformity, strong nitrification capacity and high concentration of organic matter. A single tube feeding 180 L/h was selected as the best feeding rate, the instantaneous optimal hydraulic loading of 4.32 m^3/m^2·d.

(3) High feeding frequency and little single feeding rate facilitated the wastewater and microbes in contact longer conductively to the removal of pollutants. Low feeding frequency and large single feeding rate brings higher degree of turbulence. And this not only facilitated oxygen transfer from the air to liquid, but also can improve the dissolved oxygen level. In these experiments, 12 times/d feeding frequency was selected as the best water feeding frequency.

Acknowledgements

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