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Influence of operational mode, temperature, and planting on the performances of tidal flow constructed wetland

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ABSTRACT

In order to investigate the effect of operational mode, temperature, and planting on the performance of tidal flow constructed wetland (TFCW), four lab-scale units were operated in parallel experiments. They were operated in three cycles d^{-1} tidal flow mode with planting (3TF+P), three cycles d^{-1} tidal flow mode without planting (3TF), one cycle d^{-1} tidal flow mode with planting (1TF+P), and continuous flow mode with planting (CF+P), respectively. The results demonstrated that the multi-cycle tidal flow operational mode promoted the biofilm growth and pollutant removal with the low relative clogging coefficient (RCC) of 21.42% during the whole experimental period. The average COD, NH_4^+-N, and PO_4^{3-}-P area removal rate in 3TF+P reached 18.00, 2.38, and 0.24 g m^{-2} d^{-1}, respectively. Meanwhile, the influence of low temperature on the performance of TFCW in the winter was partially compensated by the multi-cycle operational mode, which made the performance of TFCW more stable than that of other systems under temperature variation. Planting *Canna indica* L. (Cannaceae) led to an increase in average area removal rate of N with 24.17%. The net uptake of N by planting was 0.35 g m^{-2} d^{-1}, which accounted for 17.95% of the total nitrogen removal. Besides the direct uptake, the combination of aerobic zone close to rhizosphere and anaerobic zone around rhizosphere may also play an important role in the nitrification–denitrification process. The direct P removal by *Canna indica* L. (Cannaceae) was quantified as 0.01 g m^{-2} d^{-1}, which only accounted for 4.17% of the PO_4^{3-}-P removal.

Keywords: Tidal flow constructed wetland; Temperature; *Canna indica* L; Oxygen transport; Clogging

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1. Introduction

Constructed wetlands (CWs) have been proved to be an attractive and promising technique in wastewater treatment because of their low-cost, self-remediation, self-adaptation, and easy maintenance [1]. However, the widespread application of this technique in cold areas is still restricted by the low-temperature and low-oxygen availability. Meanwhile, the COD/N ratio of wastewater is low in China, which restricts the biological N removal in wastewater treatment process because of the lack of organic carbon source [2]. Therefore, how to improve the performance of CWs for treating wastewater with low COD/N ratio under low temperature have become an urgent issue and a research hotspot.

Studies showed that artificial aeration was an effective method to improve the performance of CWs, which would enhance organic matter mineralization [3–5]. However, additional energy input and cost are required by the artificial aeration. Additionally, some researches demonstrated that the stimulated growth of biofilms by aeration resulted in the hydraulic clogging [6–8]. A new type CW, tidal flow constructed wetland (TFCW), has attracted more and more research interests in recent years [9,10]. The operation of TFCW is similar to the conventional sequencing batch reactor for wastewater treatment, which involves "fill" phase, "react" phase, "draw" phase, and "idle" phase, but without "aerate" phase [11]. TFCW takes advantage of the rhythmical input and output of wastewater to promote the air transfer into CWs, and the alternant aerobic/anaerobic circumstances enhance the pollutants removal [12].

Although, TFCW shows the advantages in terms of improving organic matter and ammonia removal, the problem of matrix clogging caused by the biofilm cumulation has also been discovered [13,14]. Little is known about the possibility of reducing the clogging risk and maintaining the good performance of TFCW by optimizing the "react" and "idle" cycle. Meanwhile, it is known that low-oxygen availability is a limiting factor for the performance of CW in winter [15]. Through the artificial cycle of "wet" and "dry" periods in TFCW, the wastewater could act as a passive air pump to repel and draw oxygen into the wetlands. Therefore, it is necessary to investigate the possibility of partially compensating the performance of TFCW by optimizing the "react" and "idle" cycle, reducing the influence of low temperature in cold climate. Although, it was reported that the pollutant removal could be promoted by plants [1], few researchers investigated the effect of plants on the performance of TFCW. The exact role of plants for pollutant removal in TFCW was still uncertain. Therefore, the objectives of this paper were: (1) to examine the effect of operational mode on pollutant removal and clogging in TFCW; (2) to investigate the effect of temperature and plants on the performance of TFCW with optimal operational mode.

2. Materials and methods

2.1. Synthetic wastewater

Synthetic wastewater containing organic matters (COD), ammonium (NH_4^+-N) and phosphate (PO_4^{3-}-P) was employed to minimize variability in experiments, which was prepared with $C_6H_{12}O_6{\cdot}H_2O$, NH_4Cl and KH_2PO_4, and the loadings of different pollutants were shown in Table 1. Meanwhile, the average concentrations of other nutrients in the synthetic wastewater were Mg^{2+} of 10 mg L^{-1}, Ca^{2+} of 20 mg L^{-1}, Fe^{2+} of 1 mg L^{-1}, Cu^{2+} of 0.1 mg L^{-1} for the growth of the plants [16]. The hydraulic load of each CW unit was 0.2 m^3 m^{-2} d^{-1}.

2.2. Experimental setup and system operation

Four parallel lab-scale CWs with a diameter of 300 mm and a height of 800 mm were built with plexiglas. The CWs consisted of three functional layers (total 650 mm in height). Cobbles with a diameter of 25–50 mm were placed at the bottom to reduce the potential of clogging with a height of 150 mm, medium gravels with a diameter of 8–12 mm were put in the middle with a height of 200 mm, and fine gravels with a diameter of 3–5 mm were placed on the top with a height of 300 mm (as shown in Fig. 1).

The operation of CWs was automatically controlled by programmable logic controller. The wastewater was pumped into CWs from the top-down by peristaltic pumps, and the effluent discharge was controlled by motorized valves.

Four different operational modes were carried out in the experiments. Two CWs were operated in a tidal flow mode of three cycles per day. Each cycle was for 8 h, including 4 h for wastewater media "react" phase and 4 h for "idle" phase. *Canna indica* L. (Cannaceae) collected from local watercourses was planted in one unit (3TF+P), and another unit was not planted (3TF). The third unit was operated in a tidal flow mode of one cycle per day and the *Canna indica* L. was planted in it (1TF+P), the cycle of which was set as 24 h with 12 h for wastewater media "react" phase and 12 h for "idle" phase. Both the "fill" phase and "draw" phase of three TFCWs was 10 min. The fourth unit was

Table 1
Pollutant removal performance of the lab-scale TFCWs

Parameters	TFCWs	Influent concentration (mg/L)	Effluent concentration (mg/L)	Removal efficiency (%)	Area removal rate (g m^{-2} d^{-1})
COD	3TF+P	139.91	32.78	76.57	18.00
	1TF+P		44.45	68.23	16.04
	CF+P		63.62	54.53	12.82
NH_4^+-N	3TF+P	37.25	23.59	36.67	2.38
	1TF+P		27.88	25.14	1.66
	CF+P		33.23	10.78	0.71
NO_3^--N	3TF+P	1.82	4.25		
	1TF+P		3.17		
	CF+P		2.81		
TN	3TF+P	39.57	29.03	26.64	1.95
	1TF+P		32.42	18.07	1.32
	CF+P		37.65	4.85	0.36
PO_4^{3-}-P	3TF+P	4.77	3.57	25.15	0.24
	1TF+P		3.70	22.46	0.21
	CF+P		4.53	5.13	0.05

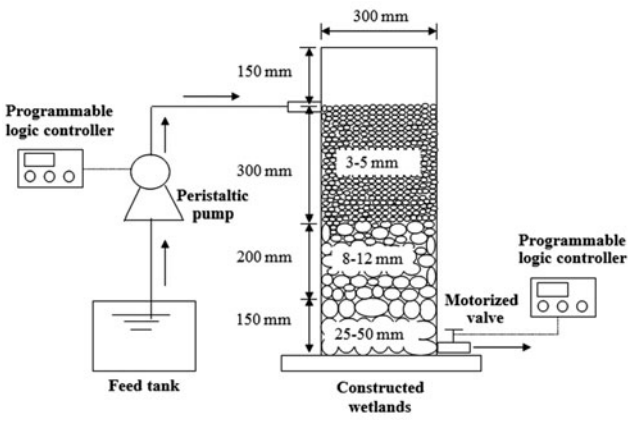

Fig. 1 Schematic of experimental setup.

operated in a continuous flow mode and the *Canna indica* L. was planted in it (CF+P).

2.3. Sampling and analysis

The influent and effluent were collected in triplicate every four days. The analysis of chemical oxygen demand (COD), ammonium nitrogen (NH_4^+-N), nitrate–nitrogen (NO_3^--N), total nitrogen (TN), and phosphate (PO_4^{3-}-P) of influent and effluent were immediately conducted in laboratory according to the following standards [17]. COD was measured using the potassium dichromate method. NH_4^+-N, TN, PO_4^{3-}-P, and NO_3^--N were determined using the Nessler's reagent spectrophotometric method, potassium persulfate oxidation-ultraviolet spectrophotometry, molybdenum-antimony anti-spectrophotometric method, and ultraviolet spectrophotometric screening method, respectively.

Temperature and dissolved oxygen (DO) in different systems were measured onsite using a portable DO meter (YSI Model no. 51, America). pH value was measured with a portable pH meter (WTW Model 3200 with SenTix 41 pH electrode, Germany).

Respiration intensity of micro-organisms is an indicator of microbial activity. Its measurement was determined by alkali absorption method (ISO 16072-2002, Germany standard). The specific O_2 transfer rates (OTR, g m^{-2} d^{-1}) in CWs were calculated as Eq. (1) [18]:

$$\mathrm{OTR} = 0.7[\mathrm{COD_{in}} - \mathrm{COD_{out}}] + 4.3[\mathrm{NH_4\text{-}N_{in}\text{-}NH_4\text{-}N_{out}}] \quad (1)$$

where $[\mathrm{COD_{in}} - \mathrm{COD_{out}}]$ is the mass of COD removed in the system (g m^{-2} d^{-1}), and $[\mathrm{NH_4\text{-}N_{in}} - \mathrm{NH_4\text{-}N_{out}}]$ is the mass of nitrogen nitrified in the bed (g m^{-2} d^{-1}).

RCC was defined as Eq. (2) to quantitatively describe the substrate clogging [19]:

$$\mathrm{RCC} = (H_t - \mathrm{H_0}) \times A_\mathrm{h} \times 1,000/V_0 \times 100\% \quad (2)$$

where H_0 is the initial height of water level at the start of experimental and H_t is the height after t days' operation (m), A_h is the area of tidal bed (m^2), V_0 is the initial pore water volume, and/or the fixed inflow water volume (L).

2.4. Plant uptake estimation

The initial plants before the experiments and all of plants in 3TF+P after the end of experiments were collected. All parts of plants were cleaned, dried at 50℃ in the oven for 48 h, to estimate the dry weight. Then the dried plants were milled into homogeneous powder and screened through a 40 mesh for N and P analysis [20].

3. Results and discussion

3.1. Effect of operational mode on pollutants removal

The performances of three CWs (3TF+P, 1TF+P, and CF+P) were monitored for one year. The removal efficiencies and area removal rates of COD, NH_4^+-N, and PO_4^{3-}-P were presented in Table 1, which showed that 3TF+P had better performance than 1TF+P and CF+P. The COD removal efficiency and area removal rate of 3TF+P reached 76.57% and 18.00 g m^{-2} d^{-1}, respectively. In contrast, the COD removal efficiency and area removal rate of CF+P were only 54.53% and 12.82 g m^{-2} d^{-1}, respectively. The oxygen transfer rate in 3TF+P was 22.83 g m^{-2} d^{-1}, which was higher than that in 1TF+P (18.37 g m^{-2} d^{-1}) and CF+P (12.02 g m^{-2} d^{-1}). Meanwhile, the average effluent DO in 3TF+P (2.23 mg L^{-1}) was higher than that in 1TF+P (1.65 mg L^{-1}) and CF+P (0.37 mg L^{-1}). These results illustrated that O_2 transporting in CW beds could be greatly improved by the periodical water and air movement depending on the frequency of tidal cycles. Additionally, the multi-cycles tidal flow running mode allowed supersaturated weak acidic gases, such as CO_2, to pass from biofilm into atmosphere in time during the "idle" phase, which helped pH to maintain in the neutral range. The increase in DO and neutral pH value in 3TF+P (between 6.8 and 7.8) was suitable for microbial growth. The results of respiration intensity of micro-organisms demonstrated that the average respiration intensity of micro-organisms in 3TF+P was 2.57 μg CO_2, which was higher than that in 1TF+P (2.18 μg CO_2) and CF+P (1.75 μg CO_2).

Meanwhile, clogging was obviously observed in CF+P as indicated by the increase in RCC value during the experimental period. It was possible due to the excessive accumulation of organics without sufficient oxygen for biodegradation, which could reduce the effective interstitial volume and change the hydraulic properties, then influence the CW performances [21]. Some researches illustrated that the excessive growth of heterotrophic biofilms with tidal flow operational mode could also result in clogging [13,14]. However, in this research with the 3TF+P mode, the value of RCC only increased to about 21.42% by the biofilms growth during the experimental period. This value was similar with that reported by Platzer [18], in which the tidal operation of "react" and "idle" cycle was set for 6 h. The results demonstrated that clogging did not seriously happen in 3TF+P. The possible reason is that the "draw" phase disturbed the biofilm cumulation. The aging biofilms were discharged from the system frequently during the "draw" phase. This deduction was confirmed by the SEM images of effluent samples from different CWs. More algae and micro-organisms were observed in the effluent samples from 3TF+P after the system was operated for 60 d.

The highest NH_4^+-N removal was observed in 3TF+P with a removal efficiency of 36.67% and an area removal rate of 2.38 g m^{-2} d^{-1}. CF+P displayed the lowest removal efficiency and area removal rate of NH_4^+-N (10.78% and 0.71 g m^{-2} d^{-1}, respectively). The average concentration of NO_3^--N in 3TF+P was 4.25 mg/L, which was higher than that in 1TF+P (3.17 mg/L) and CF+P (2.81 mg/L). It was consistent with the results of oxygen transfer rate and respiration intensity of micro-organisms in 3TF+P. These results demonstrated that multi-cycle tidal flow operational mode was helpful for the nitrification process and nitrifier activity. Biofilm adsorption and microbial nitrification may be another mechanism for NH_4^+-N removal [22]. For the CF+P and 1TF+P mode, the biofilm growth was limited by the insufficient oxygen supply through surface air and plant-mediated oxygen transfer. Meanwhile, the excessive accumulation of organics caused by the low DO concentration would also influence the NH_4^+-N adsorption and nitrification on biofilm surfaces. However, the multi-cycles operational mode could help to gradually form the stable biofilms in TFCWs [23]. When wastewater flowed through the TFCW system, the NH_4^+-N was adsorbed onto the biofilm surfaces charged negatively in "react" phase, then oxygen was drawn into the porous bed matrix in "draw" and "idle" phases to promote a successful nitrification process by nitrobacteria, which enhanced the NH_4^+-N removal [24].

It should be noted that an appropriate wetland "react" time is crucial for NH_4^+-N adsorption onto charged media, which could be used as substrate for subsequent nitrification in the "idle" time. Chang et al. [25] demonstrated that 3 h "react" time for NH_4^+-N adsorption was apparently sufficient to treat artificial sewage with the initial NH_4^+-N concentration of 30 mg/L. Additionally, a longer "idle" time would stimulate higher respiration and aerobic activities of nitrifiers, providing better nitrification performance. Therefore, the ratio of "idle" time and "react" time should be further optimized for better NH_4^+-N removal.

As shown in Table 1, anaerobic denitrification process also conducted in the system, as indicated by TN removal. However, the TN removal under different operational modes in this study was lower than 27%. Various factors could influence the completion of denitrification process. The CF+P operational mode could provide good anaerobic condition for denitrification, but the nitrate concentration was limited. The low COD/N ratio of 3.75 may also result in the low denitrification potential of 3TF+P and 1TF+P. Zhao et al. [26] demonstrated that the TN removal of CWs increased from 25 to 62%, when the COD/N ratio increased from 2.5 to 10. Fan et al. [27] also found that sufficient carbon source in an influent with a high COD/N ratio greatly promoted the denitrification process in conventional CWs.

As shown in Table 1, the removal efficiency and area removal rate of PO_4^{3-}-P in TFCWs (1TF+P and 3TF+P) were higher than those in CF+P. The accumulation of organic matters might be caused by the continuous flow operational mode, which could inhibit the PO_4^{3-}-P adsorption performance of CWs. Three main mechanisms may be used to explain the results. Firstly, the organics may specially adsorb to the bed matrix, competing with PO_4^{3-}-P adsorption on sorption sites. Secondly, the soluble organic matters may complex with surface-bound metals to form soluble organic metal compounds and release the PO_4^{3-}-P adsorbed previously. Thirdly, the organic matters may be adsorbed to substrate particles at nonspecific sorption sites, which would increase negative charges of bed matrix. The electrostatic attraction PO_4^{3-}-P to the substrate would be weakened and more PO_4^{3-}-P remained in solution [28]. As shown in Table 1, the removal efficiency and area removal rate of PO_4^{3-}-P in 3TF+P was a little higher than that in 1TF+P.

3.2. Effect of temperature on pollutants removal

As discussed before, 3TF+P showed the best performance for pollutants removal among four parallel lab-scale CWs, so the effect of temperature on pollutants removal was investigated in 3TF+P. Two periods were chosen to present the effect of temperature on pollutants removal, winter period from November to January with an average effluent temperature of 9℃, and summer period from July to September with an average effluent temperature of 25℃.

As showed in Fig. 2(a), the area COD removal rate ranged from 14.39 to 17.42 g m^{-2} d^{-1} during the winter period, and increased to a range between 18.06

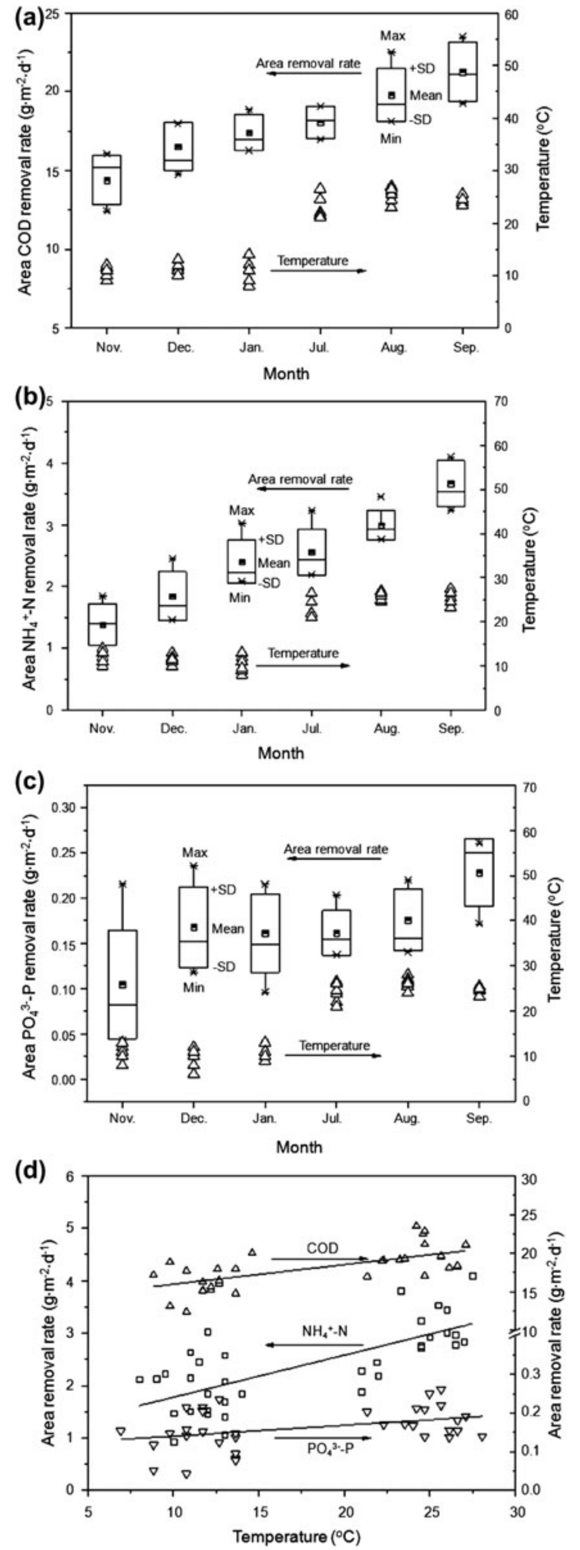

Fig. 2 Area removal rate of COD (a), NH_4^+-N (b), PO_4^{3-}-P (c) in 3TF+P under different temperatures, and correlation between area removal rate of pollutants and temperature (d) (Min: Minimum; Max: Maximum; SD: Standard Deviation).

and 21.27 g m^{-2} d^{-1} during the summer period. The average area COD removal rate in summer was 22.80% higher than that in winter. This is also shown by correlation analysis in Fig. 2(d), which displayed a positive relation between area COD removal rate and temperature. The removal of organic matters is mostly attributed to the microbial activity of aerobic and anaerobic bacteria, which was easily affected by the temperature [29]. The area NH_4^+-N removal rate ranged from 1.38 to 2.40 g m^{-2} d^{-1} during the winter period. Comparatively, the performance for NH_4^+-N removal was also better in summer with an increase in average NH_4^+-N area removal rate of 65.05% (as shown in Fig. 2(b)). Fig. 2(d) showed that temperature also influenced the NH_4^+-N removal. Although, the poor oxygen availability under low temperature could be alleviated with the multi-cycle tidal flow operational mode, the low temperature influenced the nitrifier activity and corresponding nitrification process. In addition, the N uptake by plants significantly reduced, even completely stopped due to the wilting of plants in winter [30]. However, temperature insignificantly affected the PO_4^{3-}-P removal. As shown in Fig. 2(c) and (d), the average area PO_4^{3-}-P removal rate almost kept stable. This is because the main mechanisms for PO_4^{3-}-P removal in CWs are chemical precipitation and physicochemical adsorption, which are independent on temperature [31].

The average area removal rates of COD and NH_4^+-N in 3TF+P in winter were similar or even higher than those in 1TF+P for the whole experimental period (as shown in Table 1). The average oxygen transfer rate in 3TF+P in winter was 19.26 g m^{-2} d^{-1}, which was higher than that in 1TF+P for the whole experimental period (18.37 g m^{-2} d^{-1}). Meanwhile, the average respiration intensity of micro-organisms in 3TF+P in winter was 2.16 μg CO_2, which was close to that in 1TF+P (2.18 μg CO_2) for the whole experimental period. These results demonstrated the superiority of multi-cycle operational mode compared with the single-cycle operational mode. The growth of partial heterotrophic and autotrophic aerobic bacteria (nitrifiers) might be effectively promoted by the superior oxygen supply potential of multi-cycle operational mode, after the micro-organisms adapted to the low temperature in winter. Therefore, the influence of low temperature on the performance of TFCW could be partially compensated by the multi-cycle tidal flow mode.

3.3. Effect of planting on pollutants removal

Comparison of the performances of 3TF+P and 3TF showed that planting *Canna indica* L. (Cannaceae) led to an increase in average area removal rate of COD and TN with 12.22 and 24.17%. In contrast, plants were relatively unimportant for PO_4^{3-}-P removal.

The net N uptake by *Canna indica* L. (Cannaceae) during the whole experimental period was 0.35 g m^{-2} d^{-1}, which accounted for 17.95% of the TN removal. Besides the direct uptake, the combination of aerobic zone close to rhizosphere and anaerobic zone around rhizosphere also played an important role in the nitrification–denitrification process. The direct P removal by plants was quantified as 0.01 g m^{-2} d^{-1}, which only accounted for 4.17% of the PO_4^{3-}-P removal. Therefore, planting did not play a major role

Table 2
N removed by plant uptake in various CWs

Type of CWs	Pollutants	Influent concentration (mg/L)	Type of plants	Plant uptake (%)	Literatures
Surface flow	Nitrogen	18.8	*Typha orientalis, Phragmites australis, Scirpus validus, Iris pseudacorus*	8.4–34.3	[20]
Subsurface flow	Nitrogen	13.33–25.70	*Typha angustifolia* L.	88	[32]
Subsurface flow	Nitrogen	483	*Aerobacter aerogene, Bacillus subtilis, Cellulomonas biazotea, Pseudomonasdenitrificans, P. stutzeri, Rhodopseudomonas palustris, Nitrosomonas* sp., *Nitrobacter winogradskyi, Acinetobacter*	0.5	[33]
Vertical flow	Nitrogen	607	*C. alternifolius*	22	[34]
Subsurface flow	Nitrogen	10.28, 20.55	*Typha latifolia*	2.6–3.0	[35]
Tidal flow	Nitrogen	37.25	*Canna indica* L.	17.95	This research

Table 3
P removed by plant uptake in various CWs

Type of CWs	Pollutants	Influent concentration (mg/L)	Type of plants	Plant uptake (%)	Literatures
Surface flow	Phosphorus	1.56	*Trema orientalis, Phragmites australis* *Schoenoplectus validus, Iris pseudacorus*	4.81–22.33	[36]
Surface flow	Phosphorus	0.87	*Zizania Caduciflora Turez Hand-maz,* *Phragmites australis (Cav.) Trin.ex Steud*	30	[37]
Subsurface flow	Phosphorus	0.81, 1.63	*Typha latifolia*	1	[35]
Tidal flow	Phosphorus	4.77	*Canna indica* L.	4.17	This research

on P removal in the multi-cycle TFCW. The main mechanisms for P removal in TFCW might be chemical precipitation and physicochemical adsorption.

Tables 2 and 3 showed the N and P removal by plant uptake in various CWs, respectively. The performance of N and P uptake was significantly different, which might result from the difference in experimental setup, substrate, plant species, and climate.

4. Conclusions

(1) The oxygen transfer rate and average respiration intensity of micro-organisms in 3TF+P were higher than those in 1TF+P and CF+P, which demonstrated that multi-cycle tidal flow operational mode could promote the biofilm growth and pollutants removal. Meanwhile, the RCC of 3TF+P only increased to 21.42% during the experimental period. It illustrated that clogging did not obviously occur during the whole experiments.

(2) Temperature could influence TFCW performances in winter. However, the influence could be partially compensated by the multi-cycle operational mode, which made the performances more stable than those of other systems under temperature variation.

(3) Planting *Canna indica* L. (Cannaceae) led to an increase in average area removal rate of TN with 24.17%. The net *N* uptake by *Canna indica* L. (Cannaceae) during the whole experimental period was 0.35 g m^{-2} d^{-1}, which accounted for 17.95% of the TN removal. Besides the direct uptake, the combination of aerobic zone close to rhizosphere and anaerobic zone around rhizosphere also played an important role in the nitrification–denitrification process. The direct P removal by plants was quantified as 0.01 g m^{-2} d^{-1}, which only accounted for 4.17% of the PO_4^{3-}-P removal. The main mechanisms for *P* removal in TFCW might be chemical precipitation and physicochemical adsorption.

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