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Long-term performance of aerated and planted constructed wetland treatment on domestic wastewater

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ABSTRACT

In this study, the course of BOD, TN, and TP removal in four stable operating lab-scale horizontal subsurface flow constructed wetlands (HSSF CWs) for domestic wastewater treatment was evaluated using a large pool of data from 7 years of operation. The aim of this study was to compare the impact of the different designs and the operational (planted and aeration or not) variables on the long-term treatment. The four devices used in the experiment, including aerated and planted CW (APCW), planted CW (PCW), aerated CW (ACW) and unaerated and unplanted CW(UCW), had the identical dimensions of 3 m in length, 0.7 m in width and 1 m in depth. Removal efficiencies of BOD and TN in APCW reached up to 94.4% and 86.0%. Also, BOD and TN removal of APCW varied little with the seasonal change, while that of PCW, ACW, and UCW had considerable fluctuation. Aeration had a significant influence on phosphorus removal in the long term, and plants could disrupt the structure of substrate to extend the time of absorption saturation. Correlation analysis showed that aeration and plants could accelerate CW to obtain a steady state either for BOD or TN removal. In the long run, we also found that removal rates of TN, TP, and organic matter were increased, decreased and almost constant, respectively.

Keywords: Artificial aeration; Constructed wetland; Domestic water; Long-term performance

1. Introduction

Today, constructed wetlands (CWs) are widely used to treat domestic wastewater in the suburb areas of China due to their lower cost of operation and easier maintenance [1,2]. However, the low oxygen availability leads to incomplete nitrification [3–5] and blocking the removal of high levels of ammonia and total nitrogen (TN) [6–8] could induce clog problems and thus, decrease the lifetime of the CWs.

To enhance the treatment performance, artificial aeration via a blower and coarse bubble air diffusers was introduced into horizontal sub-surface flow constructed wetlands (HSSF CWs) [7,9–12]. Artificial aeration in CWs was first used to treat wastewater in cold climates and researchers discovered that artificial aeration enhanced pollutant removal in an HSSF CW [10,13,14]. Chanprasartsuk et al. [15] noted that the aerated CW outperformed the non-aerated one when treating a wastewater containing Agent Orange. Artificial aeration could significantly improve TN removal because it provides sufficient DO for nitrification [16–21]. P removal could be

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enhanced by increasing wetland adsorption capacity under aerobic conditions, and aeration was found to have a significant effect ($p < 0.05$) with an increase in up to 30% for PO_4^{-3}–P removal [22].The possible explanation for this phenomenon was that phosphorus accumulating organisms could absorb much phosphorus at that condition. It was found that, the aeration supply could also improve the plant growth and bacterial population [23].

On the other hand, clogging was a major operational and maintenance issue associated with the use of subsurface flow wetlands for wastewater treatment and could ultimately limit the lifetime of the system [24]. The lifespan of the CWs was determined by the clogging of the substrate [25–27]. The accumulation of organic matter in the substratum pores was regarded as an important factor causing clogging separately in SSF CWs [28]. However, some wetlands were not prone to clogging in practice [26]. Additionally, various management strategies have been developed to extend the life of clogged treatment wetlands [29]. Drizo et al. [9] noted that artificial aeration not only promoted biological activities and stimulated nitrifying/denitrifying processes but also increased the CW's lifespan [10,14].

Ecological systems should be monitored for performance after the point of establishment (2–3 years) for regulatory purposes [30]. The removal efficiencies for bacteria and several chemical parameters were more apparent during the initial year compared with the second year of operation, suggesting concern for long-term efficiency and stability of CWs [31]. It was relatively rare that constructed storm wetlands were monitored once the practice had aged 4 years, and the overall nitrogen event mean concentration was reduced as the wetland matured but not TP [30]. These storm wetlands were valid and could be generalized in low-lying coastal environments for alternation of dry and wet periods. Data from Langergraber et al. [32] showed that after the third year, nitrogen elimination increased and stabilized. Due to the nature of the phosphorus (P) removal mechanisms associated with CWs, the sustainability of P treatment was usually of high interest [33]. CWs were important sinks of P in agricultural landscapes; however, the long-term ability of these systems to retain P often diminished with time [34]. Mustafa et al. [35] demonstrated that molybdate reactive phosphorus concentration was effectively reduced even after 7 years of operation (P in this paper was soluble reactive phosphorus and referred molybdate reactive phosphorus was related to its analytic method). As mentioned above, there had been many studies on CWs. Nevertheless, the effect of long-term aeration operation and the exact lifespan of CWs had not been verified, which was bound to hinder the application of artificial aeration for CWs.

Therefore, this study focused on the problem of the long-term aeration effects of CWs. To fill this knowledge gap, research on the long-term viability of CWs, with or without plants or aeration, was necessary for every type of CW during its lifespan. Thus, it is meaningful to trace and analyse the development of system performance for the use of limited artificial aeration in CWs. The objective of this study was to evaluate the impact of long-term (7 years) operation on wastewater removal in a lab-scale horizontal subsurface flow CW with limited artificial aeration and plants. At the same time, CWs with plants or aeration only and a CW without plants and aeration were also studied as controls.

2. Materials and methods

2.1. Lab-scale system description

The description in detail of the four lab-scale systems is presented in Fig. 1. For more information on the effect of

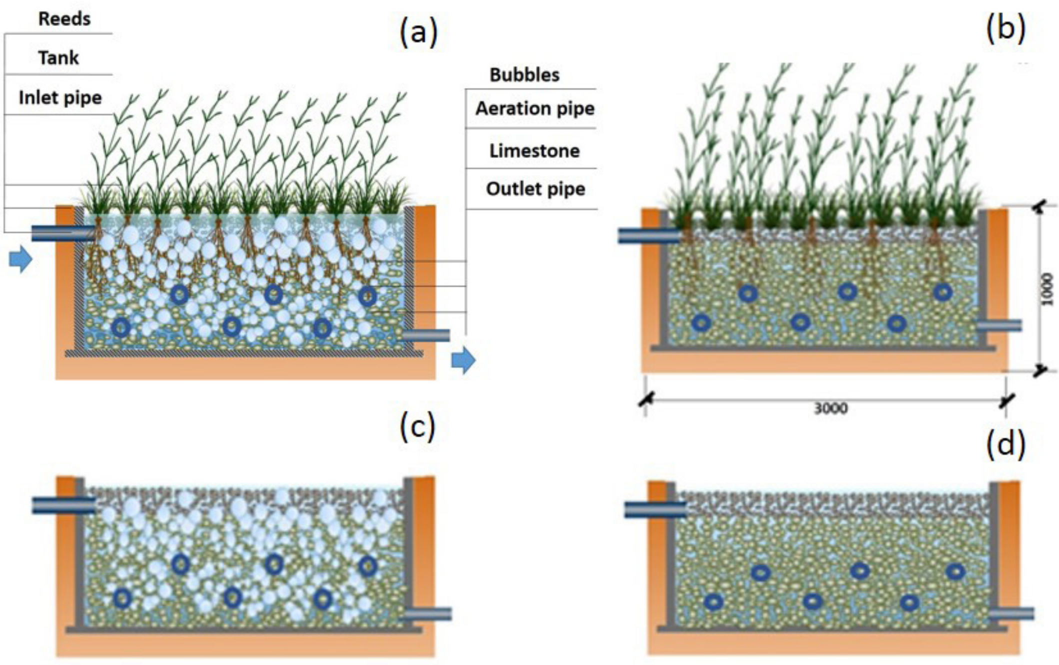

Fig. 1. A cross-sectional view of four types of wetlands (a): APCW; (b): PCW; (c): ACW; (d): UCW.

limited artificial aeration on constructed wetland treatment of domestic wastewater, see Zhang et al. [1].

The four units shown in Fig. 1—aerated and planted constructed wetland (APCW), planted constructed wetland (PCW) (plants were *Phragmites australis*), aerated constructed wetland (ACW) (The aeration systems were activated when the oxygen concentrations in the constructed wetlands were lower than 0.2 mg/L and ceased when the oxygen concentrations in the constructed wetlands were higher than 0.6 mg/L controlled by automated systems [1]) and unareated and unplanted constructed wetland (UCW)—began to be operated on January 1st, 2007, and were fed domestic wastewater continuously from the same feed tank. All of the units were filled with 8–16-mm limestone as substrate, which had identical dimensions of 3 × 0.7 × 1 m (in length, width and depth, respectively) [1]. *Phragmites australis* density of all of the units was approximately, 3–6 plants per square metre, and the height of the mature plants was approximately, 1–2 m. The wastewater was collected from the effluent of septic tank serving for a dormitory building in Shanghai Jiao Tong University. The average water qualities of the domestic wastewater were listed in Table 1. The flow rates of the inflows were controlled by peristaltic pumps at 130 L/d [1].

2.2. Sampling and analysis

During the whole period from January 2007 to December 2013, inflow and outflow water samples were collected from the constructed wetland systems monthly and analysed for BOD_5, TN and TP following the methods issued by the EPA of the P.R. China [36]. The statistical procedures were carried out using SPSS 22.0 and Origin 8.0 for Windows. Pearson's correlation methods were used to check the influence of each factor considered in all samples.

Without accounting for evapotranspiration, the contaminant removal rate can be expressed as follows:

$$\text{Average removal capacity (ARC) (mg)} = \sum_{j=1}^{12}(C_j^i - C_j^o)\cdot V/12 \quad (1)$$

$$\text{Removal concentration efficiency (\%)} = \left(1 - C^o/C^i\right)\times 100\% \quad (2)$$

where C_j^i and C_j^o are the influent and the effluent concentration every month in mg/L, respectively. V means waste water volume in L.

$$\text{Annual variation rate (AVR) (\%)} = \left[\frac{A(t_{k+1})}{A(t_k)} - 1\right]\times 100 \quad (3)$$

Table 1
Average concentrations of the main parameters in the inflowing domestic wastewater, 2007–2013

BOD_5 (mg/L) mean ± SD[a]	285.2 ± 40.2
TN (mg/L) mean ± SD	47.2 ± 10.3
TP (mg/L) mean ± SD	8.4 ± 0.9

[a] SD: standard deviation, $n = 84$.

In which t_k begins with the year 2007, t_{k+1} is the next year, and $A(t_k)$, $A(t_{k+1})$ represent the ARC in the APCW, PCW, ACW and UCW of BOD, TN and TP in any adjacent years during the period 2007–2013.

3. Results and discussion

3.1. Annual variation

3.1.1. BOD removal

ARCs of the four units from 2007 to 2013 are shown in Table 2. The average BOD removal rates were above 85% in all units from 2007 to 2013, whereas they were even more so for the planted aerated system, which showed a rate above 95%, except for the first year when it was 94.59% Fig. 2(a). Among the four types of CWs, during the entire experimental period, BOD removal rates remained highest in the APCW, lowest in the UCW and intermediate in the PCW and ACW. Compared with the UCW, the improvements in both the PCW and ACW, as well as the slight but important difference between the PCW and ACW, showed that both plants and limited artificial aeration improved the removal performance and that artificial aeration not only fully compensated for the absence of plants but also exceeded the performance of the PCW. It could be interpreted that the oxygen required for bacteria was more available in the ACW than in the PCW, in spite of the plants' dormancy in winter. The combination of the plants and aeration further improved the removal efficiency, which also indicated a positive correlation between the BOD removal and oxygen. There was no obvious change in the four CWs over time; nevertheless, their removal rate had an improving trend for showing significant positive correlations ($p < 0.01$) between different years, suggesting a relatively stable removal performance and an unsaturated substrate for BOD. The BOD removal rate of different years in the PCW and ACW also had significant positive correlations ($p < 0.05$). For APCW, the correlations of the first 6 years were significantly positive ($p < 0.05$). In 2013, an exception appeared representing a turn in the course of events ($p > 0.05$), which could imply that the BOD removal rate reached saturation for the system and that the plants and aeration could accelerate this process.

3.1.2. TN removal

In another study, TN removal efficiencies remained relatively unchanged during the entire 9-year study period [37]. As stated above, artificial aeration can significantly improve TN removal for favoring nitrification [16–21].

From the overall trend perspective, the TN removal in the APCW remained both high and relatively stable, except for the first year (with a minimum of 86.75%), whereas TN removal appeared as a rising trend in the other CWs (Fig. 2(b)). The slow increase in the TN removal in the PCW and ACW started at the beginning of the research and then retained nearly the same level (approximately 84% and 85%, respectively). The effect of aeration on the CW was superior to that of the plants, which could be attributed to plant uptake accounting for less than 20% and the long-term fate of the N storing in sediments through denitrification loss [38]. Although, plant presence played a significant role, artificial aeration was the main contributor to the oxygenation of the

Table 2
Average removal capacity (ARC) of the four units from 2007 to 2013 (All data units are g·d^{-1} m^{-2})

		2007	2008	2009	2010 mean ± SD[a]	2011	2012	2013
APCW	BOD	16.7 ± 0.2	17.0 ± 0.1	17.0 ± 0.1	17.1 ± 0.2	17.2 ± 0.2	17.2 ± 0.2	17.1 ± 0.2
	TN	2.6 ± 0.2	2.6 ± 0.1	2.6 ± 0.1	2.6 ± 0.2	2.6 ± 0.2	2.6 ± 0.2	2.6 ± 0.1
	TP	0.5 ± 0.01	0.5 ± 0.01	0.4 ± 0.09	0.3 ± 0.03	0.2 ± 0.02	0.1 ± 0.01	0.1 ± 0.01
PCW	BOD	15.9 ± 0.7	15.9 ± 0.6	16.1 ± 0.6	16.2 ± 0.6	16.0 ± 0.6	16.1 ± 0.7	16.2 ± 0.7
	TN	2.2 ± 0.2	2.3 ± 0.2	2.4 ± 0.2	2.4 ± 0.2	2.4 ± 0.2	2.5 ± 0.2	2.5 ± 0.2
	TP	0.5 ± 0.01	0.5 ± 0.01	0.5 ± 0.01	0.3 ± 0.02	0.1 ± 0.02	0.1 ± 0.02	0.1 ± 0.02
ACW	BOD	15.9 ± 0.5	16.1 ± 0.4	16.3 ± 0.3	16.3 ± 0.3	16.2 ± 0.4	16.3 ± 0.2	16.3 ± 0.3
	TN	2.2 ± 0.2	2.3 ± 0.2	2.4 ± 0.2	2.5 ± 0.2	2.5 ± 0.2	2.5 ± 0.2	2.5 ± 0.2
	TP	0.5 ± 0.02	0.4 ± 0.03	0.4 ± 0.02	0.2 ± 0.08	0.1 ± 0.02	0.1 ± 0.02	0.1 ± 0.01
UCW	BOD	15.4 ± 0.8	15.2 ± 0.5	15.3 ± 0.6	15.4 ± 0.6	15.4 ± 0.6	15.4 ± 0.6	15.5 ± 0.6
	TN	1.1 ± 0.2	1.2 ± 0.1	1.3 ± 0.1	1.5 ± 0.1	1.6 ± 0.1	1.8 ± 0.1	1.8 ± 0.2
	TP	0.5 ± 0.02	0.4 ± 0.01	0.4 ± 0.02	0.2 ± 0.06	0.1 ± 0.02	0.1 ± 0.02	0.1 ± 0.01

[a] SD: standard deviation, $n = 12$.

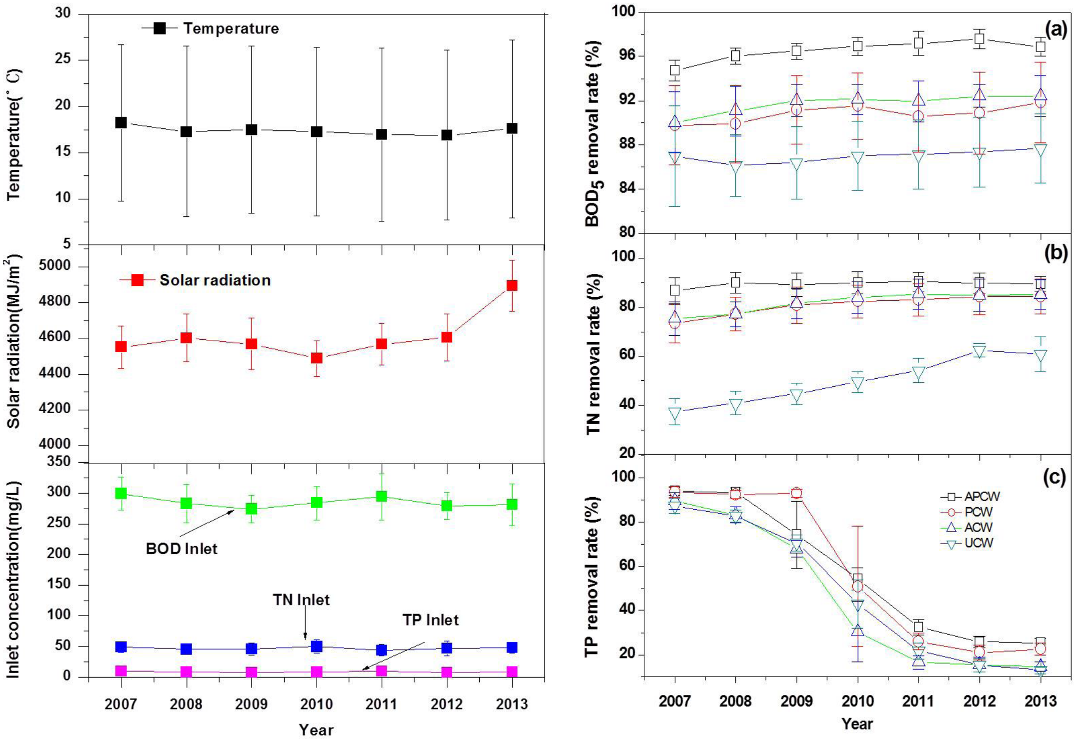

Fig. 2. Average temperatures, solar radiations and BOD$_5$, TN, and TP concentrations of the inflow in operation years (left); annual variation of BOD$_5$, TN and TP removal percentage in four wetland units (right, (a): BOD removal rate, (b): TN removal rate, (c): TP removal rate). Error bars represent ±1 standard error of the mean.

wetland matrix [38]. Artificial aeration could partially substitute the effects of plants in oxidizing the wetland matrix, but the other roles of plants cannot be easily substituted without seriously altering the extensive nature of the CWs [38].

The efficiency of the CW soared steadily with time, from a minimum of 37.42% up to a maximum of 62.42%, but it declined to 60.75% in the last year, 2013, for reasons that are unknown. Given the tendency presented, time was required for performance optimization in the four types of CWs—1 year for the APCW, 4 years for the ACW, five for the PCW and an estimated 6 years for the UCW. In other words, aeration CW units arrived at favorable performance faster than the non-aerated counterparts. The gaps of TN removal rates between the APCW and the other CWs, as well as between UCW and PCW, ACW, decreased year by year. We believed that among the four types of CWs, there were very few differences in TN removal in the long run. For the APCW, PCW and ACW, correlations for the 7 years were all significantly positive ($p < 0.01$), while the UCW showed a diverging pattern; it showed remarkable similarity for the first 3 years but not subsequently, and its correlation for the final year was markedly negative. One explanation for this phenomenon could be

Fig. 3. Parts photos at the test scene (the left photo was taken in summer, while the right one was taken in winter).

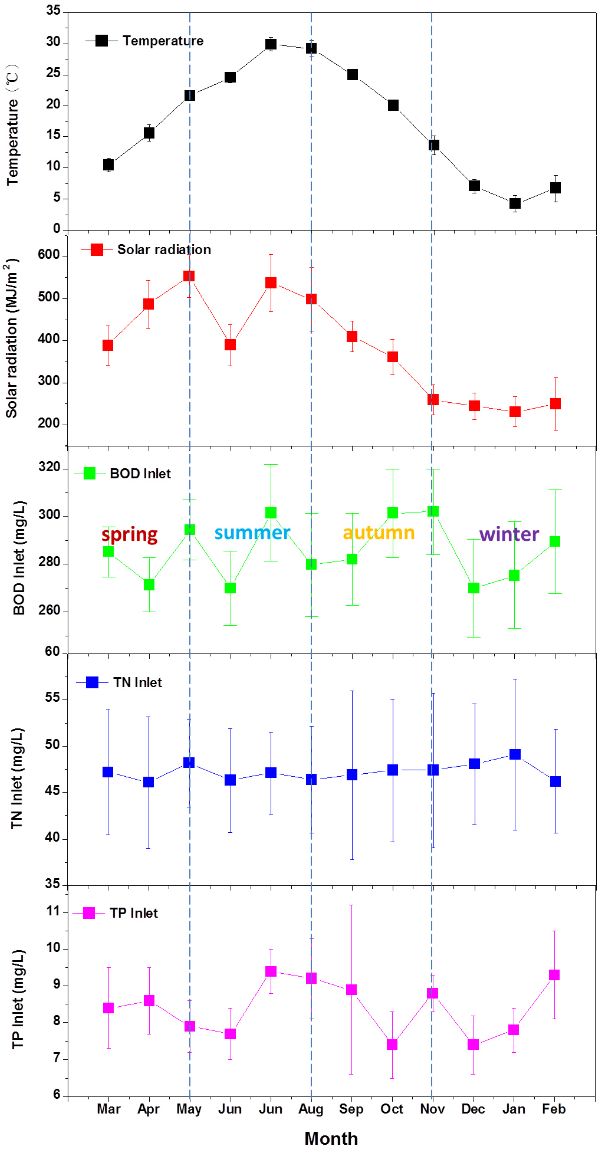

Fig. 4. Monthly means of the average outdoor temperatures, total solar radiation and inlet. Error bars represent ±1 standard error of the mean.

that the CW without plants and aeration was unstable and the inter-annual variation was greater for TN removal.

3.1.3. TP removal

Unlike the case of BOD and TN removal, the TP removal of the four CWs showed some different characteristics. As illustrated in Fig. 2(c), there was a sharp decrease in all of the CWs (from 93.83% to 25.42% for APCW, 94.08% to 22.58% for PCW, 90.25% to 14.58% for ACW and 87.92% to 12.83% for UCW) during the 7 years, and the simple explanation was likely substrate saturation after long-term operation. It was indicated that the substrate played an important role in the removal of phosphorus pollutant [9,11,13]; however, adsorption and/or precipitation of phosphorus by the substrate in the CWs was a finite process: once the material became saturated, the removal efficiency would go down.

In the first 2 years, all CWs exhibited relatively high removal rates (more than 80%); the two planted units had advantages over the unplanted ones, which was more obvious in the second year and provides evidence that in a short time, plants can help remove phosphorus by plant uptake, promoting microbial assimilation and substrate adsorption. The advantage of planted units over unplanted units again highlights the importance of plants in phosphorus removal, though it was less important than the phosphorous removal action of the substrate. Correlation analysis indicated that interannual variability was mostly not significant.

3.2. Impact of seasonal changes

3.2.1. BOD removal

According to Fig. 3, we can apparently see the changes of the reaction unit along with the seasonal variations. Plants bloom in summer, while wither in winter. From Fig. 4, We get the exact data of BOD, TN, TP in different seasons of the whole year. Hijosa-Valsero et al. [39] observed that seasonality had a great influence on the CWs. Wang et al. [40] indicated that the treatment effects of the two-stage CW project were influenced by seasonal temperature changes. After the study of several CWs in the Czech Republic, Jan [41,42] concluded that the efficiencies of long-term HSSF CWs were steady throughout the year and were not affected by season or the length of operation. Despite the significant seasonal variations with respect to temperature, rainfall and humidity, the chemical/microbiological composition of the wetland output remained relatively constant [43]. Bulc [44] also stated that the performance of CWs did not vary significantly with regard to temperature.

In our study, seasonal variation had different effects on the BOD removal percentage in the four types CWs. According to Fig. 5(a), the range of the BOD removal rate in APCW was narrow. However, the other variables measured fluctuated notably depending on the season. In general, removal efficiency was best in summer and worst in winter. Based on these data, the planted CWs had obvious advantages compared with the aeration CWs, especially in the winter. The PCW showed a similar trend of variation compared with the ACW in every season except winter, and their removal efficiencies had only narrow differences, which could demonstrate that aeration and plants had similar functions for CWs, such as improving the characteristics of the substrate, accelerating the growth of bacteria, promoting hydraulic conditions, and so on. However, aeration could not totally substitute for the plants apart from the energy cost because of the thermal insulation of the rhizosphere for bacteria and the substrate of the CWs, particularly in winter, which coincided with the results reported by Hijosa-Valsero et al. [39]. The greater microbial presence observed in the planted mesocosms compared with those lacking vegetation [31,45] could explain these results. Additionally, Leverenz et al. [46] indicated that the plants were found to have several beneficial effects, including buffering against the effects of low temperature. Artificial aeration improved the removal for the unplanted units, but the additional aeration did not fully compensate for the absence of plants, which suggests that the role of macrophytes goes beyond solely adding oxygen in the rhizosphere [10]. In the APCW unit, the benefits of the plants and aeration complemented each other and led to the highest removal efficiency, even in winter.

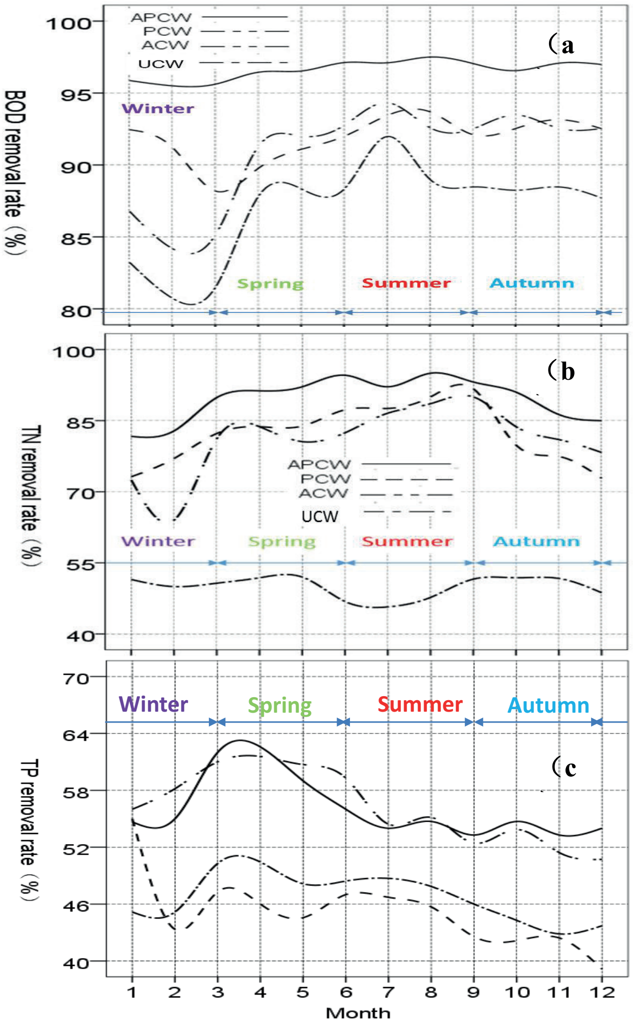

Fig. 5. Variation of the percentage removal of BOD, TN, and TP by season of one representing year (2010) in four wetland units ((a): BOD removal rate, (b): TN removal rate, (c): TP removal rate).

The maximum BOD and TN removal rates of these four units generally appeared in the 250th day, approximately at the turning point between summer and autumn. The average temperature of 32°C at that time was most suitable for all of the units. Additionally, the plants flourished and bacteria could obtain enough oxygen to grow in the APCW and PCW units. Additionally, the BOD removal rate improved year by year, which indicated that the pollutant removal capacity had not yet been saturated.

3.2.2. TN removal

Nitrification and denitrification have been proven to be the main pathways for nitrogen removal in CWs [47]. The major removal mechanisms for TN were attributed to microbial processes and uptake by plants [48]. Langergraber et al. [32] reported that vegetation as well as the biofilm development in the two-stage VF CW system played the major roles for the enhancement of the nitrogen elimination rate. The removal of TN was higher in summer and in the planted and aerated units [38], which suggests that the plants affected N cycling via increased oxygenation and alteration of hydrology, which were good predictors for nitrification and denitrification, respectively. The treatment effects indicated that the mean removal rates of TN were approximately, 75% in the summer and autumn and decreased to 30% in the winter [40].

As shown in Fig. 5(b), the highest TN removal rate reached 97% in the summer for the APCW, which far exceeds other results reported to date. The planted and aerated units had the highest export of oxidized nitrogen (NOy), a proxy for reduced denitrification [38]. The peak values for the PCW and ACW also appeared in summer. The removal efficiency of the unplanted groups showed a wider range of seasonal fluctuations than that of their counterparts. However, note that the TN removal rate of the UCW fell to its lowest level in the summer, likely because the solubility of oxygen decreased with the rise in temperature and the dissolved oxygen required for nitrification was absent. This could also explain the slight decrease in the TN removal percentage in mid-summer.

The nitrogen removal was temperature-dependent [49], as was BOD removal. As expected, on the whole, the TN removal in the APCW was higher than in the PCW and ACW, which were similar to each other and significantly superior to the UCW. The positive role of plants in nitrogen removal in CWs has been repeatedly observed under a wide range of experimental conditions. However, in this research, artificial aeration was also proved to substantially improve the TN removal in the unplanted CWs. Thus, artificial aeration, which could improve N retention under colder conditions [38], should be added to planted systems if costs permit.

3.2.3. TP removal

Phosphorus removal was attributed to plant uptake and soil adsorption [48,50]. When they studied the long-term effects of aquatic plant systems for polluted river, Sato et al. [51] found that the seasonal changes in plants were small and that the TP purification effects of all of the plants declined after 2 years. The research of Wu [52] and his group demonstrated that phosphate removal efficiency declined from 91% to 10% within 5 years. Szögi et al. [53] found that the long-term phosphorus removal is limited by the sorption capacity of the matrix. Sani et al. [26] reported that the removal of ortho-phosphate-phosphorus and suspended solids was independent of the season. However, the treatment effects indicated that the TP was 78% in summer and autumn, while it decreased to 73% in winter [40].

As shown in Fig. 5(c), we found that TP removal fluctuated with the seasons. Aeration CWs prevailed over the non-aeration ones, which showed that aeration produced a positive effect on TP removal because phosphorus-accumulating bacteria absorbed P in the aerobic condition. Additionally, the peak value appeared not in the summer but in the spring. This might be attributed to the combined action of the oxygen solubility and bacteria. As we all known, the higher water temperature was, the lower the content of dissolved oxygen in water. In other words, oxygen solubility decreased as elevation of temperature in summer. Both the temperature and dissolved oxygen in spring was appropriate for phosphorus-accumulating bacteria to absorb excessive phosphorus. TP removal in PCW was worse than that in UCW, which might demonstrate that the plants changed the structure of the substrate and led to poorer absorption of P. Adsorption of substrate was main mechanism of TP removal in horizontal-flow wetland. Amount of plants uptake accounted for only 9.1% of TP removed by wetland [54]. Although, literature studies mostly supported the opposite [9,11,13,30], studies on root channels and their phosphorus removal mechanism in wetlands showed that the oxidized soil had the highest adsorption rate and inner fillings in dead root channels had the lowest [55]. This finding might explain why TP removal in UCW was better than that in PCW.

4. Conclusions

We evaluated the effect of limited artificial aeration on the constructed wetland treatment of domestic wastewater after long-term operation. Based on the experimental results, conclusions can be drawn as follows:

- The BOD and TN removal of the APCW showed little seasonal variation, while the other CWs showed substantial seasonal variation.
- The aerated CW units achieved favorable performance faster than the non-aerated counterparts. The differences in the TN removal rates between the APCW and the other CWs, as well as between the UCW, PCW and ACW, showed year-over-year decreases.
- The TP removal of the four CWs showed a decreasing trend based on the long-term investigation. Aeration had a significant effect on the TP removal in the long run and helped to slow the decrease. The plants could disrupt the structure of the substrate to extend the time of absorption saturation.

Acknowledgements

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