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Original Research

How Artificial Aeration Improved Sewage Treatment of an Integrated Vertical-Flow Constructed Wetland

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Abstract

Artificial aeration was added to an integrated vertical-flow constructed wetland (called aerated IVCW hereafter) for improving water purification performance. The results showed that both oxygen levels and aerobic zones were increased in the wetland substrates. The electric potential (Eh) profiling demonstrated that artificial aeration maintained the pattern of sequential oxic-anoxic-oxic redox zones within the aerated IVCW chambers in winter, while only two oxic-anoxic zones were present inside the non-aerated IVCW in the cold seasons. The nitrification/denitrification processes and organic matter decomposition were enhanced by artificial aeration since the removal efficiency of NH_4^+-N and BOD_5 were significantly improved in all seasons, particularly in winter. It seemed that artificial aeration could compensate for the absence of plant-mediated oxygen supply, though the low temperatures and plant dieback still affected the removal efficiency of COD and TN in the winter. Eight hours of artificial aeration per day was sufficient to eliminate the significant accumulation of NO_3^--N previously observed in the effluent from continuously aerated subsurface-flow constructed wetlands. These results suggest that the aerated IVCW could treat domestic sewage more efficiently, especially in winter.

Keywords: integrated vertical-flow constructed wetland (IVCW), artificial aeration, redox potential, purification effects, domestic sewage

Introduction

Due to the low construction and maintenance expenses and high removal efficiency, constructed wetlands are widely used for the treatment of domestic sewage, fish-farm pollution, industrial wastewater, and landfill leachate in recent decades [1-5]. Constructed wetlands may be an appropriate technology for treating domestic sewage in the rural areas of China with climatic, population, and socioeconomic considerations. However, there are still questions and limitations to wider application of constructed wetlands. One of the problems is the poor performance of outdoor constructed wetlands in the cold climates. Cold temperatures severely affect microbial processes and water purification performance of constructed wetlands [6]. Low aeration and oxygen levels are among the limiting factors for a better performance of constructed wetlands, mainly due to the dieback of aquatic macrophytes that could transport oxygen to their rhizospheres for microbial respiration [7], although the exact contribution of plants remains in debate [8, 9]. Wetland oxygen is rapidly depleted by microbial nitrification and decomposition of organic matter, resulting in a large anaerobic zone. Studies suggested that natural aeration of constructed wet-

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lands did not meet the oxygen demand for treating pollutants [7, 10, 11]. Oxygen limitation led to the incomplete nitrification and lower aerobic decomposition of organic matter [11, 12]. Thus, it is important to improve the oxygen supply for enhancing treatment performance of constructed wetlands, especially in the cold seasons.

It is necessary to reconsider the design of the constructed wetland systems for better performance in the cold seasons. Additional oxygen could be introduced into the wetland system through some design and manipulations such as the vertical-flow pre-treatment filter [13], frequent water level fluctuation [14], air pipes [15], passive air pumps [3, 16, 17] and mechanical aeration in the gravel bed [4, 5, 18, 19]. All these measures resulted in an improvement of ammonia removal while oxygen levels inside wetlands were enhanced. However, it remained unclear whether artificial aeration could improve the purification efficiency of constructed wetlands in the treatment of domestic sewage and how the redox environments influence the removal of pollutants.

We have intensively investigated the integrated vertical-flow constructed wetlands (IVCW) and our previous results have shown that the upper layer from the surface down to a depth of 20-25 cm in the down-flow chamber is the major purifying zone in IVCW, probably due to a better aeration [20]. Therefore, an artificial aeration system was built in at the bottom of the down-flow chamber in a small-scale IVCW for increasing the purifying capacity and making full use of the whole chamber, and we called this system the aerated IVCW. We have evaluated the performance of the aerated IVCW in the treatment of domestic sewage, especially in the cold seasons, and also investigated the relationship between pollutant removal efficiency and redox environments by comparing the aerated and non-aerated IVCWs for a better understanding of purification mechanisms. It has been demonstrated that nitrogen removal processes and organic matter decomposition were significantly enhanced by artificial aeration in the aerated IVCW.

Materials and Methods

Experimental Systems

Two small-scale integrated vertical-flow constructed wetlands (IVCW) were set up in a greenhouse at the Institute of Hydrobiology, Wuhan, China in March 2007 for treating the domestic sewage from a small neighborhood. The IVCW was a vertical/reverse-vertical flow constructed wetland, based on the design given by Grosse et al. [21] and Perfler et al. [22]. Each wetland plot (2 m^2) was divided equally into two chambers: a down-flow chamber and an up-flow chamber, which was connected at the bottom. Each chamber was composed of two different layers of matrix particles of different sizes: the 150 mm layer of gravel (5-8 mm in diameter) in the bottom and the 550 mm (in the down-flow chamber) or 450 mm (in the up-flow chamber) upper layer of sand (<4 mm in diameter). The down-flow and up-flow chambers were planted with *Canna generalis* and *Acorus tartarinowii*, respectively (Fig. 1).

One of the experimental IVCWs was equipped with an artificial aeration system that consisted of an air compressor, a PVC air distribution header (3 cm in diameter), and two parallel perforated tubes (1 m in length) with pores (0.5 cm in diameter). The tubing was placed at the bottom of the down-flow chamber (about 60 cm in depth) with an average airflow of 0.25 m^3/h. Air was delivered to the wetland beds for about 8 hours per day (from 9 a.m. to 5 p.m.) to enhance oxygen-dependent microbial processes and also allow anaerobic processes to occur by turning off aeration during night-time. Another experimental IVCW without aeration was used as the control. The influent was domestic sewage collected from a small neighborhood on the campus of the Institute of Hydrobiology, and hydraulic loading was 200 L/d, with discontinuous filling.

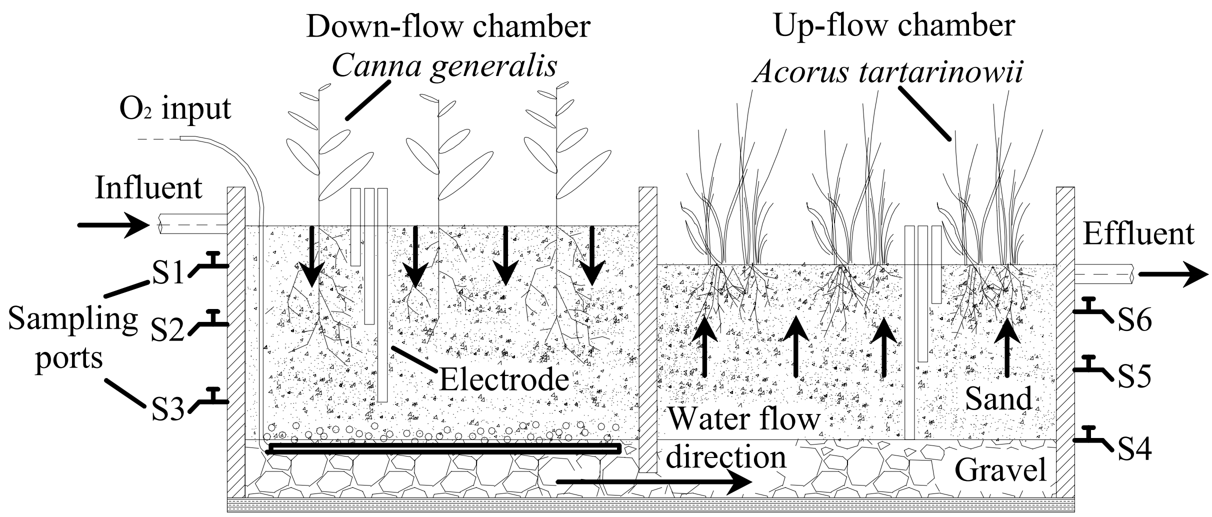

Fig. 1. Section view of aerated integrated vertical-flow constructed wetland.

Table 1. Qualities of domestic sewage by season.

Parameter	Summer (Jun-Aug)	Fall (Sep-Nov)	Winter (Dec-Feb)	Spring (Mar-May)
pH	7.8±0.4	8.0±0.5	7.5±0.3	7.6±0.4
T_{air} (ºC) (out of greenhouse)	28.1±4.7	19.2±4.5	4.0±2.5	19.1±4.5
T_{air} (ºC) (in the greenhouse)	31.0±5.6	21.3±5.2	6.4±2.2	21.8±3.9
T_{water} (ºC)	27.0±4.0	18.8±4.4	6.6±2.2	19.7±4.5
TSS (mg/L)	124±56	113±41	86±37	95±25
COD_{Cr} (mg/L)	240±51	221±46	176±43	193±39
BOD_5 (mg/L)	53±24	50±21	40±19	44±18
TN (mg/L)	49±15	46±19	28±8.7	39±7.4
NH_4^+-N (mg/L)	11±2.4	12±2.0	8.4±1.5	9.8±1.7
NO_3^--N (mg/L)	0.9±0.4	0.9±0.3	0.6±0.3	0.7±0.4
TP (mg/L)	2.3±0.4	2.2±0.4	1.5±0.7	2.0±0.3

Water Sampling and Redox Potential Profiling

Experiments were conducted from June 2007 to May 2008 and water samples were regularly collected from the influents and the treated effluents at 8 a.m. every day. Additional samples were collected from three sampling ports at different depths (10, 25 and 45 cm) in both down-flow and up-flow chambers in winter 2007 to investigate the relationship between pollutant removal efficiency and redox environments. These sampling sites were labeled as S1, S2, S3, S4, S5, and S6 along the direction of water flow (Fig. 1). Total suspended solid (TSS), chemical oxygen demand (COD), five-day biochemical oxygen demand (BOD_5), total nitrogen (TN), ammonium (NH_4^+-N), nitrate (NO_3^--N), and total phosphorus (TP) were measured on a weekly basis according to standard methods [23]. The pH value, dissolved oxygen (DO) and water temperature were measured using a Thermo Orion Five-Star portable meter. Air temperature was measured using a thermometer.

The redox potential (Eh) of wetland substrate was measured in situ using the HS-29 portable acidity meter with the platinum electrode and potassium chloride (KCl) reference system (accuracy: ±10 mV) twice per hour. The electrode was pre-lay at different depths (10, 25 and 45 cm) in both down-flow and up-flow chambers, labeled as S1, S2, S3, S4, S5, and S6 along the direction of water flow (Fig. 1). No pH-based calibrations of redox potential have been made to the presented data since the measured pH values inside the wetland were close to 7 at all sites. Therefore, the measured redox potentials were transformed into standard hydrogen electrode potentials with only temperature-based calibrations.

Statistical Analysis

Two-way ANOVAs followed by tests of comparison of means (LSD test) to assess the influences of artificial aeration and seasonal changes on the removal efficiency of TSS, COD, BOD_5, TN, NH_4^+-N, NO_3^--N and TP by using SPSS 13.0. All analyses were considered significant at the 0.05 level.

Results and Discussion

System Operation, Air Temperatures, Macrophytic Growth and Sewage Profiles

The transplanted emergent macrophytes, *Canna generalis* and *Acorus tartarinowii*, grew very well in the IVCWs, and the depths of root systems and above-ground biomass increased from spring to fall. Plant growth started in March inside the greenhouse, though these plants did not start growing in the outside ambient environments until April, when nocturnal air temperature was higher than 10ºC [6]. During the experiment, mean ambient air temperatures ranged from 4.0ºC to 28.1ºC, while the average air temperatures ranged from 6.4ºC to 31.0ºC, and water temperatures from 6.6ºC to 27.0ºC inside the greenhouse. The greenhouse effect enhanced air temperatures by about 2-3 degrees, and therefore the constructed wetland systems were not frozen and still in operation during the cold periods. The higher temperatures were obviously beneficial to plant growth and microbial activities. Seasonal mean pollutant loads of sewage were presented in Table 1 and the rich nutrients of nitrogen and phosphate in the influents could have supported plant growth.

Effects of Artificial Aeration on Oxygen Levels

Oxygen was rapidly consumed in the down-flow chamber, and oxygen shortage was one of the limiting factors for water purification. In the non-aerated control IVCW, the average dissolved oxygen (DO) levels sharply decreased from 2.3 to 0.8 mg/L and from 3.0 to 0.6 mg/L in the summer and winter, respectively, as sewage moved from the inlet to the S3 site at the bottom (Fig. 2). With the artificial aeration, the DO in the down-flow chamber (represented by the sampling sites of S1, S2, and S3) was maintained at higher levels (> 1 mg/L) in the aerated IVCW, allowing more aerobic decomposition to occur.

Our redox potential (Eh) measurements were also consistent with the detected dissolved oxygen profiles. The surface strata of the down-flow chamber (represented by S1 and S2) and the up-flow chamber (S6) remained oxic (Eh>+300 mV) in the non-aerated IVCW, while the bottom layers (S3 and S4) of the down-flow chamber were anoxic (from -100 mV to +300 mV). The oxic, anoxic, and oxic zones sequentially appeared along the direction of water flow inside the non-aerated IVCW in the summer, while a larger anoxic zone appeared after depletion of dissolved oxygen in the winter, resulting in a simpler pattern of oxic-anoxic zones. On the other hand, in the aerated IVCW the sequential oxic-anoxic-oxic zones were sustained by artificial aeration in the winter, which may facilitate the removal of some pollutants under cold temperatures. As constructed wetlands are biological treatment systems, their performance largely depends on the soil oxygen status [24]. Recent studies have suggested that Eh of subsurface-flow constructed wetlands remained within the anoxic range, resulting in incomplete nitrification [25]. Our data indicate that artificial aeration did significantly improve the oxygen supply in the aerated IVCW, particularly in the winter, which may in turn improve the nitrification and decomposition of organic matter.

Removal Efficiency of Major Pollutants

Total Suspended Solids

Total suspended solids (TSS) removal efficiency remained high during the whole experiment period and ranged from 93.3% to 95.7% and from 88.0% to 90.2% in the aerated and non-aerated IVCW, respectively (Fig. 3). There was no significant relationship between TSS removal efficiency and seasonal changes ($p>0.05$), indicating that TSS removal was mainly due to physical processes. However, there was a slight and significant improvement in the TSS removal efficiency in the aerated IVCW ($p<0.05$). It was suggested that the additional oxygen supply increased the aerobic microbial activities, allowing for a more efficient removal efficiency of suspended organic materials. This observation is consistent with that previously reported [4].

Organic Matter

The average COD removal efficiency of the aerated IVCW ranged from 68.3% to 81.2%, while the non-aerated control system had relatively lower removal efficiency (from 56.1% to 76.4%). The fluctuation of COD removal is significantly related to the artificial aeration and seasonal changes ($p<0.05$). COD removal efficiency in aerated IVCW was slightly higher (4.7%) than that of the non-aerated control in the summer and fall. But a more significant

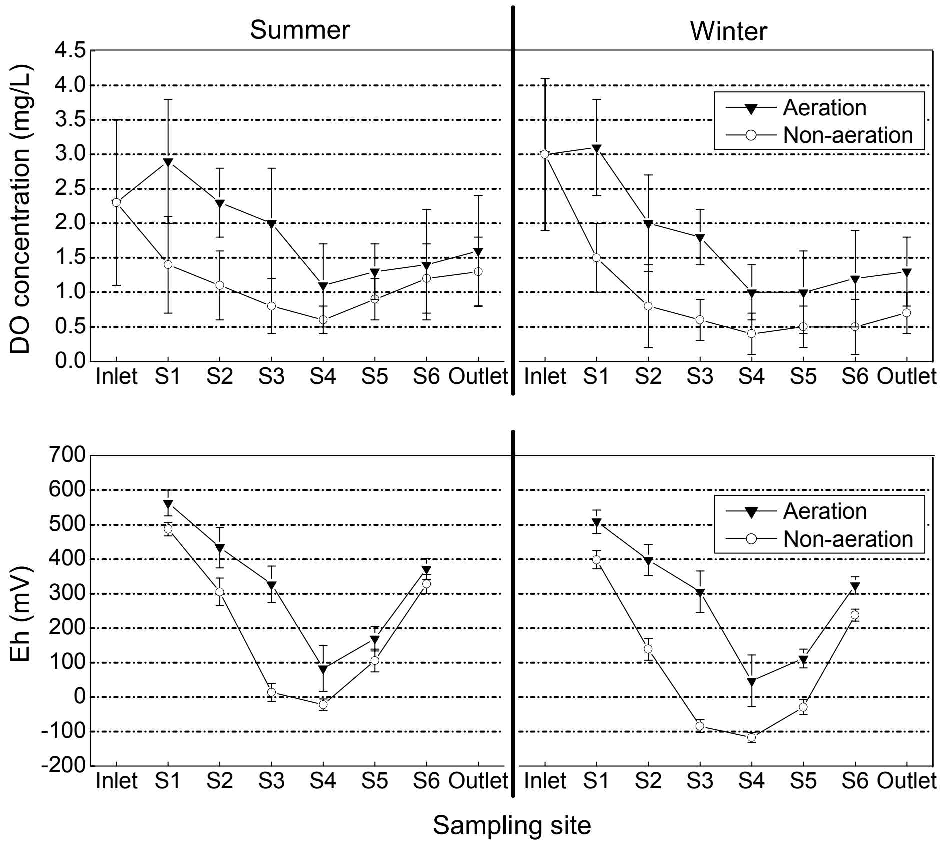

Fig. 2. DO concentration of water and redox potential of substrate at the sampling sites, for aerated and non-aerated IVCWs in summer and winter. Error bars are standard deviations of the mean.

improvement, as high as 13.0%, was observed in the winter and spring. However, the average COD removal efficiency in the aerated IVCW in the cold seasons were still not comparable to those non-aerated in the summer, though artificial aeration significantly improved the performance. Thus, the additional oxygen supply somehow compensated for the absence of plant-mediated aeration, but it could not completely counterbalance the adverse effects of low temperatures and plant dormancy in the cold seasons.

The removal efficiency of BOD_5 exhibited significantly seasonal variations ($p<0.05$), higher in the warm seasons and lower in the cold seasons. Reed reported that the BOD_5 decomposition process significantly slowed down in the wetlands at cold temperatures [26]. However, a similar slow-down had not been observed in the aerated IVCW in the winter, suggesting that the increased oxygen supply might have counteracted the adverse effects of low temperatures on the removal of BOD_5. There were significant improvements in the removal efficiency of BOD_5 in the aer-

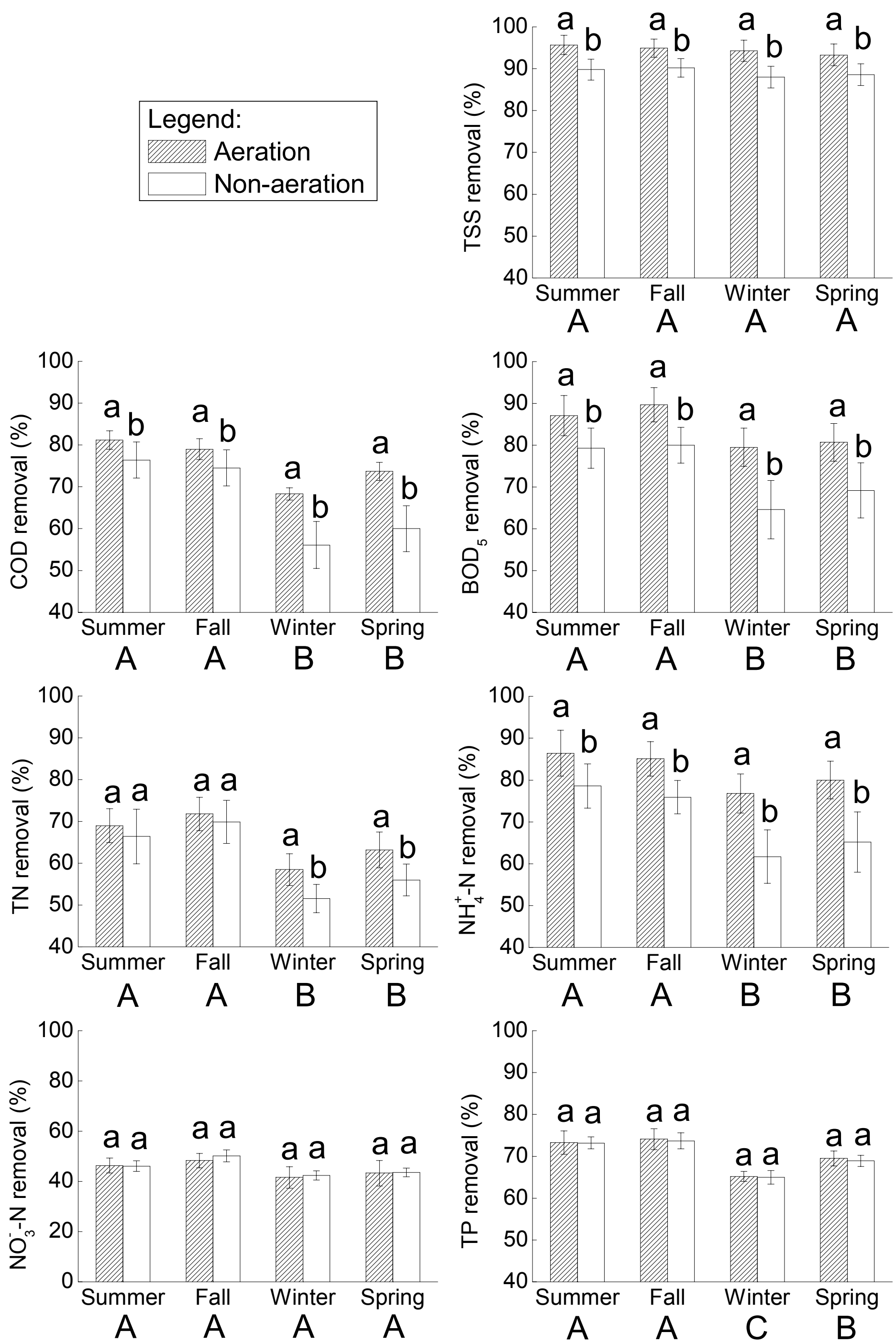

Fig. 3. Removal efficiency for TSS, COD, BOD_5, TN, NH_4^+-N, NO_3^--N and TP, for aerated and non-aerated IVCWs by season. Small letters denote a significant difference between aerated and non-aerated conditions within a season. Capital letters denote significant differences among four seasons using an LSD test regardless of the presence or absence of aeration ("A" the greatest removal, "C" the smallest). Error bars are standard deviations of the mean.

ated IVCW (p<0.01), which were 8.8% higher in the summer and fall, and 13.2% higher in the winter and spring than those of the control. The BOD_5 was removed primarily by particle precipitation and microbial decomposition [1]. Artificial aeration might have enhanced the aerobic decomposition of organic matter by increasing the activity of aerobic microorganisms in the aerated IVCW.

Nitrogen

Average removals of total nitrogen (TN) were significantly lower in the winter and spring than in the summer and fall seasons (Fig. 3). This was probably due to the lower temperatures and decreased redox potentials in the plant rhizospheres in the cold seasons [27]. Artificial aeration had improved the TN removal efficiency by 6.9% in the cold winter. However, winter TN removal efficiencies in the aerated IVCW were still not comparable to those of the non-aerated in the summer, suggesting that artificial aeration did not fully compensate for the adverse effects of the low temperatures and plant dormancy on TN removal in the cold seasons.

Overall, nitrogen was removed from wastewaters mainly by microbial nitrification and denitrification processes [28]. Nitrification occurred in the aerobic zones of the water column, soil-water interface, and the rhizospheres. On the other hand, denitrification normally occurred in the anoxic areas and could not take place if NO_3^--N was not in adequate supply [29]. Therefore, nitrification could be limited if the aerobic zone is too small, resulting in low TN removal in constructed wetlands. Artificial aeration had significantly increased nitrification rates, converting more NH_4^+-N to NO_3^--N for the subsequent denitrification process and thereby improving the net removal of nitrogen, particularly in the winter.

The removal of ammonium (NH_4^+-N) in the sub-surface constructed wetlands was often low because the amount of oxygen available for nitrification was generally limited [11]. However, average removal efficiencies of NH_4^+-N were higher than 60% in both IVCW systems over the whole experimental period, which was probably because of lower hydraulic loading (200 L/d). In the aerated IVCW, there was an obvious improvement of 15.0% in the NH_4^+-N removal efficiency in the cold winter and spring seasons, while only slight improvements, 7.8% and 9.2%, were observed in the summer and fall, respectively. These data confirmed that artificial aeration exerted positive effects on nitrification.

Nitrate (NO_3^--N) was removed predominantly through anaerobic denitrification in wetlands. The additional oxygen supply could improve nitrification and impede denitrification in the meantime [12]. The accumulation of NO_3^--N in the effluents was previously reported under the condition of continual aeration [30]. However, there was no significant difference between the effluent nitrate concentrations of the aerated and non-aerated IVCWs (p>0.05), though the removal efficiency of NH_4^+-N remained very high in our experiment. Thus the intermittent aeration, with an aeration cycle of 8 h on and 16 h off in this experiment, might provide both the aerobic environment for an efficient nitrification in daytime and the anoxic condition for denitrification at night. Anaerobic denitrification had not been affected by artificial aeration in the aerated IVCW.

Total Phosphorus

Artificial aeration had no significant influence on the removal efficiency of total phosphorus (TP) (p>0.05), and we observed the obvious seasonal variations (p<0.01), ranging from 65.0% to 74.1%. The well-accepted mechanisms underlying phosphorus removal by constructed wetlands were adsorption and sedimentation, while plant uptake was believed to play a minor role only [31, 32]. Phosphorus removal efficiency was usually high and stable in the first year of operation, mainly because of substrate adsorption and plant community establishment. As a result, TP removal was higher in the plant growth seasons and lower during plant dormancy. In addition, total phosphorus removal was also dependent on the retention time [33]. The higher TP removal in this experiment may also be attributed to a longer retention time in the IVCW as compared to those of other sub-surface flow constructed wetlands [34].

Relationship Between Pollutants Removal and Redox Potential Changes

The Eh measurements clearly demonstrated that the upper layer of down-flow chamber, from the surface down to the S1 site, remained aerobic in all seasons with or without artificial aeration (Fig. 2), which might be due to the diffusion of air, plant-mediated oxygenation, and the dissolved oxygen carried by the influents. By comparing the pollutant concentrations at different depths in the IVCWs (Fig. 4), we found that the artificial aeration mainly acted to enhance the purification capacity of this aerobic zone in the aerated IVCW. The artificial aeration may have several advantages:

(1) to enlarge the aerobic zone down to a depth of 45 cm from the original 25 cm in the summer and from the 10 cm in the winter,
(2) to increase the activities of microorganisms and enzymes, and
(3) to enhance activities of plant rhizomes and root systems.

As a result, the aerobic and facultative microorganisms could utilize the additional oxygen to degrade more organic matter and oxidize more ammonia to nitrate (nitrification), particularly in the winter. On the other hand, the control IVCW system had a smaller aerobic zone for aerobic microbial decomposition. In addition, artificial aeration could prevent the partially degraded organic matter from accumulating in the bed matrix [10]. Our measurements of TSS also revealed that organic matter mainly accumulated in this aerobic zone (Fig. 4), resulting in higher nitrogen removal. The intermittent artificial aeration created the alternate aerobic/anoxic redox conditions, allowing the occurrence of the coupled nitrification/denitrification processes.

Based on the Eh data, the lower zones below the S3 site in the down-flow chamber and up to the S5 site in the up-flow chamber were in anoxic or anaerobic states, and may become suitable habitats for facultative and/or anaerobic bacteria, which may mediate the anaerobic decomposition of some obstinate organic pollutants such as di-n-butyl phthalate (DBP). In addition, denitrification could occur in the anoxic or anaerobic zones, leading to the net removal of nitrogen released as dinitrogen gas.

The Eh measurements also demonstrated that the upper zone of up-flow chamber from the S6 site up to the surface could revert to the aerobic condition in the summer as a result of air diffusion and plant-mediated aeration. However, this zone remained anaerobic in the winter unless artificial aeration was added to the aerated IVCW. This aerobic zone may facilitate the further decomposition of pollutants and is important for a better performance of IVCW.

On the whole, the addition of an intermittent artificial aeration could change the redox environments of IVCW, which in turn could promote the rapid aerobic decomposition of organic matter and the coupled nitrification/denitrification processes for higher removal efficiency of both carbon and nitrogen in the aerated IVCW.

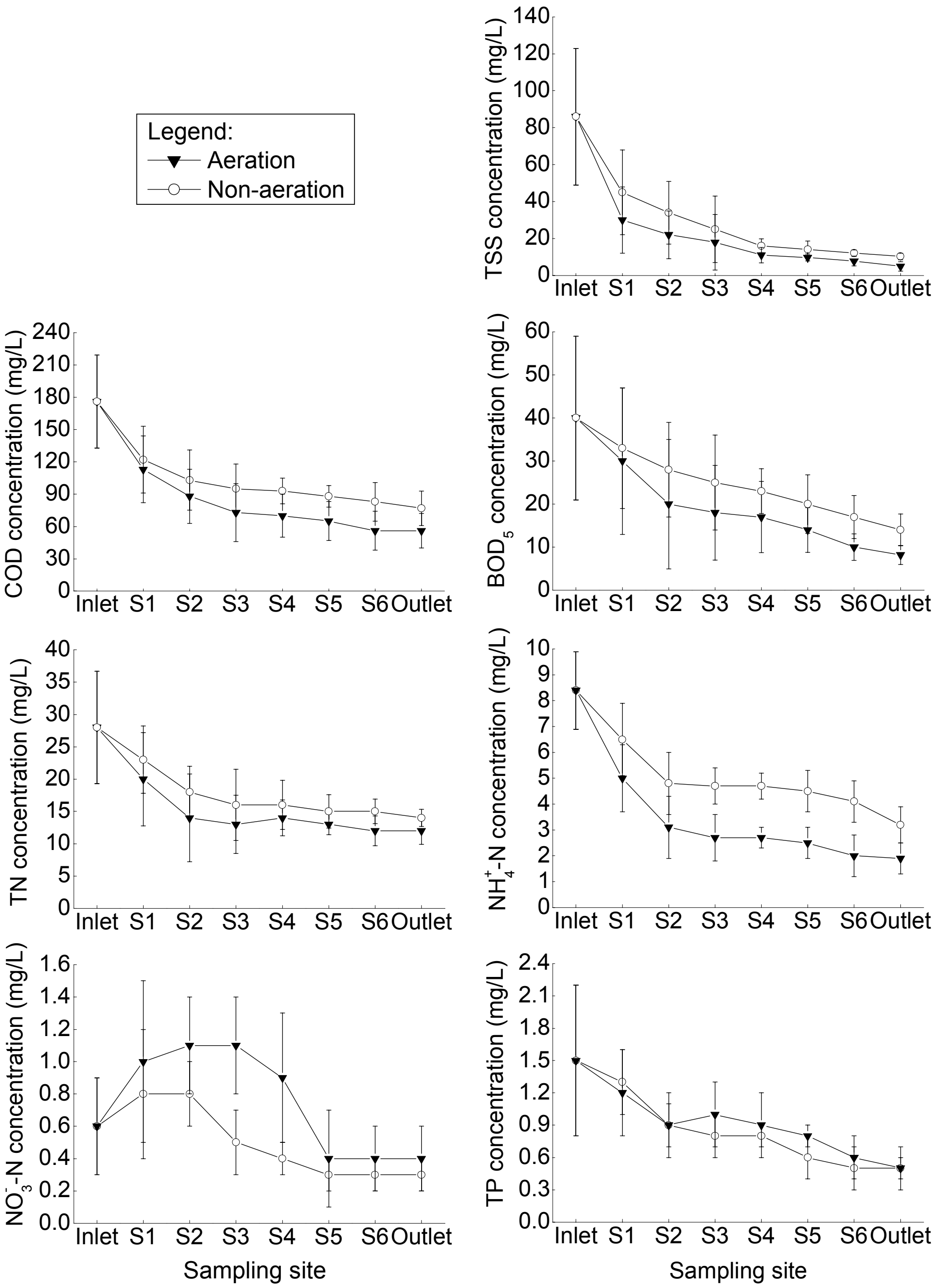

Fig. 4. Mean concentrations for TSS, COD, BOD_5, TN, NH_4^+-N, NO_3^--N and TP at the sampling sites, for aerated and non-aerated IVCWs in winter. Error bars are standard deviations of the mean.

Conclusions

Our year-round operation and monitoring have demonstrated that artificial aeration significantly, improved the oxygen supply in the wetland matrix and the performance of IVCW in the treatment of domestic sewage during cold seasons. The Eh profiling revealed that along the direction of water flow, the sequential oxic-anoxic-oxic redox zones appeared in the summer and were sustained inside the aerated IVCW in the winter. Artificial aeration might have enhanced the nitrification/denitrification processes and aerobic decomposition of organic matter since the removal efficiency of BOD_5 and NH_4^+-N was significantly improved in all seasons. It seemed that artificial aeration could fully compensate for the absence of plant-mediated ventilation in the winter. The removal of COD and TN was also improved in the winter, though low temperatures and plant dormancy still affected the performance of the aerated IVCW. More importantly, the artificial aeration of 8 hours per day eliminated the significant accumulation of NO_3^--N in the effluents from the aerated IVCW. Artificial aeration also slightly enhanced the removal of TSS around the year, though TP removal was not improved. These results demonstrate that the aerated IVCW is an efficient and low-cost system applicable for the treatment of domestic sewage in rural areas, and could still be operated in the winter. We will continue to work on the optimization of system design and operation schemes. For instance, the alternative energy sources such as wind and solar energy may be also utilized for artificial aeration.

Acknowledgements

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