Comparative evaluations of organic matters and nitrogen removal capacities of integrated vertical-flow constructed wetlands: Domestic and nitrified wastewater treatment

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Two groups of integrated vertical-flow constructed wetland (IVCW) microcosms were established for treating two types of representative wastewater: domestic and nitrified wastewater under two loading rates (LRs) over about two years. Their removal capacities of organic substance and nitrogen as well as the effects of loading rate (LR), outflow temperature and dissolved oxygen (DO) concentration were investigated and compared. Efficient chemical oxygen demand (COD) eliminations were achieved by the IVCWs, with the mass removal rates increasing linearly with the increasing LRs strongly, achieving average value of 56.07 g m−2 d−1 at the highest loading rate. Nevertheless, the effluent COD concentrations also increased, with the average value exceeding Class I A discharge standard (< 50 mg L−1) for municipal wastewater treatment plants in China at the highest loading rate. Greater total nitrogen (TN) mass removal rates but lower efficiencies were obtained at the high LR for both types of wastewater, and better removal was achieved for nitrified wastewater (NW) in comparison to domestic wastewater (DW), probably due to the prevailing anoxic conditions inside the IVCW beds restricted nitrification process of DW. The influences of LR, temperature and DO on COD removal were slight, but all remarkable on TN reduction. As compared to DO, temperature was more crucial for nitrogen removal, and the temperature dependence coefficient for TN removal of low LR of NW was significantly greater than others.

Keywords: COD removal, dissolved oxygen, domestic wastewater, integrated vertical-flow constructed wetlands, loading rate, nitrified wastewater, nitrogen removal, temperature.

Introduction

Effective treatment of various types of wastewater, such as municipal and industrial sewage, agricultural runoff, nitrified effluent from sewage treatment plant, is an urgent task worldwide due to that severe environmental problems, e.g., eutrophication and hypoxia of receiving water bodies, can be caused by random discharges of these wastewaters.1] Furthermore, the reuse of wastewater was one of the essential approaches for solving the problem of water shortage, which has been highly severe in China.2]

Domestic wastewater (DW) and nitrified wastewater (NW) are two types of representative wastewater produced abundantly every year, with distinct properties: high contents of oxygen consumers including organic matter and ammonium are predominantly contained in DW while nitrate dominates in NW.

Constructed wetland (CW), based on functionings of natural ecosystem involving complex physical, chemical and biological processes but within a more controlled environment, have been substantially proven to be an attractive and practical alternative for treatment of a wide variety of wastewaters especially in small communities and rural areas, providing a range of benefits, such as low-costs for construction and maintenance, easy-operation, recycling and/or generating resources, wildlife and aesthetic values, etc.3–7] Treatment performance of CW can be significantly influenced by operational conditions such as loading rate (LR) and environmental variables such as temperature and dissolved oxygen (DO) concentration.3,6]

Loading rate (LR), involving hydrology and pollutant levels, plays a very important role in pollutant removal and land area requirement of a CW, thus is a crucial

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parameter for its practical design and operation.\cite{8} It has been reported that mass removal rates of organic substances and nitrogen increased with loading rates (LRs) increasing while the concentration reduction efficiencies, especially for nitrogen, decreased in CWs.\cite{9, 10} Additionally, temperature and DO concentration are identified to be crucial environmental parameters affecting biological processes responsible for pollutant removal in CW, especially for nitrogen due to the processes including ammonification, nitrification and denitrification are all temperature dependent.\cite{11, 12}

Integrated vertical-flow constructed wetland (IVCW), combining a down-flow cell and another up-flow one in series, has been extensively applied in ecological engineering projects in China for treating various wastewater sources, in which domestic and nitrified wastewater take a considerable proportion, due to its compact structure yielding relatively small land area occupation, and effective pollutant removal under suitable operations.\cite{13-15} However, the knowledge on the differences of its organics and nitrogen removal capacities dosing domestic and nitrified wastewater based on a relatively long-term experience is limited to date, which is urgently desired for its better application. Moreover, the influences of important environmental and operational factors on the treatment performance of IVCWs fed with the two types of wastewater may vary greatly and interact, therefore relevant assessment and comparison were also required.

Accordingly, in this work, two groups of small-scale IVCWs were established for treating domestic and nitrified wastewater respectively, with two replicates for each type of wastewater, for about 2 years under two loading rates, with the aims of (1) evaluating the differences of organic matters and nitrogen removal capacities of the IVCWs for DW and NW, and (2) assessing and comparing the effects of loading rate, temperature and DO concentration on the treatment performance for the two types of wastewater.

Materials and methods

Experimental setup

Four small-scale IVCW microcosms, each consisting of a down-flow cell measuring 1.0 m × 1.0 m × 1.0 m (L × W × H) and another identical up-flow one in series with the bottom connected and a total area of 2 m², were installed outdoors with bricks and concrete in a garden near Donghu Lake in Wuhan, China (30° 33′ N, 114° 23′ E). The schematic diagram of the experimental wetland system was shown in Figure 1 and its details were presented in our previous study.\cite{12}

Typha orientalis and Arundo donax var. versicolor were transplanted evenly into the down-flow and up-flow cells of two of the systems, respectively, at density of 8 stems m⁻², and similarly, Canna indica and Pontederia cordata into the other two in April 2010. After the first operation period finished in February 2011, withered plants were removed from the microcosms. Although in April 2011, just Arundo donax var. versicolor and Canna indica were chosen to transplant into the down-flow and up-flow cells of all wetland microcosms, respectively, on the basis of the first year’s experience. The macrophytes used were all native species and collected from a nearby pond.

Wastewater and operational conditions

Artificial domestic wastewater (DW) were uniformly dosed into two of the IVCW microcosms (with different plant combinations in the first operation phase) intermittently through two parallel perforated pipes set up above the surface of the down-flow cell twice a day, and nitrified wastewater (NW) into the other two systems. About 4 months were allowed for the establishments and developments of plants and microorganisms in the IVCWs to achieve relatively reliable pollutant removal prior to the formal experiment.

The experimentation was divided into two operation periods. The period 1 lasted from September 2010 to January 2011, with a high loading rate (LR) applied, and period 2, introducing a low LR, was conducted from April 2011 to June 2012. The details of operation conditions and influential characteristics of the IVCWs were summarized in Table 1. It was seen that similar TN concentrations were contained in the two types of wastewater, with NH₄⁺ predominating largely in DW while NO₃⁻ in NW. Furthermore, organic matter content was relatively high in DW while greatly low in NW, generating a low COD/N ratio for NW. According to the typical composition of DW,\cite{16} the DW dosed during the period 1 could be characterized as medium-strength wastewater while low-strength during the period 2.

Water quality analysis

Water samples were collected approximately on a weekly basis from the inlet and outlet. DO concentration and temperature (T) were immediately measured at field using an
Nitrogen removal capabilities of constructed wetlands

Table 1. Operational conditions and inlet water quality characteristics (mean ± standard deviation) of the IVCWs.

<table>
<thead>
<tr>
<th>Item</th>
<th>DW</th>
<th>NW</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>High LR</td>
<td>Low LR</td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>0.125</td>
</tr>
<tr>
<td></td>
<td>2.56</td>
<td>2.56</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>1.28</td>
<td>2.56</td>
</tr>
<tr>
<td></td>
<td>1.28</td>
<td>2.56</td>
</tr>
<tr>
<td>Hydrualic loading rate (m(^3) m(^{-2}) d(^{-1}))</td>
<td>0.25</td>
<td>0.125</td>
</tr>
<tr>
<td>Feeding frequency (time d(^{-1}))</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Theoretical retention time (d)</td>
<td>1.28</td>
<td>2.56</td>
</tr>
<tr>
<td>DO (mg L(^{-1}))</td>
<td>1.86 ± 1.62</td>
<td>2.56 ± 2.13</td>
</tr>
<tr>
<td>COD (mg L(^{-1}))</td>
<td>299.8 ± 18.8</td>
<td>107.6 ± 15.4</td>
</tr>
<tr>
<td>COD loading rate (g m(^{-2}) d(^{-1}))</td>
<td>74.96 ± 4.70</td>
<td>13.45 ± 1.93</td>
</tr>
<tr>
<td>TN (mg L(^{-1}))</td>
<td>32.44 ± 3.65</td>
<td>11.60 ± 1.45</td>
</tr>
<tr>
<td>TN loading rate (g m(^{-2}) d(^{-1}))</td>
<td>8.11 ± 0.91</td>
<td>1.45 ± 0.18</td>
</tr>
<tr>
<td>NH(_4)(^+) (mg L(^{-1}))</td>
<td>20.31 ± 4.95</td>
<td>7.12 ± 1.75</td>
</tr>
<tr>
<td>NO(_3)(^-) (mg L(^{-1}))</td>
<td>2.30 ± 0.73</td>
<td>1.26 ± 0.84</td>
</tr>
<tr>
<td>NO(_2)(^-) (mg L(^{-1}))</td>
<td>0.15 ± 0.19</td>
<td>0.10 ± 0.10</td>
</tr>
<tr>
<td>COD/TN</td>
<td>9.34 ± 1.07</td>
<td>9.37 ± 1.53</td>
</tr>
<tr>
<td>n</td>
<td>12</td>
<td>52</td>
</tr>
<tr>
<td>n</td>
<td>14</td>
<td>52</td>
</tr>
</tbody>
</table>

DW: domestic wastewater; NW: nitrified wastewater.

Orion 5-star portable multimeter (Thermo Fisher Scientific Company, Waltham, MA, USA). Then the samples were taken back to laboratory and analyzed within 24 h. COD was determined employing a spectrophotometer (DR/2010, Hach Co., Loveland, CO, USA), and TN, NH\(_4\)\(^+\), NO\(_3\)\(^-\), NO\(_2\)\(^-\) were analyzed according to the standard methods.

Treatment performance and kinetics calculations

Removal efficiency and mass removal rate of the IVCW system was calculated by the concentration and mass reduction, respectively, due to the evaporation rate was insignificant compared with the hydraulic loading rate and could be ignored.

\[
\text{Removal efficiency(\%)} = \left(\frac{C_{in} - C_{eff}}{C_{in}}\right) \times 100
\]

\[
\text{Mass removal rate (g \cdot m}^{-2} \cdot \text{d}^{-1}) = \text{HLR} \times \left(\frac{C_{in} - C_{eff}}{C_{in}}\right)
\]

Where \(C_{in}\) and \(C_{eff}\) are concentrations (mg L\(^{-1}\)) of the influent and effluent, respectively, and HLR is the hydraulic loading rate (m d\(^{-1}\)).

Presuming a plug flow in the IVCW, the area-based first-order removal rate constant \(k\) was estimated by the following equation in accordance with Kadlec and Knight:

\[
k = \text{HLR} \times \left[\ln\left(\frac{C_{in}}{C_{out}}\right)\right]
\]

To assess the impact of temperature on pollutant removal, the modified Arrhenius relationship was applied:

\[
k(t) = k(20) \times \theta^{(t - 20)}
\]

Where \(t\) is temperature (°C), and \(\theta\) is the temperature dependence coefficient of \(k\) value.

Statistical analysis

Statistics 17.0 software package for windows was applied for statistical analysis. The significant differences in treatment performance of the IVCWs fed with different wastewaters under two LRs in terms of removal efficiency, mass removal rate and \(k\) value were determined by one-way between groups analysis of variance (ANOVA) followed by the least significant difference (LSD) test. Pearson correlation analysis was carried out to find significant relationship between physicochemical parameter of the effluent and pollutant removal efficiency, giving the significance level values \((p)\) and corresponding determination coefficient \(R\). Differences and correlations were regarded to be significant when \(P < 0.05\) and highly significant when \(P < 0.01\).

Results

Water quality characteristics of the outflow and organics and nitrogen removal performances of the IVCW microcosms during the experimental period were summarized in Table 2. DO contents declined obviously after the wastewater passing through the wetland beds, especially for NW. The mean COD removal efficiencies varied between 62.64%–83.72%, while mass removal rates were in a wide range of 1.51–56.07 g m\(^{-2}\) d\(^{-1}\) depending on the LRs. The average \(k\) values ranged from 0.142 to 0.361 m d\(^{-1}\), with the lowest value recorded for the treatment of low LR of NW. Similar \(k\) values were observed for the two types of wastewater at the high LR, which were significantly greater than those at the low LR (\(P < 0.05\)).

Regarding TN removal, the highest average efficiency (54.32%) and \(k\) value (0.126 m d\(^{-1}\)) were achieved for the treatment of low LR of NW, while the poorest performance (18.18% and 0.053 m d\(^{-1}\)) was recorded for high LR of DW. Despite of the lower efficiencies and \(k\) values,
higher mass removal rates were obtained at the high LR, averaging 1.57 and 1.63 g N m\(^{-2}\) d\(^{-1}\) for DW and NW respectively, compared to 0.57 and 0.81 g N m\(^{-2}\) d\(^{-1}\) at the low LR.

**Temporal variations of outflow temperature and DO concentrations**

Temporal variations of outflow temperature and DO concentrations of the IVCWs during the experimental period were depicted in Figure 2. Obvious annual outflow temperature fluctuations were recorded with the range of 3.1–33.3°C. DO content in outlet of NW was higher than that in DW, although the difference was not significant in period 1 when consistently low concentrations were recorded for both types of wastewater. The outlet DO levels increased remarkably during period 2 with the low LR, and a noticeable rise was observed between the late November 2011 and March 2012, especially in NW.

**COD removal**

Temporal variations of COD removal efficiencies of the IVCWs during the study period were depicted in Figure 3. Relatively better removal with slight fluctuation was achieved for the treatment of low LR of DW. On the contrary, the efficiencies for low LR of NW were low and fluctuated greatly especially since the late November 2011, probably due to the low influent concentration. In spite of the high COD loading of DW during period 1, acceptable elimination performance was still achieved, with removal efficiencies of 61.02%–86.39%.

The COD mass removal rates increased significantly and linearly with the increasing loadings \((r^2 = 0.978)\), with a slope of 0.758 (Fig. 4). Nevertheless, the data points of the low LR of DW were more close to the line of LR = removal rate (RR), which represents total removal, suggesting an optimal COD removal at this LR \((13.45 ± 1.93 \text{ g m}^{-2} \text{ d}^{-1})\) in the IVCWs.

**N removal**

Temporal variations of TN removal efficiencies of the IVCWs throughout the study period are shown in Figure 5. It was seen that similar removal performances were attained for the two types of wastewater in period 1 despite of the negative efficiencies during January 2011 for DW. However, markedly higher reduction efficiencies

![Fig. 2. Temporal variations of outflow temperature (A) and DO concentrations (B) of the IVCWs during the study period. The data for NW during operation period 2 was cited from Chang et al.\(^{[15]}\)](image)
were achieved for NW during period 2 till the end of November 2011, then again since May 2012. A greatly drastic drop was observed for TN removal in NW at the late November 2011, with negative efficiencies in some cases during December 2011 and March 2012. While with regard to TN removal in DW, no negative efficiency or smaller fluctuation were recorded, despite the significantly lower average rate.

It was revealed in Table 2 and Figure 6 that NH$_4^+$ was still the dominant form of N in the outflow of DW, and NO$_3^-$ in NW, especially at the low LR. Organic N was efficiently eliminated in all IVCW microcosms. Noticeably, NH$_4^+$ and NO$_2^-$ took up a nonnegligible proportion in the outflow of NW in period 1.

In general, concerning TN removal, the IVCW performed better when treating NW, although no significant difference was detected in period 1 with the high LR (Table 2).

Higher mass removal rates of TN were achieved at the high LR for both types of wastewater, although they were both far away from the line of LR=RR, which represents total removal (Fig. 7A) in contrast to COD removal. However, the reduction efficiencies and $k$ values obtained at the high LR were significantly lower than those at the low LR, especially for NW (Figs. 7B, 7C).

The influences of temperature and DO concentration on COD and TN removal under different operations

Values of significance level and Pearson correlation coefficient (in parentheses) between outflow temperature (T), DO concentration and removal efficiencies of COD and TN under different operations were presented in Table 3, and temperature dependence coefficients ($\theta$) for COD and TN removal were listed in Table 4.

COD removal efficiency for DW was positively correlated with outflow DO concentration significantly at the high LR. Yet at the low LR, it was found to be positively related to effluent temperature, although the $R$ values were relatively low, with a $\theta$ value of 1.011 for DW and 1.035 for NW.

With regard to TN removal, the reduction efficiency was detected to be associated with the effluent DO concentration of DW at the high LR (positively) and that of NW at the low LR (negatively). Moreover, they were significantly correlated with outflow temperature positively under all operational conditions, with the $R$ values ranging from 0.402 to 0.811 and $\theta$ values from 1.029 to 1.120. As compared to TN, the impacts of temperature and DO concentration on COD removal were greatly less.

Discussion

COD removal and the influences of crucial factors

The removal of organic substances mainly depends on aerobic biochemical degradation of heterotrophs in CWs.

However, anaerobic decomposition might account for a considerable proportion in the IVCWs, especially at high COD LR due to the low DO levels in the wetland beds.

COD mass removal rate of the IVCWs increased with the increasing LRs, which was consistent with the results obtained in other CWs and was probably due to the enhanced microbial production and metabolism under higher LR. Nevertheless, a tendency of leveling off for mass removal rate at high LR was observed by Dan et al., suggesting that the organics removal capacity of CW was not infinite. Actually, too high organic matter loading was not recommended for the application of CW due to microbial activities could be inhibited by severe overloading.
Concerning the IVCWs, COD removal efficiency decreased at the highest LR, and the outflow COD concentration also increased as the LRs increased, averaging 75.5 mg L\(^{-1}\) at the highest LR (74.96 \(\pm\) 4.70 g m\(^{-2}\) d\(^{-1}\)), which exceeded the Class I A discharge standard (<50 mg L\(^{-1}\)) for municipal wastewater treatment plants in China.\(^{[25]}\) Thus a lower COD loading, such as 50 g m\(^{-2}\) d\(^{-1}\), was recommended for future design and operation of IVCW system. Considering DO requirement for NH\(_4^+\) removal in DW, COD loading needs further reduction. The slope of the linear regression line between COD mass loading and removal rate in this study was greater than those derived in some horizontal subsurface flow CWs,\(^{[18, 24]}\) probably indicating a larger COD removal capacity of the IVCW especially under high LR. In addition, the \(k\) values of COD removal in the IVCWs were in the high range of some references,\(^{[18, 23, 24]}\) and higher than some others.\(^{[5, 10, 21]}\)

Very low effluent COD concentration (7.2 mg L\(^{-1}\)) was obtained when treating low LR of NW with an average...
influent concentration of 19.3 mg L\(^{-1}\), probably due to the organic materials in the simulated wastewater being easily degradable and utilized adequately for denitrification. And, it might also suggest the superiority of IVCW in elimination of low level of organic substance under this operational condition.

The effect of temperature on pollutant removal can be evaluated by the temperature-dependence coefficient (\(\theta\)). Just slight influence of temperature on COD removal was detected (Table 4), which was also documented by others,\(^{26, 27}\) due to the microbial processes responsible for organic matter degradation could still proceed even when temperature declined to 5°C.\(^{28}\)

**Nitrogen removal and the influences of crucial factors**

Microbial denitrification transforming nitrate produced by nitrification to \(\text{N}_2\) or \(\text{N}_2\text{O}\) is generally regarded as the long-term removal pathway for nitrogen in CW, which depends greatly on environmental parameters and operational conditions of the system, including loading rate, temperature, DO, vegetation, etc.\(^{3, 6, 11, 15}\) As compared with COD, poor TN removal capacity was attained in the IVCWs due to the detrimental environmental conditions such as severely insufficient oxygen for nitrification of DW or carbon source shortage for denitrification of NW. In addition, longer retention time was required for efficient removal of N in comparison to COD.\(^{16, 7}\)

Higher TN removal rate was achieved for the treatment of NW compared to DW, due to the low DO level within the wetland bed, was beneficial to the denitrification process but detrimental to nitrification. Furthermore, the biodegradation of organics could consume DO more competitively than nitrification, especially under high LR.\(^{7, 29}\) However, the nitrogen removal for NW was still unsatisfactory, primarily due to the low ratio of COD/N in influent, which meant insufficient available carbon source for denitrification. Moreover, the low temperature in winter, which could largely weaken microbial processes for N removal, could be another important reason contributing to the limited nitrogen eliminations in all IVCW microcosms.

It was abundantly reported that the nitrogen mass removal rates increased with the increasing LRs in CWs,\(^{3, 9, 21, 24, 27, 30}\) and higher TN removal rates were also achieved at the high LR in the IVCW systems. Nevertheless, it was generally recorded that the increase was slight or leveled off or even dropped considerably when the LR was too high,\(^{21, 22, 24, 30}\) probably due to more severe restriction of environmental conditions for microbial nitrogen removal processes.

In this study, the TN mass removal rates obtained at the high LR were far away from the line of \(LR = RR\), probably demonstrating a smaller nitrogen removal capacity of the
IVCW as compared to COD. Moreover, the TN removal efficiencies decreased significantly at the high LR, showing a much more remarkable influence of LR on TN elimination than that on COD, which agreed with other references.\cite{10, 23, 31} Taking the low and fluctuated nitrogen removal efficiencies at the high LR into consideration, a loading rate of around 1.0 and 1.5 g N m$^{-2}$ d$^{-1}$ were recommended for DW and NW to be dosed into the IVCW, with substantial reduction in winter, to achieve satisfactory nitrogen removal if no approach for improvement of N removal was applied. Further investigation on saturation kinetics of pollutant removal in IVCW is considerably necessary, which is significant and profitable for its better design and operation.

Unlike COD removal, lower $k$ values for TN removal were derived at the high LR (Fig. 7C), which was consistent with Trang et al.,\cite{10} probably indicating a larger limitation of nitrogen removal capacity under high LR. Although the average $k$ value for low LR of NW was significantly higher, the $k$ (20) values under all operational conditions did not greatly differ (Table 4), probably suggesting similar TN removal speeds and capacities at 20 in the IVCWs. The average $k$ values of 0.053–0.126 m d$^{-1}$ obtained for TN removals in the IVCWs were in the high range of values recorded in some CWs\cite{3,10,31} and higher than others treating DW or NW.\cite{24,32}

As compared with COD, the influences of temperature and DO on nitrogen removal were more significant (Table 3), probably indicating that their impacts on microbial nitrogen removal processes were much greater than those on organic compounds biodegradation.

Moreover, larger impact of temperature on TN removal in the IVCWs was detected in comparison to DO content. Actually, several external factors, such as evapotranspiration, solar radiation and rain, which can affect nitrogen removal conditions in CWs, are directly correlated with the temperature of the outflow.

Concerning the effect of temperature, $\theta$ value for TN removal of low LR of NW was much larger than those obtained under other operations (Table 4), indicating the most significant influence of temperature. But it was noticeable that the DO level in the outflow of NW increased, apparently in period 2 since late November (Fig. 2), which was unfavorable for the denitrification process, likely resulting in an overestimation of the impact of temperature. On the other hand, the rise in DW, despite being relatively small, was beneficial to nitrification; thus, the influence of temperature might be weakened, yielding a low $\theta$ value. Regarding TN removal at high LR, low $\theta$ values determined for both types of wastewater might be attributed to the possibility that the effect of temperature was insignificant as compared to the overloading.

**Table 3.** Values of significance level and Pearson correlation coefficient (in parentheses) between effluent DO, temperature (T) and removal efficiencies of COD and TN.

<table>
<thead>
<tr>
<th>Item</th>
<th>DW</th>
<th>NW</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>High LR</td>
<td>Low LR</td>
</tr>
<tr>
<td>COD removal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outflow DO</td>
<td>0.000* (0.824)</td>
<td>0.058 (−0.158)</td>
</tr>
<tr>
<td>Outflow T</td>
<td>0.115 (0.254)</td>
<td>0.001* (0.307)</td>
</tr>
<tr>
<td>TN removal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outflow DO</td>
<td>0.000** (0.850)</td>
<td>0.066 (−0.152)</td>
</tr>
<tr>
<td>Outflow T</td>
<td>0.000** (0.677)</td>
<td>0.000** (0.402)</td>
</tr>
<tr>
<td>n</td>
<td>24</td>
<td>100</td>
</tr>
</tbody>
</table>

**Table 4.** Temperature dependence coefficient ($\theta$) of COD and TN removal.

<table>
<thead>
<tr>
<th>Item</th>
<th>DW</th>
<th>NW</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>High LR</td>
<td>Low LR</td>
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<tr>
<td>COD removal</td>
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</tr>
<tr>
<td>$\theta$</td>
<td>1.009</td>
<td>1.011</td>
</tr>
<tr>
<td>$k$ (20)</td>
<td>0.365</td>
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</tr>
<tr>
<td>R</td>
<td>0.245</td>
<td>0.312</td>
</tr>
<tr>
<td>$\rho$</td>
<td>0.248</td>
<td>0.002</td>
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<tr>
<td>TN removal</td>
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</tr>
<tr>
<td>$\theta$</td>
<td>1.027</td>
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<td>$k$ (20) m d$^{-1}$</td>
<td>0.071</td>
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<tr>
<td>R</td>
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<td>0.134</td>
<td>&lt;0.0001</td>
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<tr>
<td>n</td>
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<td>100</td>
</tr>
</tbody>
</table>

DW: domestic wastewater; NW: nitrified wastewater. The data of TN removal for low LR of NW was cited from Chang et al.\cite{15}

*The correlation is statistically significant.

**The correlation is statistically highly significant.

Note: $P < 0.01$ indicates the correlation is statistically highly significant. The data of TN removal for low LR of NW was cited from Chang et al.\cite{15}
Conclusions

Organic substances in domestic and nitrified wastewater with different LRs could be efficiently eliminated by the IVCWs, with removal efficiencies in the range of 62.64%–83.72% on average. The areal COD mass removal rates had a significant linear relationship with the increasing LRs. However, the outflow COD contents also increased as the LRs increased, and exceeded Class I A discharge standard for municipal wastewater treatment plants in China at the highest LR of 74.96 g m⁻² d⁻¹. Higher TN mass removal rates but lower efficiencies and constants were observed at the high LR in the IVCWs for the treatment of both types of wastewater. In general, the IVCW achieved better TN removal when treating NW as compared to DW, probably mainly due to the prevailing anoxic conditions in the wetland beds largely restricted microbial nitrification process in IVCWs fed with DW.

The influences of loading rate, temperature and DO concentration on COD removal were slight, while significant on TN removal. Temperature played a more crucial role in TN removal compared with the DO content, and the impact of temperature on TN removal for low LR of NW was significantly greater than those on others.

Funding

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