Treatment of domestic wastewater by vertical flow constructed wetland planted with umbrella sedge and Vetiver grass

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ABSTRACT

The aim of this study was to investigate the efficiency of wastewater treatment by vertical flow constructed wetland systems under different hydraulic loading rates (HLR). The comparison of two types of plants, *Cyperus alternifolius* (Umbrella sedge) and *Vetiveria zizanioides* (Vetiver grass), was also conducted. In this study, six circular concrete tanks (diameter 0.8 m) were filled with fine sand and gravel to the depth of 1.23 m. Three tanks were planted with Umbrella sedge and the other three tanks were planted with Vetiver grass. Settled domestic wastewater from Chiang Mai University (chemical oxygen demand (COD), NH₄⁺-N and suspended solids (SS) of 127.1, 27.4 and 29.5 mg/L on average, respectively) was intermittently applied for 45 min and rested for 3 h 15 min. The HLR of each tank was controlled at 20, 29 and 40 cm/d. It was found that the removal efficiency of the Umbrella sedge systems was higher than the Vetiver grass systems for every parameter, and the lowest HLR provided the maximum treatment efficiency. The removal efficiency of COD and nitrogen in terms of total Kjeldahl nitrogen (TKN) was 76 and 65% at 20 cm/d HLR for Umbrella sedge compared to only 67 and 56% for Vetiver grass. Nitrogen accumulation in plant biomass was also higher in Umbrella sedge than in Vetiver grass in every HLR. Umbrella sedge was thus proved to be a suitable constructed wetland plant in tropical climates.

Key words | constructed wetland, domestic wastewater, Umbrella sedge, vertical flow, Vetiver grass

INTRODUCTION

Constructed wetlands have been proven to be a suitable wastewater treatment system for developing countries in tropical areas where land is available at low cost and warm temperatures are suitable for biodegradation. Recently the application of a vertical flow constructed wetland system (VFCW) has increased due to the reduction of required land area and its high removal efficiency. Many studies of VFCW were conducted in order to find the maximum removal efficiencies such as the study of different kinds of media (Korkusuz et al. 2005), different bed depth (Tanigushi et al. 2009) and different loading regimes (Kantawanichkul & Boontakhum 2012).

In Thailand, the use of Umbrella sedge (*Cyperus alternifolius* L.) in a constructed wetland has been practised for more than 10 years and has proved efficient for wastewater treatment (Kantawanichkul et al. 2002; Kantawanichkul & Somprasert 2005; Kantawanichkul et al. 2009; Kantawanichkul & Boontakhum 2012). Umbrella sedge, besides being capable of tolerating a high concentration of pollutants, can be used as ornamental plants as well. The increasing popularity of Umbrella sedge for decoration leads to its high price.

Vetiver grass (*Vetiveria zizanioides*) was first recognized in 1995 for wastewater treatment in Australia (Truong 2000). Vetiver is highly tolerant to frost, drought, flood and inundation and it uses more water than other wetland plants such as *Typha* spp., *Phragmites australis* and *Schoenoplectus validus* (Truong & Hart 2001). In Thailand, Vetiver grass has been proven to be a suitable plant for wastewater treatment in VFCW under an organic loading rate (OLR) of 11 gCOD/m²d (Kantawanichkul et al. 1999). Umbrella sedge and Vetiver have different root structures and this makes it interesting to compare these two plants in constructed wetland systems. In this study, the comparison
between Umbrella sedge and Vetiver grown in sand and gravel media under different organic and hydraulic loading rates (HLR) was conducted to evaluate the optimum conditions for domestic wastewater treatment in tropical climates.

MATERIALS AND METHODS

Six laboratory scales of VFCW made of circular concrete tanks, 0.8 m in diameter and 1.23 m deep, were used in this study. Each tank was filled with gravel (9.5–12.5 mm) to 0.13 m from the bottom. A layer of fine sand \((D_{50} = 0.6 \text{ mm})\) was added to a depth of 0.9 m and then coarse sand \((D_{50} = 1.2 \text{ mm})\) for 0.1 m. The top layer consisted of gravel (9.5–12.5 mm, for 0.1 m) as shown in Figure 1. Geotextile was laid between the gravel and fine sand to prevent the intrusion of sand into the gravel layer. Umbrella sedge was planted in three tanks and Vetiver in the other three.

The study was carried out for 180 d from January to June 2012. Settled domestic wastewater from Chiang Mai University campus with pH in the range of 6.6–6.8 and average temperature of 27°C was applied intermittently for 45 min, followed by a resting time of 3 h 15 min. The flow rate was adjusted to achieve the designed OLR of 25, 35 and 50 gCOD/m² d or 20, 30 and 40 cm/d HLR in each tank. The influent and effluent of every tank were collected weekly to analyse for pH, COD (chemical oxygen demand), Alk (alkalinity), TKN (total Kjeldahl nitrogen), \(\text{NH}_4^+\)-N (ammonia nitrogen), \(\text{NO}_2^-\)-N (nitrite nitrogen), \(\text{NO}_3^-\)-N (nitrate nitrogen), and SS (suspended solids) as described in the Standard Methods for the Examination of Water and Wastewater (2005). To estimate water loss by evapotranspiration, the volume of inflow and outflow of the same day were measured at least once a week. Two way analysis of variance (ANOVA) was used to analyse the relationship between variables.

RESULTS AND DISCUSSION

The average COD, TKN, \(\text{NH}_4^+\)-N, \(\text{NO}_2^-\)-N, SS, alkalinity and pH of wastewater were 127.1, 29.03, 27.44, 0.2, 29.5, 138.33 mg/L and 6.7, respectively. The average influent flow rates of the three tanks were 103, 144 and 200 L/d, and the fluctuation of COD in the wastewater, resulted in the average OLR of 25.2, 35.3 and 49.1 gCOD/m² d and HLR of 20, 29 and 40 cm/d, respectively. The water loss due to the evapotranspiration was 16, 9.7 and 9.1% at 20, 29 and 40 cm/d for Umbrella sedge and 10, 7.8 and 12.3% at 20, 29 and 40 cm/d for Vetiver.

The fast growth of Umbrella sedge and Vetiver was noticed during the first 6–12 weeks, and then the growth rate declined. On the 23rd week, Vetiver leaves began to wilt, which might have been caused by the dryness of sand media during the resting period (3 h 15 min) of the intermittent water application in the dry season of Thailand. This phenomenon was correlated with nitrification, which was markedly reduced from the 23rd week onwards. The removal efficiency of the system planted with Umbrella sedge was higher than Vetiver for every parameter at every loading rate. The maximum removal efficiencies were achieved at the lowest HLR according to the longest hydraulic retention time (HRT). The maximum removal efficiency of COD was 76.8% for Umbrella sedge and 67.7% for Vetiver or equivalent to the removal rate of 21.4 and 18.5 g/m² d for Umbrella sedge and Vetiver, respectively (Figure 2). It is concluded then that the combination of sand media and gravel contributed to higher removal efficiency than gravel alone, since in a previous study with the same constructed wetlands, Kantawanichkul & Wannasri (2015) reported that COD removal efficiency by a
VFCW filled with gravel ($D_{50} = 1$ cm) using the same source of wastewater and the same HLR (20 cm/d) planted with Umbrella sedge was only 32.9% or 12.9 g/m² d removal rate. The removal efficiencies of TKN and NH$_4^+$-N maximized at 65.2 and 66.7% for Umbrella sedge and 56.6 and 60.7% for Vetiver, at HLR of 20 cm/d or equivalent to the removal rate of 4.05 and 3.64 gNH$_4^+$-N/m² d for Umbrella sedge and Vetiver, respectively. It was found that from the 23rd week, the concentration of TKN started to increase (Figure 3). Therefore, the oxidized nitrogen (NO$_2^-$-N and NO$_3^-$-N) was fluctuating during the first 22 weeks and suddenly decreased on the 23rd week (Figure 4). The increase of alkalinity was correlated to the reduction of oxidized nitrogen ($p < 0.05$) and the production of alkalinity could confirm denitrification reaction in the system which occurred from the 23rd week. It could be assumed that anoxic conditions developed after 23 weeks of the experiment. The dissolved oxygen (DO) meter was used to monitor aerobic conditions within the bed but the results were not accurate due to some problems of the equipment. Therefore, to assure the anoxic/aerobic condition, oxygen transfer rate (OTR) presented by Cooper (2005) was calculated using the following formula:

$$\text{OTR} \left( \text{g/m}^2 \text{d} \right) = \text{flow rate} \times \left( \frac{\text{BOD}_{5\text{in}} - \text{BOD}_{5\text{out}}}{C_0} + 4.3 \left( \text{NH}_4\text{N}_{\text{in}} - \text{NH}_4\text{N}_{\text{out}} \right) / \text{total area of beds} \right)$$

Figure 2 | COD removal efficiency at different HLR of both plants.

Figure 3 | TKN concentration in the influent and the effluent of both plants at 40 cm/d HLR.
where: \([\text{BOD}_{5\text{in}}-\text{BOD}_{5\text{out}}]\) is the mass of biochemical oxygen demand (BOD) removed by the system \((\text{g/m}^2\text{ d})\), \([\text{NH}_4\text{N}_{\text{in}}-\text{NH}_4\text{N}_{\text{out}}]\) is the mass of nitrogen \((\text{g/m}^2\text{ d})\), \(\text{BOD}_5\) can be replaced by \([0.7 \text{ COD}]\) (Platzer 1999).

The decline of oxidation conditions within the bed of both plants after the 23rd week \((p < 0.05)\) (Figure 5 for Umbrella sedge and Figure 6 for Vetiver) was probably due to some clogging which did not cause any serious problems to the flow, although a reduction of flow rate could be observed from all the six tanks. Zhao et al. (2009) concluded that both biofilm and the accumulation of organic matter could reduce the infiltration rate of constructed wetland systems. Therefore, anaerobic conditions could occur after a period of time when the sand became more compact. Kantawanichkul & Wannasri (2013), using a gravel bed planted with Umbrella sedge in a VFCW, reported only 46.8% removal of \(\text{NH}_4\text{-N}\) at 20 cm/d. This is shown that sand bed achieves higher removal efficiency than the gravel bed. The fine particles of sand provide a longer retention time for biological processes such as nitrification and denitrification. Moreover, sand particles provide a larger surface area for the microorganisms to attach to; Vymazal (2001) mentioned that microbial populations influence the nitrification reaction. Moreover, the depth of their gravel bed was only 60 cm, so shorter HRT could limit the capacity of nitrification and denitrification within the bed.

SS removal by fine particles of sand media could achieve 86.7, 77.0 and 73.1% for Umbrella sedge, and 78.5, 72.3 and 67.5% for Vetiver, at 20, 29 and 40 cm/d, respectively. However, the different HLR or the type of plant did not markedly influence the SS removal efficiency of the system.

It was found that wastewater treatment efficiency of Umbrella sedge beds was higher than Vetiver beds for every parameter. Liao et al. (2005) studied the ability of Vetiveria zizanioides and Cyperus alternifolius on pig farm wastewater treatment and found that the removal rates of
BOD, COD and $\text{NH}_4^+$-N were higher in the Umbrella sedge (*Cyperus alternifolius*) bed.

At the end of the experiment, plants were removed from the bed to investigate the root system and measure biomass and nitrogen content. Liao *et al.* (2005) revealed that the above ground biomass of Umbrella sedge was greater than Vetiver and vice versa for the below ground part in a subsurface flow constructed wetland system treating pig farm wastewater. This was opposite to this study, in which the above ground biomass of Umbrella sedge was found to be lower than Vetiver as shown in Table 1. The structure of the root system of Umbrella sedge was different from Vetiver. The roots of Umbrella sedge were larger and longer (1.5 m long in average) when compared to the root of Vetiver, which had fine dense roots around 10 cm from the surface and below was composed of fibrous root knitted together along the depth of the bed.

$N$ accumulation in Umbrella sedge was 5.2, 7.0 and 9.3 gN/g dry mass compared to 4.2, 5.4 and 6.3 gN/g dry mass of Vetiver for 20, 29 and 40 cm/d HLR, respectively. $N$ accumulation in the above ground part was much higher than in the roots for both plants as shown in Figure 7. Liao *et al.* (2005) also found that $N$ accumulation in Umbrella sedge was higher than Vetiver, at 22.69 and 15.4 mg/g, respectively. Suracoop & Kantawanichkul (2011) found $N$ content in Umbrella sedge planted in gravel VFCW was around 6.2 gN/g.

Nitrogen balance in the system was also calculated, and it was found that $N$ uptake by Umbrella sedge was higher than Vetiver at every HLR. However, the uptake of $N$ was 3.3–3.4% (22.9–23.85 gN) for Umbrella sedge compared to only 1.5–1.7% (10.24–12.23 gN) for Vetiver. In the previous studies, by using VFCW system planted with Umbrella sedge in tropical climate, Kantawanichkul *et al.* (2009) found an uptake of 16.9%, Suracoop (2010) reported 3.4–10.1%, Kantawanichkul & Wannasri (2013) reported 13.7% and Kantawanichkul *et al.* (2008) found 0.43–3.68% of influent

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**Table 1** | Dry biomass above and below ground of Umbrella sedge and Vetiver grass

<table>
<thead>
<tr>
<th>Macrophytes</th>
<th>Above ground biomass (g/m²)</th>
<th>Below ground biomass (g/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Umbrella sedge 20 cm/d</td>
<td>556.6</td>
<td>395.7</td>
</tr>
<tr>
<td>Vetiver grass 20 cm/d</td>
<td>766.7</td>
<td>213.9</td>
</tr>
<tr>
<td>Umbrella sedge 29 cm/d</td>
<td>731.7</td>
<td>411.9</td>
</tr>
<tr>
<td>Vetiver grass 29 cm/d</td>
<td>848.9</td>
<td>242.4</td>
</tr>
<tr>
<td>Umbrella sedge 40 cm/d</td>
<td>825.3</td>
<td>425.0</td>
</tr>
<tr>
<td>Vetiver grass 40 cm/d</td>
<td>917.3</td>
<td>249.4</td>
</tr>
</tbody>
</table>

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Figure 6 | OTR of Vetiver bed at different HLR.

Figure 7 | Nitrogen accumulation in above and below ground of Umbrella sedge (U) and Vetiver (V) at HLR of 20, 29 and 40 cm/d.
total nitrogen (TN). The variation of nitrogen uptake by plant may be caused by the concentration of available nitrogen in the wastewater.

CONCLUSIONS

The treatment of domestic wastewater by VFCW system planted with Umbrella sedge and Vetiver grass at OLR of 25.2, 35.3 and 49.1 gCOD/m²d or 20, 29 and 40 cm/d HLR was satisfactory, and the effluent quality reached the national effluent standard of Thailand. The lowest HLR of 20 cm/d provided the highest removal efficiency due to the longest HRT. The small particles of sand media also provided longer retention time and higher surface area for the attachment of biofilm. Umbrella sedge exhibited higher removal efficiency compared to Vetiver. However, from the 23rd week onwards, the reduction of oxidation condition inside the bed was assumed to be caused by some clogging and compaction of sand media resulting in lower reduction of NH₄-N and hampering the nitrification reaction. However, the removal of COD and SS were not affected by the low oxidation condition. Nitrogen accumulation in plant biomass of Umbrella sedge was higher than Vetiver, and nitrogen content in the biomass of both plants was higher in the above ground part than the below ground part. Therefore, the harvest of the above ground part can reduce nitrogen from the system.

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