Seeking a way to promote the use of constructed wetlands for domestic wastewater treatment in developing countries

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ABSTRACT

The aim of this study was to evaluate the domestic wastewater treatment efficiency as well as the survivability of commercially valuable ornamental plants in subsurface flow wetlands (SSFW) for domestic wastewater (DWW) treatment in laboratory and pilot wetland studies. The laboratory scale study included five different species (Zantedeschia aethiopica, Strelitzia reginae, Anthurium andreanum, Canna hybrids and Hemmerocallis dumortieri) that were evaluated in horizontal flow subsurface treatment cells. All the plants survived during the 6-month experimental period demonstrating high wetland nutrient treatment efficiency. In order to validate and expand these preliminary results, a pilot-scale wetland study was carried out in SSFWs under two different flow regimes (horizontal and vertical flow). Four ornamental species were tested during a 1-year period: Zantedeschia aethiopica, Strelitzia reginae, Anthurium andreanum and Agapanthus africanus. The removal efficiencies were significantly higher in the vertical subsurface-flow constructed wetlands (VFCW) for all pollutants, except for nitrate (NO₃-N), total nitrogen (TN) and total suspended solids (TSS). These results show that it is feasible to use select non-wetland plants with high market value in SSFWs without reducing the efficiency of the wastewater treatment system, although future work should continue in order to apply this technology in a large scale. The added value of floriculture in treatment wetlands can help to promote the use of constructed wetlands (CW) for domestic wastewater treatment in developing countries where economical resources are scarce and water pollution with DWW is common.

Key words | developing countries, domestic wastewater, ornamental plants, subsurface-flow constructed wetlands

INTRODUCTION

Constructed wetlands have been widely recognized as a simple, effective, reliable and economical alternative to other conventional wastewater treatment systems (Tuladha et al. 2008) and, for decades, have been used globally to treat a range of wastewaters. It has been demonstrated that wetland treatment is particularly appropriate for the treatment of grey water and domestic or municipal wastewaters (Conkile et al. 2008). Owing to their low operational cost and relatively simple design and operation, they have been strongly recommended as an effective technology for improving water quality in developing countries (Denny 1997; Kivaisi 2001). Up to 90% of domestic wastewater in developing countries is discharged in surface waters without treatment and this can lead to degradation of surface water quality in the receiving aquatic system (WSP-LAC 2006). However, in spite of the enormous potential for the use of CW for wastewater treatment, there are some challenges faced in the universal adoption of this technology due to the fact that it is still difficult to convince...
people to invest additional resources (time, space, money) in a treatment plant as opposed to discharging untreated effluent into rivers and other surface waters. It is apparent that in order to increase the implementation rate of constructed wetlands in developing countries, additional benefits of wastewater treatment must be documented in order to make this technology more attractive to individuals and communities.

One potential benefit includes linking a profitable harvestable product to the wastewater treatment operation. Therefore, it is necessary to demonstrate the feasibility of alternative vegetation by substituting conventional treatment wetland macrophytes with commercially valuable ornamental plants while still maintaining wastewater treatment efficiency. The use of ornamental plants as the dominant emergent plant in SSFW could encourage the adoption of CW treatment by communities because of the added direct economic benefit which in turn, would encourage maintenance of the wastewater treatment system.

The use of commercially valuable ornamental plants is possible in many developing countries because of suitable climate. The abundance of ornamental plants in most developing countries allows for the potential inclusion of a wide variety of plants which can be raised for profit in CW. The combination of domestic wastewater treatment and floriculture in CW can therefore encourage the implementation of wetland treatment in developing countries, such as Mexico, where economical resources are scarce and surface water pollution with domestic wastewater is common. In this study five ornamental species were evaluated at the laboratory scale wetlands and four in a pilot treatment wetland. The goals of the study were to evaluate the survival rate and development of ornamental plants in SSFW, as well as to evaluate the DWW treatment efficiency of the treatment wetland system.

**MATERIALS AND METHODS**

The studies were carried out in Ocotlán, Jalisco Mexico in the Centro Universitario de la Ciénega, where the climate is classified as warm and wet with rainfall in summer. For the lab-scale experiments, the system consisted of five cells for SSFW with their individual sedimentation units (Figure 1). Each one of the subsurface flow cells was filled with tezontle gravel (0.5–1 cm diameter and 0.53 porosity) and planted individually with two adult plant of an ornamental species (Zantedeschia aethiopica, Strelitzia reginae, Anthurium andreanum, Canna hybrids and Hemmerocallis dumortieri). Plastic cells of $67 \times 37 \times 30$ cm ($L \times W \times H$) or acrylic cells of $80 \times 30 \times 30$ cm ($L \times W \times H$) were used for the SSFW. Acrylic cells measuring $100 \times 30 \times 30$ cm ($L \times W \times H$) were used for the sedimentation units. The volume of water in each sedimentation cell was 75 l, while the volume in each SSFW ranged from 32–39 l. The total volume involved in the experiment was approximately 555 l. The pre-settled (prior removal of solids) domestic wastewater flow rate was maintained between 3.5 and 5.5 ml min$^{-1}$ for a mean retention time of 4 days in each one of the SSFW. The system was installed in an unintentionally shadowed area due to the presence of buildings and trees within the university such that it was exposed to direct sunlight for approximately 6 hr per day. In addition Anthurium andreanum was protected with shade due to its sensitivity to direct sunlight using a shadecloth. The monitoring period of the experiment was from September 2004 to January 2005.

The pilot-scale treatment system was installed outside the urban area of Ocotlán close to the Ocotlán’s wastewater treatment plant (WWTP) and consisted of an 1100-l feeder tank used to store prescreened wastewater from the inlet of the WWTP. This wastewater was fed into a pair of horizontal subsurface-flow constructed wetlands (HFCW) measuring...
3.6 m × 0.9 m × 0.3 m (L × W × H) and into a pair of VFCWs measuring 1.8 m × 1.8 m × 0.7 m (L × W × H) (Figure 2); each wetland had a planted surface of 3.24 m². The 0.3 m depth of the HFCWs was selected because the maximum length reached by the roots of the different species in the lab-scale study was approximately 25 cm. In the HFCWs, the domestic wastewater was fed continuously at a rate of 128 l d⁻¹ which corresponds to a hydraulic retention time of 4 d. In the VPCW, the domestic wastewater was fed intermittently by means of an automatic siphon, discharging 16 l every 3 hr directly over the non-stratified substrate surface for a total hydraulic loading of 128 l d⁻¹. One each of the HFCW and VFCW were planted with just one species (30 healthy young plants of *Z. aethiopica*) and the other two with three species each (6 adult plants of *Strelitzia reginae*, 6 adult plants of *Anthurium andreanum* and 3 adult plants of *Agapanthus africanus*). All the units were built of brick and concrete and were filled with 1.2-cm tezontle gravel. The pilot-scale treatment wetland was exposed to the environmental conditions but protected from direct sunlight by shade screens. The pilot-scale study was carried out from March, 2006 to February, 2007 with a monitoring period from June 2006 to February 2007.

In both studies, the survival rate of plants was evaluated in terms of the percentage of live plants at the end of the experimental period. In addition, the physical appearance of the plant, as well as incidence of flowering was recorded. With regard to pollutant removal, chemical and biological water quality parameters including temperature, pH, dissolved O₂, BOD, COD, TSS, ammonium, nitrate, organic N, total N, total P and total coliforms were measured as described in the Standard Methods for the examination of Water and Wastewater (*APHA 1998*). The statistical analysis was performed with the software Statgraphics Plus 4.0 and included analysis of varianza (ANOVA) and comparison of the multiple range test with the Least Significant Difference (LSD) for differences between means.

**RESULTS AND DISCUSSION**

**Plant growth**

In the lab-scale study, all the ornamental plants had a survival rate of 100%. However, *Zantedeschia aethiopica* and *Canna hybrids* exhibited a faster growth rate and higher shoot and flower production compared to the other three species. *Z. aethiopica* flowered throughout the study and increased production of flowers during the colder months (December and January). It produced the highest quantity of flowers and shoots per plant, around 6 and 10 respectively, likely as a result of its better tolerance to the continuous flooding condition in the HFCW. Such significant flowering in such a short study period was due to the fact that adult plants were transplanted. *Canna hybrids* produced 2–3 flowers and 4 shoots per plant. With regard to the other three ornamental plants, their development was more limited. *Anthurium andreanum* was planted in the system already flowering and did not produce new flowers during the study but yielded several shoots to produce new plants (4–5 per plant). *Strelitzia reginae* only produced new leaves and the leaves looked unhealthy. *Hemerocallis dumortieri* showed good development and produced several shoots (approximately 3 per plant); unfortunately it was recurrently attacked by ants which extensively damaged the plant.

In the pilot-scale study, the ornamental species development was dependent on the flow regimen. *Z. aethiopica* had a survival rate of 100% under the two flow regimen but had faster and better plant development in the HFCW in comparison to the VFCW. This difference was documented through the significantly higher production of leaves, shoots and flowers, leaf size and stem size (*Zurita et al. 2008*). Approximately 60 flowers were produced in the HFCW, in contrast, only 10 smaller flowers were produced in the VFCW. These results confirmed that this species possesses tolerance mechanisms to waterlogging which allowed for their vigorous growth in this type of CW. *S. reginae* and *A. africanus* also had a survival rate of 100% in the two types of wetlands. However they had better development in the VFCW with significantly higher production of leaves, leaf size and stem size as well as the number of flowers (*Zurita et al. 2009*). Five of the six plants of *S. reginae* flowered in the VFCW and the flowers reached a noticeable higher size. In the HFCW only three of the six plants flowered during the study. All the
plants of *A. africanus* flowered in the two types of CW, but in the HFCW the flowers withered very quickly and the stems lost rigidity. These results suggest that these two species can not survive in flooded conditions. *A. Andreanum* showed a different development in the pilot scale study in comparison to the lab-scale one. In the lab-scale this species had a survival rate of 100% while in the pilot scale the plants survived only around 6 months, so after the 1-year period of experimentation, the survival rate was 0%. This was due to the fact that this sensitive species was more exposed to environmental conditions in the pilot scale such as low temperatures during the coldest months, dust, wind current etc. which affected negatively its development; in the lab-scale study it was more protected because the system was surrounded by buildings and trees within the university.

*C. hybrids* and *H. dumortieri* were not included in the pilot-scale study because it was well documented that the *C. hybrids*’ flowers do not possess any commercial value in Mexico and *H. dumortieri*, is particularly susceptible to pests. Consequently, *A. africanus* was included in the pilot scale evaluation in order to increase the number of evaluated species.

### Pollutant removal rate

The concentration of pollutants in the influents at both lab-scale study and pilot-scale study are shown in Table 1 and are discussed below.

**BOD and COD.** Reduction efficiencies for both BOD and COD were high in both the lab-study and the pilot scale wetland (Figure 3). In the lab-scale study, the average BOD removal rate was 73.85.1% with no significant difference among the cells (p = 0.180) while the average COD removal rate was 79.61.7% with no significant difference among cells (p = 0.178). In the pilot-scale study, the average BOD removal rates were significantly different at 77.94.0% and 81.94.0% for the HFCWs and the VFCWs, respectively, (p = 0.017). Similarly, the COD removal rate was significantly (p = 0.0194) higher in the VFCWs (80.32.5%) in comparison to the HFCW (76.32.5%). For both BOD and COD reductions, the type of plant was also significant (p = 0.0228).

The removal efficiencies observed in both scales of experimentation fall within the range reported in the literature (Kadlec & Knight 1996; Vymazal 2002, 2005a). These results demonstrate that the presence of ornamental plants do not decrease the capacity of CW to remove the organic load from DWW measured as BOD or COD. The higher removal efficiencies in the VFCWs were likely a result of the higher oxygen transfer into the subsurface of the system.

### Pollutant concentrations in the domestic wastewater used for the two experiments. Average ± 95% confidence interval; lab-scale study (n = 16), pilot-scale study (n = 36).

<table>
<thead>
<tr>
<th>Parameter (mg/L)</th>
<th>Lab-scale influent</th>
<th>Pilot-scale influent</th>
</tr>
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<tbody>
<tr>
<td>Biochemical Oxygen Demand (BOD)</td>
<td>50.6 ± 2.2</td>
<td>115.5 ± 15.7</td>
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<tr>
<td>Chemical Oxygen Demand (COD)</td>
<td>190.2 ± 7.7</td>
<td>247.5 ± 32.4</td>
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<tr>
<td>Total Suspended Solids (TSS)</td>
<td>10.9 ± 1.7</td>
<td>57.5 ± 12.7</td>
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<tr>
<td>Organic Nitrogen (Org-N)</td>
<td>27.6 ± 1.6</td>
<td>4.1 ± 1.0</td>
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<tr>
<td>Ammonium (NH₄-N)</td>
<td>8.8 ± 0.5</td>
<td>15.7 ± 0.8</td>
</tr>
<tr>
<td>Nitrate (NO₃-N)</td>
<td>12.7 ± 0.5</td>
<td>9.3 ± 0.9</td>
</tr>
<tr>
<td>Total Nitrogen (Total-N)</td>
<td>48.8 ± 2.6</td>
<td>28.7 ± 1.3</td>
</tr>
<tr>
<td>Total Phosphorus (Total-P)</td>
<td>10.0 ± 1.7</td>
<td>8.3 ± 1.2</td>
</tr>
<tr>
<td>Total Coliform x 10⁵ (TC)*</td>
<td>7800 ± 2700</td>
<td>4700 ± 1800</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>19.3 ± 0.2</td>
<td>21.1 ± 0.5</td>
</tr>
<tr>
<td>pH</td>
<td>7.9 ± 0.02</td>
<td>7.4 ± 0.07</td>
</tr>
<tr>
<td>Solids (TSS)</td>
<td>6.8 ± 0.10</td>
<td>5.7 ± 0.15</td>
</tr>
<tr>
<td>Dissolved Oxygen (DO)</td>
<td>0.18 ± 0.05</td>
<td>0.0 ± 0.0</td>
</tr>
</tbody>
</table>

* MPN (Most Probable Number).

**Total suspended solids (TSS).** The average removal efficiency of TSS in the lab-scale study was nearly 100% perhaps due to the low TSS concentration in the influent (10.9 mg L⁻¹) due to the front end sedimentation unit (Zurita *et al.* 2006). For the pilot-scale study, contrary to what

![Figure 3](https://iwaponline.com/wst/article-pdf/63/4/654/445410/654.pdf)
occurred with BOD and COD, the average TSS reduction was significantly (p<0.001) higher in the HFCWs (81.66.4%) compared to the VFCWs (61.56.2%). These results confirm that TSS are removed by physical processes (sedimentation and filtration) rather than biological processes as the water flowed quickly through the 1.2 cm-size tezontle substrate in the VFW.

**Total nitrogen (TN).** In the lab-scale study, high average removal rates of TN were obtained with no significant differences seen among the cells (Figure 4). The average TN removal percentage in the lab-scale study was 72.95.5%. In contrast, the reduction of TN in the pilot-scale study was lower for both type of wetlands (Figure 4) without significant difference (p=0.271). The mean values were 49.38.6% and 52.78.6% in the VFCWs and the HFCWs respectively. One possible reason the TN reductions were higher in the lab-scale study may be due to the low BOD in the influent. When BOD is high, the nitrifying bacteria and heterotrophic bacteria may compete for the limited oxygen (Verhagen et al. 1992; Vaillant 2005). Possibly, the lower TN loading rate in the pilot-scale (1.1 g m⁻² d⁻¹) in comparison to that applied at the lab-scale (1.4 g m⁻² d⁻¹) contributed to the relatively lower percentage reductions in the pilot-scale study as suggested by Kadlec & Knight (1996).

**Total phosphorus (TP).** TP removal rates were very high in the lab-scale experiment (Figure 4) resulting in an average value of 70.34.9% with significant difference between plant type (p=0.045). The cell planted with Z. aethiopica showed the higher removal rate of TP (Zurita et al. 2006). In the pilot-scale study, the TP removal rates were lower with significant difference between vertical and horizontal subsurface flow wetland cells (p<0.001). This difference could be related to the bigger size of substrate used at pilot-scale study. The smaller-size substrate in the lab-scale experiment contains a higher overall surface area available for the phosphorous sorption (Stottmeister et al. 2005) which resulted in higher TP reductions. In the HFCWs the average removal rate was 40.24.7% while in the VFCW, the average removal rate was 50.14.7% (Figure 4). The type of plant was also significant (p=0.015) as well as the interaction between the type of flow and the type of plant (p=0.002). The most effective systems were the HFCW planted with Z. aethiopica and the VFCW planted with Anthurium-Agapanthus-Strelitzia. The plants exhibited greater growth in these two systems which suggests a higher P uptake.

**Total Coliforms (TC).** The average TC removal rate was 99.30.05% in the lab-scale experiment with a statistical difference for plant type (p=0.009). The cell planted with A. andreanum was the least effective for TC removal. In the pilot-scale study, the average TC removal efficiency was 96.91.6% and 92.71.6% in the VFCWs and the HFCWs, respectively. As expected, the difference between the type of wetland was significant (p<0.001), the higher reductions in the VFCWs may have been due to the major abundance of predators generally found with higher oxygen (García et al. 2003; Edwards et al. 2006; Wand et al. 2007). The lower reductions for the pilot-scale HFCWs was likely due to several factors, such as the lower water temperature (the water temperature dropped from 21.1°C in the influent to 18.9°C in the effluent), less available oxygen and the higher substrate size (Quiñonez-Díaz et al. 2001; García et al. 2003; Vymazal 2005b, Edwards et al. 2006). There was not a significant difference among plant type for TC reduction.

**CONCLUSIONS**

This work demonstrates that it is possible to substitute the conventional wetland macrophytes (cattail, bulrush and reed), for commercially valuable ornamental plants without decreasing the overall treatment efficiencies of the subsurface flow constructed wetlands fed with domestic wastewater. In general, the treatment efficiencies for the pollutants evaluated at both scales of experimentation fall within the range of results reported in the literature for constructed wetlands planted with conventional wetland macrophytes. The use of ornamental plants is feasible in developing countries with warm climate where the richness of biodiversity allows the selection of a range of species which may be compatible for use in treatment wetlands. In this regard, future work should expand on this work by evaluating a wider variety of...
ornamental plants for both flower production and effective wastewater treatment. The ability to utilize a greater number of ornamental species seems more promising in the VFCWs because the conditions in this type of wetland are more similar to the conditions preferred by terrestrial plants with greater oxygen concentrations in the root zone. However, this type of CW is generally more expensive and therefore may not be the preferential system adopted in developing countries. It is possible also to find species able to tolerate and flourish to the continuously flooded conditions characteristic of HFCWs, such as did Z. aethiopica in this study. In this way, ornamental flower production in CWs can be used to provide an additional value to building and maintaining treatment wetland systems in developing countries. The treated water can then be used for different purposes such as agricultural irrigation. Nevertheless, additional work is required to overcome the challenges of getting individuals as well as local governments to embrace CW in developing countries. The additional economic benefit provided by using ornamental flowers in these systems may help convince them into investing in these systems.

REFERENCES