Performance of Laboratory-Scale Wetlands Planted with Tropical Ornamental Plants to Treat Domestic Wastewater

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This work proposes an innovative wastewater treatment system that consists of a constructed subsurface flow wetland planted with ornamental flowers of high market value. In addition to the benefit of the water treatment, this cash crop provides a profitable business by producing commercial flowers that can meet all biological and safety requirements in order to be commercialized. This characteristic of the treatment system makes it very valuable for application in developing countries. Five different species of ornamental plants were studied from September 2004 to January 2005. Several water quality parameters were evaluated at the inlet and outlet of a laboratory-scale system. COD was reduced by more than 75% in all cases; BOD and nitrogen were removed by more than 70%, except in one cell; phosphorus was reduced by more than 66% and the dissolved oxygen increased from 0.175 to 5.8 mg L⁻¹. Total and fecal coliforms were removed in the wetland by more than 99.3%. According to these results, it is feasible to couple ornamental flower production with wastewater treatment. A pilot-scale study is recommended in order to validate the preliminary results under more realistic conditions.

Key words: ornamental plants, constructed wetlands, subsurface wetlands, wastewater treatment, municipal wastewater, Lake Chapala

Introduction

The world is experiencing significant growth in human population, and fresh water is becoming a scarce resource. Lakes represent a major source of such fresh water, but are coming under increasing pressure through exploitation by agriculture, industry, drinking water and hydroelectricity generation. This is particularly the case in tropical developing countries.

Many authors (Ryding and Rast 1989; Welch 1992; Maniak 1997) suggest that the most effective long-term measure for the control of eutrophication in a water body is the reduction of the input of external nutrients. One way to reduce the nutrients coming from point sources, is to remove them by biological treatment. Unfortunately, the cost of installation and operation of a wastewater treatment plant (WWTP) does not permit the municipal governments of developing countries to invest in such technologies (Kivaisi 2001; Belmont et al. 2004).

Lake Chapala is the most important natural lake in Mexico and the main fresh water supply for Guadalajara City. The primary tributary to Lake Chapala is the Lerma River. Large quantities of domestic, agricultural and industrial sewage from the entire Lerma-Chapala basin still flow untreated into the watershed and eventually into the lake, resulting in excessive inputs of phosphorus (P) and nitrogen (N), both known to cause eutrophication (de Anda and Shear 2001). Human water demand from Lake Chapala surpasses the surface supply and groundwater recharge rate (de Anda et al. 1998). This has resulted in a hydrologic imbalance in the lake basin. In addition, high nutrient concentrations in the lake have led to degraded water quality, resulting in growth of floating aquatic vegetation and blue-green algae. The adverse environmental impacts are clearly reflected in the considerable reduction of native and migratory fauna and in the severe reduction of the water storage volume.

A solution to reduction of the severe environmental impacts and eutrophication of Lake Chapala is to develop a cost-effective treatment technology, namely a constructed subsurface flow wetland (SSWF), which could permit a significant reduction of nutrient contamination along the Lerma River and around the lake shore. The proposed treatment system is less expensive than the existing commercial systems, and is easier to build and operate (Linsley et al. 1992; Seoánez-Calvo 1999; Kivaisi 2001; Belmont and Metcalfe 2003; Dallas 2004). SSWF are useful not only for the control of pollution with nutrients but also to remove persistent organic pollutants from wastewater and runoff (Belmont et al. 2006).

This sewage treatment system allows the development of a profitable business by producing commercial ornamental flowers that meet all biological safety requirements in order to be delivered to the market.
Because of the subtropical climatic conditions of the area, it is possible to maintain flower production all year long. The great advantage of the constructed wetlands operating with ornamental plants is that they represent an economical alternative for developing countries, where the wastewater treatment represents a large expenditure of the municipal budget (Belmont and Metcalfe 2003; Belmont et al. 2004).

Materials and Methods

Laboratory-Scale Wetland

The laboratory-scale study was carried out on the campus of the University of Guadalajara at Ocotlan City. This campus is located close to the east shoreline of Lake Chapala. The climate in the area is classified as warm and wet with rainfall in summer (ACw). The altitude of the area is between 1530 and 1600 m amsl. The main economic activities in the area are agriculture, cattle, furniture manufacturing, and chemical and food processing industries (INEGI 2004). Ocotlan City alone produces close to 500 L s⁻¹ of wastewater, but only 50% is treated by using conventional extended aeration treatment systems (CEAS 2004).

The laboratory-scale experiments were carried out in cells, simulating a system of constructed wetlands, including a pretreatment consisting of settling of solids at the inlet of the system (Fig. 1).

For the sedimentation process, acrylic cells measuring 100 × 30 × 25 cm (L × W × H) were used. For the subsurface flow wetlands, plastic cells of 67 × 37 × 30 cm (L × W × H) and acrylic cells of 80 × 30 × 25 cm (L × W × H) were filled with a volcanic red-orange or red-yellow extrusive rock commonly named tezontle (from the native word in “nahuatl” language “tezontli”) as substrate. Tezontle and basalt rocks have the same chemical compounds, but tezontle is a rock with a highly porous surface area and low hardness and density. The high content of iron dioxide and the high porosity of tezontle make it a good candidate as substrate for SSFWs. The substrate used had a porosity of 0.53 and an average diameter of 1 cm. The water level was maintained 5 cm below the surface of the substrate. The sewage flow was maintained between 3.5 and 5.5 mL min⁻¹ in order to maintain a mean retention time of 4 d in each of the cells. The hydraulic retention time (HRT) was calculated by using the following equation (U.S. EPA 1993; Kadlec and Knight 1996; Lara-Borrero 1999):

\[ \text{HRT} = \frac{L W y}{\eta Q} \]  

Five cells were studied; each cell was planted with one different monocotyledonous ornamental plant. The ornamental plants were acquired from a nursery located near the university campus. The plants were fed with diluted sewage over three weeks. Anthurium andreanum was protected with shade due to its sensitivity to direct sunlight. The rest of the plants were fully exposed to the sun.

Sampling and Analyses

The monitoring period of the experiment was from September 2004 to January 2005. During this period, chemical and biological water quality parameters were measured as described in the Standard Methods for the Examination of Water and Wastewater (APHA 1998). A potentiometer ORION model 410-A plus was used to measure pH.

Data Analysis

The statistical analysis of results (ANOVA) was performed using the software Statgraphics Plus 4.0.

Results

Plant Growth

All plants developed well during the study period. Zantedeschia aethiopica and Canna hybrids showed a faster growth and higher embryo production. Zantedeschia aethiopica produced a much higher number of flowers. This plant flowered throughout the study period and increased its production of flowers during the colder months (December and January). Anthurium andreanum is a plant with a high market value but with low flower production. Therefore, it was planted in the system already in flower from origin. It did not produce new flowers during the study but yielded several embryos that were easy to remove and able to produce new plants. Strelicia reginae develops very slowly and produced only new leaves in the laboratory cell. This particular plant did not show stable development during the period of study. Hemerocallis dumortieri showed good development, producing several embryos, but unfortunately it was recurrently attacked by ants which extensively damaged the plant. Nevertheless, the plant recovered its structure without flower production during the period of study.
Water Analyses

The results of the water analyses performed on the influent and the effluents of the five cells are presented in Table 1. The measured water quality parameters showed an important variation due to perturbation caused by the rainfall period. Additionally, the water presented chemical and biological variations because the wastewater was stored in a closed drum for seven days before it was used to feed to the system.

The characteristics of the wastewater at the influent were similar to weak domestic sewage according to Metcalf and Eddy Inc. (1991) criteria, especially with respect to parameters such as chemical oxygen demand (COD) at an average value of 190.2 mg L⁻¹; ammonium at 8.8 mg L⁻¹, total coliforms (TC) at 7.8 × 10⁶ MPN; biochemical oxygen demand (BOD) was 50% less than the reported value of 110 mg L⁻¹ for weak domestic sewage; and suspended solids (SS) were 10.9 mg L⁻¹ because of the previous settlement process for the wastewater before entering the wetland. Total nitrogen (TN) and phosphorus (P) concentration registered higher values. TN (sum of TKN and N-NO₃) showed an observed average value at the inflow of 48.8 mg L⁻¹. The average nitrate concentration was 12.7 mg L⁻¹ in disagreement with the fact that nitrate is usually absent in domestic wastewater. Phosphorus concentration was particularly high at 40.7 ± 3.5 mg L⁻¹. The average pH of 7.9 at the inflow was optimal for a treatment wetland. The average temperature was 19.3°C during the study period, the highest being 24.7°C and the lowest 11.9°C. Dissolved oxygen (DO) showed an average measured value of 0.18 mg L⁻¹ at the inflow. Table 2 shows the average removal values obtained in the entire study period. Table 2 also shows the average concentrations including only the data from November 26, 2004, to January 21, 2005, when the wetlands were stable.

**Biochemical oxygen demand.** During the study period, the BOD removal efficiency was above 70% in all cells, with the exception of cell 4 where the removal percentage was slightly less than 70% (Table 2). There was no significant difference between the cells ($p = 0.180$). In the last period, the average BOD removal efficiency was above 80%, again without significant differences between the tested cells ($p = 0.656$).

**Chemical oxygen demand.** There was no significant difference in the COD removal ($p = 0.178$) between cells. Throughout the study period, the COD removal ranged from 77.4 to 83.2% in all cells. In general, these removal efficiencies were higher than those found for BOD (Table 2). In the last period, the removal efficiencies were a little higher, reaching values from 78.5 to 86.6%. The increments of COD during the last part of the study were smaller than the increments observed for BOD.

**Nitrate.** The measured nitrate concentrations ranged from 2.5 to 4.2 mg L⁻¹ throughout the monitoring period. However, no statistically significant difference was found between cells ($p = 0.060$) at the 95% confidence level. The calculated $p$ was close to the limit where the difference could be considered significant. The removal efficiency ranged from 64.4 to 79.1%. The cells planted with *Zantedeschia aethiopica* and *Canna hybrids* showed better performance for nitrate removal than the other cells. The least effective cell was the one planted with *Anthurium andreanum*. In the last period of the study these removal efficiencies reached values from 84.0 to 87.3% without significant difference between all cells ($p = 0.225$).

**Ammonium.** The removal efficiencies ranged from 63.6 to 70.8% with no significant difference ($p = 0.468$) for

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**TABLE 1.** Water quality parameters measured in the influent and effluent of the five cells from September 2004 to January 2005

<table>
<thead>
<tr>
<th>Water quality parameter</th>
<th>Units</th>
<th>Influent</th>
<th>Cell 1 Strelitzia reginae</th>
<th>Cell 2 Zantedeschia aethiopica</th>
<th>Cell 3 Canna hybrids</th>
<th>Cell 4 Anthurium andreanum</th>
<th>Cell 5 Hemerocallis dumortieri</th>
</tr>
</thead>
<tbody>
<tr>
<td>PH</td>
<td>PU</td>
<td>7.9 ± 0.02</td>
<td>8.1 ± 0.02</td>
<td>7.7 ± 0.04</td>
<td>7.8 ± 0.04</td>
<td>8.1 ± 0.02</td>
<td>8.3 ± 0.03</td>
</tr>
<tr>
<td>Temperature</td>
<td>°C</td>
<td>19.3 ± 0.2</td>
<td>19.3 ± 0.2</td>
<td>19.3 ± 0.2</td>
<td>19.3 ± 0.2</td>
<td>19.3 ± 0.2</td>
<td>19.3 ± 0.2</td>
</tr>
<tr>
<td>DO</td>
<td>mg L⁻¹</td>
<td>0.18 ± 0.05</td>
<td>5.2 ± 0.2</td>
<td>6.0 ± 0.3</td>
<td>5.2 ± 0.2</td>
<td>5.2 ± 0.2</td>
<td>7.4 ± 0.2</td>
</tr>
<tr>
<td>BOD</td>
<td>mg L⁻¹</td>
<td>50.6 ± 2.2</td>
<td>13.2 ± 2.0</td>
<td>10.7 ± 1.0</td>
<td>9.8 ± 1.3</td>
<td>17.5 ± 2.7</td>
<td>16.1 ± 2.8</td>
</tr>
<tr>
<td>COD</td>
<td>mg L⁻¹</td>
<td>190.2 ± 7.7</td>
<td>39.8 ± 2.8</td>
<td>31.6 ± 2.0</td>
<td>35.2 ± 2.7</td>
<td>36.5 ± 2.7</td>
<td>36.0 ± 2.7</td>
</tr>
<tr>
<td>Nitrate</td>
<td>mg L</td>
<td>12.7 ± 0.5</td>
<td>3.5 ± 0.5</td>
<td>2.5 ± 0.3</td>
<td>2.7 ± 0.4</td>
<td>4.0 ± 0.7</td>
<td>4.2 ± 0.6</td>
</tr>
<tr>
<td>Ammonium</td>
<td>mg L</td>
<td>8.8 ± 0.5</td>
<td>2.6 ± 0.2</td>
<td>2.2 ± 0.2</td>
<td>2.2 ± 0.2</td>
<td>2.5 ± 0.1</td>
<td>2.4 ± 0.1</td>
</tr>
<tr>
<td>Organic-N</td>
<td>mg L</td>
<td>27.6 ± 1.6</td>
<td>6.4 ± 1.0</td>
<td>4.5 ± 0.3</td>
<td>5.4 ± 1.1</td>
<td>8.0 ± 1.7</td>
<td>5.6 ± 0.6</td>
</tr>
<tr>
<td>Total-N</td>
<td>mg L</td>
<td>48.8 ± 2.6</td>
<td>13.3 ± 1.8</td>
<td>9.2 ± 0.6</td>
<td>10.7 ± 1.9</td>
<td>15.8 ± 2.8</td>
<td>11.6 ± 1.0</td>
</tr>
<tr>
<td>TP</td>
<td>mg L</td>
<td>40.7 ± 3.5</td>
<td>11.8 ± 0.9</td>
<td>8.8 ± 1.3</td>
<td>9.0 ± 1.3</td>
<td>11.2 ± 0.8</td>
<td>11.8 ± 0.9</td>
</tr>
<tr>
<td>TSS</td>
<td>mg L</td>
<td>10.9 ± 1.7</td>
<td>&lt;1.0</td>
<td>&lt;1.0</td>
<td>&lt;1.0</td>
<td>&lt;1.0</td>
<td>&lt;1.0</td>
</tr>
<tr>
<td>Total coliforms × 10⁵</td>
<td>MPN</td>
<td>78,000 ± 13,000</td>
<td>9.8 ± 3.9</td>
<td>4.1 ± 2.9</td>
<td>1.2 ± 0.50</td>
<td>7.6 ± 4.2</td>
<td>5.9 ± 4.1</td>
</tr>
<tr>
<td>Fecal coliforms × 10⁵</td>
<td>MPN</td>
<td>19,000 ± 5200</td>
<td>5.5 ± 3.2</td>
<td>3.0 ± 2.7</td>
<td>0.49 ± 0.24</td>
<td>3.3 ± 1.9</td>
<td>0.27 ± 0.15</td>
</tr>
</tbody>
</table>

*Average ±95% confidence interval (n = 16).*
the whole study period. In the last study period (November to January), these removal efficiencies reached values between 76.3 and 77.5%. Ammonium removal was lower than nitrate removal. This behaviour occurred because ammonification proceeds more rapidly than nitrification (Kadlec and Knight 1996); at the same time ammonium is removed from the system through nitrification, the organic-N is transformed to ammonia through ammonification at a higher rate.

**Organic-N.** During the whole period of study the removal efficiencies reached values from 69.0 to 79.8%, without significant differences between cells ($p = 0.296$). During the last 2 months of the study the removal efficiencies reached values between 85.4 and 89.6%, without significant difference ($p = 0.499$).

**Total-N.** Along the period of study the removal efficiencies reached values from 66.4 to 77.9%, without significant differences between cells ($p = 0.205$). Additionally, the removal efficiencies reached values from 84.3 to 86.9% in the last 2 months of the study.

As observed in Table 1 and Fig. 2, the TN in cell 2 showed the lowest value, however there was no significant difference when compared to the rest of the cells. The average removal of the different forms of nitrogen was similar for *Zantedeschia aethiopica* and *Canna hybrids*. These removal rates were higher than those observed for the other three species. However, when comparing only the data for the last two months of the study, the removals are similar between all cells and showed higher values (Fig. 2).

**Total phosphorus.** Similar to the results for TN, the lowest TP concentrations were observed in cell 2 (*Zantedeschia aethiopica*) with a concentration of 8.8 mg L$^{-1}$ (Table 1). TP removal efficiencies ranged between 66.2 and 78.1% (Table 2) with significant difference between the cells ($p = 0.045$). Cell 2 (*Z. aethiopica*) showed the highest removal efficiency. In the months of lower temperature the system reached removal values from 78.5 to 81.2% ($p = 0.897$).

**Total suspended solids.** Total suspend solids (TSS) concentration was very low at the influent throughout the experiment, mainly due to the primary sedimentation of the raw wastewater. The average TSS measured at the inflow of the system was 10.9 mg L$^{-1}$ and the TSS concentration was always less than 1.0 mg L$^{-1}$ at the effluent.

**Total and fecal coliforms.** Significant statistical differences were found between measured total and fecal coliforms in the cells, where $p$ was equal to 0.009 and 0.002, respectively. The cell planted with *Anthurium andreanum* (cell 4) was slightly less efficient for total

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**TABLE 2.** Percent removal of contaminants for (a) the full study period, and (b) for only the last two months of the study$^{a}$

<table>
<thead>
<tr>
<th></th>
<th>Cell 1 Strelitzia reginae %</th>
<th>Cell 2 Zantedeschia aethiopica %</th>
<th>Cell 3 Canna hybrids %</th>
<th>Cell 4 Anthurium andreanum %</th>
<th>Cell 5 Hemerocallis dumortieri %</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>September 2004 to January 2005 (n = 16)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BOD</td>
<td>75.8 ± 3.1</td>
<td>77.7 ± 3.4</td>
<td>77.6 ± 3.7</td>
<td>67.0 ± 3.9</td>
<td>71.3 ± 3.7</td>
</tr>
<tr>
<td>COD</td>
<td>79.8 ± 1.4</td>
<td>83.2 ± 1.4</td>
<td>78.5 ± 2.2</td>
<td>77.4 ± 1.7</td>
<td>79.2 ± 1.7</td>
</tr>
<tr>
<td>Nitrate</td>
<td>71.6 ± 4.5</td>
<td>79.1 ± 2.6</td>
<td>79.0 ± 3.6</td>
<td>67.8 ± 5.3</td>
<td>64.4 ± 5.3</td>
</tr>
<tr>
<td>Ammonium</td>
<td>63.6 ± 5.1</td>
<td>70.8 ± 2.9</td>
<td>70.1 ± 2.2</td>
<td>64.6 ± 3.3</td>
<td>68.6 ± 2.6</td>
</tr>
<tr>
<td>Organic-N</td>
<td>75.0 ± 3.5</td>
<td>79.8 ± 2.5</td>
<td>78.6 ± 3.6</td>
<td>69.0 ± 4.9</td>
<td>72.7 ± 4.4</td>
</tr>
<tr>
<td>Total-N</td>
<td>71.2 ± 3.8</td>
<td>77.9 ± 2.5</td>
<td>77.1 ± 3.3</td>
<td>66.4 ± 4.9</td>
<td>71.7 ± 3.9</td>
</tr>
<tr>
<td>TP</td>
<td>66.5 ± 3.2</td>
<td>78.1 ± 3.0</td>
<td>74.3 ± 2.2</td>
<td>66.6 ± 4.0</td>
<td>66.2 ± 4.5</td>
</tr>
<tr>
<td>TSS</td>
<td>100.0$^{b}$</td>
<td>100.0$^{b}$</td>
<td>100.0$^{b}$</td>
<td>100.0$^{b}$</td>
<td>100.0$^{b}$</td>
</tr>
<tr>
<td>Total coliforms</td>
<td>99.88 ± 0.03</td>
<td>99.96 ± 0.02</td>
<td>99.98 ± 0.01</td>
<td>99.79 ± 0.09</td>
<td>99.95 ± 0.02</td>
</tr>
<tr>
<td>Fecal coliforms</td>
<td>99.84 ± 0.05</td>
<td>99.92 ± 0.04</td>
<td>99.96 ± 0.02</td>
<td>99.35 ± 0.30</td>
<td>99.94 ± 0.04</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Cell 1 Strelitzia reginae %</th>
<th>Cell 2 Zantedeschia aethiopica %</th>
<th>Cell 3 Canna hybrids %</th>
<th>Cell 4 Anthurium andreanum %</th>
<th>Cell 5 Hemerocallis dumortieri %</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>November 26, 2004, to January 21, 2005 (n = 6)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BOD</td>
<td>85.0 ± 1.4</td>
<td>84.1 ± 2.2</td>
<td>86.6 ± 2.8</td>
<td>82.3 ± 1.1</td>
<td>84.1 ± 1.1</td>
</tr>
<tr>
<td>COD</td>
<td>82.7 ± 1.4</td>
<td>86.6 ± 1.3</td>
<td>85.7 ± 1.9</td>
<td>78.5 ± 1.9</td>
<td>85.5 ± 1.8</td>
</tr>
<tr>
<td>Nitrate</td>
<td>85.9 ± 0.8</td>
<td>86.9 ± 0.8</td>
<td>87.3 ± 1.0</td>
<td>84.6 ± 1.5</td>
<td>84.0 ± 1.5</td>
</tr>
<tr>
<td>Ammonium</td>
<td>77.5 ± 1.7</td>
<td>77.0 ± 2.9</td>
<td>77.2 ± 1.0</td>
<td>76.3 ± 2.9</td>
<td>77.4 ± 1.6</td>
</tr>
<tr>
<td>Organic-N</td>
<td>88.0 ± 1.2</td>
<td>88.2 ± 1.5</td>
<td>89.6 ± 0.7</td>
<td>85.4 ± 2.9</td>
<td>87.5 ± 1.0</td>
</tr>
<tr>
<td>Total-N</td>
<td>85.6 ± 1.0</td>
<td>86.0 ± 1.3</td>
<td>86.9 ± 0.7</td>
<td>85.2 ± 1.4</td>
<td>84.3 ± 0.9</td>
</tr>
<tr>
<td>TP</td>
<td>78.5 ± 1.7</td>
<td>80.2 ± 1.8</td>
<td>79.5 ± 2.1</td>
<td>81.2 ± 1.4</td>
<td>79.9 ± 2.0</td>
</tr>
</tbody>
</table>

$^{a}$Average ±95% confidence interval.

$^{b}$All measured outlet concentration where <1 mg L$^{-1}$. 

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*Average removal rates were higher than those observed for the other three species. However, when comparing only the data for the last two months of the study, the removals are similar between all cells and showed higher values (Fig. 2).*
Dissolved oxygen. Dissolved oxygen is one parameter that normally is adjusted by using mechanical systems at the end of a typical constructed wetland (U.S. EPA 1993). In the laboratory tests DO concentration at the effluent presented significant differences between cells with \( p = 0.000 \). In general, all cells showed a high average DO concentration, ranging from 5.2 to 7.4 mg L\(^{-1}\). The high oxygenation of the system was attributed to the good oxygen exchange process reached in the roots-aqueous phase, but probably also to the high porosity in the substratum used which improves the transport of the dissolved species by increasing the adsorption-desorption rates. Cell 5 presented the highest DO concentration; values reached in cells 1, 3 and 4 were practically the same. This result indicates that the species used in the wetland may play an important role in the oxygenation process of the system.

PH. The pH of the wastewater changes with significant differences during the movement through the SSFW in all cells. A slight reduction of pH was observed in cells 2 and 3 by 0.2 (\( p = 0.008 \)) and 0.1 (\( p = 0.03 \)) units, respectively. In cell 1 and 4, an increment of 0.2 pH units (\( p \) equal to 0.0000 and 0.0005, respectively) was observed. In cell 5, the observed increments reached 0.4 pH units (\( p = 0.000 \)).

Discussion

Some characteristics of concern with respect to the domestic wastewater used in this work are about nutrient concentration. Of special interest was the high concentration of nitrate which normally is not present in domestic sewage and represents a public health risk when discharged in surface waters.

Within the Ocotlan City, there are many dairy factories with small- and medium-sized production capacities that discharge their wastewater into the municipal sewer system without treatment; the effluents generated in this kind of factory can contain TN values as high as 2500 mg L\(^{-1}\) (Arrojo et al. 2003). TN in these effluents is composed mainly of organic nitrogen and a small percentage of it can be converted at a slow rate to ammonium by bacterial decomposition and hydrolysis under anaerobic conditions (Kadlec and Knight 1996; McGechan et al. 2005), and later to nitrate under low values of DO, even down to about of 0.3 mg L\(^{-1}\) (Reddy and Patrick 1984) in the municipal sewer system. Due to the high concentration of TN in dairy factory effluent and the large number of factories present in Ocotlan City, it is possible that they are the source of nitrates present in the domestic wastewater. The phosphorus sources in municipal wastewater are dissolved organic matter and dissolved detergents. In Mexico the phosphate concentration in detergents and special industrial cleaners is not regulated. Furthermore, the dairy factories are a great source of TP and TN (Arrojo et al. 2003).

BOD and COD are the two parameters most used to measure the content of organic matter in wastewater and different authors have assessed the effects of emergent plants on their removal in SSFW, but the existing information is contradictory (Karathanasis et al. 2003). Previous studies have shown that the presence of plants or species planted did not affect the BOD and COD removal in SSFW (Ayaz and Akca 2001; Belmont and Metcalfe 2003; Belmont et al. 2004). In this case, all cells showed good performance for BOD removal due mainly to the low strength of domestic wastewater utilized (Klomjek and Nitisoravut 2005); the removal efficiency is in the removal range observed for SSFW planted with typical plant species such as *Thypha and Phragmites* (Kadlec and Knight 1996; Seoánez-Calvo 1999; Crites and Tchobanoglous 2000; Klomjek and Nitisoravut 2005).

The COD removal efficiency, was higher than the values reported in other works of SSFW planted with ornamental plants (Belmont and Metcalfe 2003), where a removal efficiency of 35.1% of COD was observed with 2 days HRT by using *Zantedeschia aethiopica* in a lab-scale wetland under greenhouse conditions. The higher removal efficiency encountered in this work was due to its higher HRT, higher average temperature, and it used a different substratum that could also influence the removal efficiency due to the iron dioxide-rich chemical composition. Moreover, in a pilot-scale system, García et al. (2004) obtained COD removal efficiencies ranging between 62 and 79% in a horizontal subsurface
The comparison of TN removal throughout time for the five species of ornamental plants showed that the cells planted with *Z. aethiopica* and *C. hybrids* stabilized faster than the other cells (Fig. 2). This observation suggests that *Z. aethiopica* and *C. hybrids* adapt better to the low oxygen conditions of the SSFW flooded with wastewater than the other ornamental plants. However, in the long term, the five species perform similarly in the removal of nitrogen, which agrees with previous studies (Belmont and Metcalfe 2003; Belmont et al. 2004). It is recommended that the SSFW planted with *Anthurium*, *Strelitzia* and *Hemmerocallis* are to be flooded with clean water until the plants are well established in the wetland before introducing wastewater.

Figure 3 shows that COD removal was similar for all cells during the whole period of the study. Similar to TN, the COD removal was more stable and reached higher values at the end of the study, however, faster stabilization of the cells planted with *Z. aethiopica* and *C. hybrids* was shown.

The TP removal rates observed in this study are higher than those reported in the literature for other artificial wetland systems (Seoánez-Calvo 1999) where the reported values are between 20 and 60%. One possible explanation for the higher removal efficiencies could be the contribution of the mineral component content in the volcanic rocks used as substratum in the cells. This kind of rock is normally rich in iron dioxide, and its porosity is very high in comparison to other substrates used in typical SSFW such as gravel. Furthermore, the plants tested showed a rapid growth and firmness of their roots giving stability to the plant structure. This characteristic induces additional physical and chemical mechanisms to remove phosphorus such as adsorption, ion exchange, flocculation and settling. Such substratum could adsorb close to 80% of the removed phosphorus in an artificial wetland (Ramírez 2003). These features facilitate the nutrient uptake by plants (Qi et al. 2004) inducing their vigorous growth. Normally the phosphorus removal by this mechanism reaches a limit once the plants have matured, but the
removal efficiency could be increased by planting ornamental plants in a constructed wetland because the flowers are continuously harvested for commercial purposes.

Bacteria removal in constructed wetlands is assumed due to a combination of a large number of complex chemical, physical and biological mechanisms (Vaca et al. 2005). In this work, the TC removal and FC removal were higher than 99% in all cells. This value is considered a typical value in a well-designed and operated WWTP (Dallas et al. 2004). The high removal of TC and FC in all cells was, in part, a result of the correct HRT of 4 d and utilized porous substrate, both of which are considered key factors for microbial removal (Garcia et al. 2003, 2004). The high concentration of DO was important as well, because in this condition, bacteria removal through oxidation is more likely to occur (Decamp and Warren 2000). The significant difference of bacterial removal among all cells is in accordance with Soto et al. (1999) who have found that the type of plant affects this parameter because substrate and plants exert a strong selective influence on the microbial community in constructed wetlands (Vaca et al. 2005). The relatively less efficient cell was cell 4, which was planted with Anthurium andreanum.

Conclusions

The use of five different species of ornamental plants with commercial interest (Strelitzia reginae, Zantedeschia aethiopica, Canna hybrids, Anthurium andreanum and Hemerocallis dumortieri) in lab-scale SSFW was evaluated. BOD, COD and Total-N removal efficiencies were above 70% in each monitored cell, except for the cell planted with Anthurium andreanum. The phosphorus removal efficiency was above 66% in all cells. Even though no significant difference between the performances of plants was observed for almost all the studied parameters, Zantedeschia aethiopica and Canna hybrids adapted better to the SSFW and the maximum performance of the treatment was reached faster. The volcanic extrusive rock commonly named tezontle, which has a high content of iron dioxide, was used as substratum in laboratory-scale subsurface constructed wetlands. As expected, high removals of phosphorus were observed. The results showed the effectiveness of using ornamental plants in the treatment wetland for removal of the monitored contaminants as well as the feasibility of producing a variety of ornamental flowers in this kind of treatment system. In general, the observed performance was very similar to that measured in constructed SSFW planted with typical wetland plants such as cattails (Typha spp.) and bulrush (Scirpus spp.), which have been studied extensively.

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References


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Abbreviations

ANOVA Analysis of variance between groups
BOD Biological oxygen demand
COD Chemical oxygen demand
DO Dissolved oxygen
HRT Hydraulic retention time
L Length of the cell, m
NH₃-N Ammonium nitrogen
NO₃-N Nitrate nitrogen
Q Average flow through the cell, m³ d⁻¹
SSFW Subsurface flow wetland
TN, Total-N Total nitrogen
TKN Total Kjeldahl nitrogen
TP Total phosphorus
TSS Total suspended solids
W Width of the cell, m
WWTP Wastewater treatment plant
Y Depth of the cell, m
η Porosity of the substratum