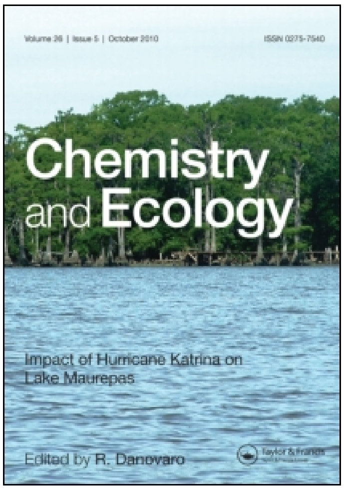

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Free water surface constructed wetlands for domestic wastewater treatment: A tropical case study

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Free water surface constructed wetlands for domestic wastewater treatment: A tropical case study

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The performance of three free water surface constructed wetlands in treating domestic wastewater was examined. One unit was planted with *Scirpus grossus* (L2), one was planted with *Typha angustifolia* (L3), and the unplanted third (L1) was the control. Biological oxygen demand (BOD_5), nitrate (NO_3-N), ammonium (NH_4-N), total phosphorus (TP), and total suspended solids (TSS) of influent and effluent were regularly measured. The average BOD_5 removal efficiencies were 44%, 68%, and 54% for units L1, L2, and L3, respectively. The plant growth was continuously monitored in marked quadrats by measuring the shoot height and other growth parameters. The above-ground biomass of L2 and L3 was harvested 8 months and 11 months after the planting date when the plants reached the maximum shoot height and at the start of inflorescence formation. *S. grossus* was superior to *T. angustifolia*, with faster establishment, higher productivity, and higher removal of BOD_5. However, the growth of *S. grossus* was possibly inhibited by continuously high NH_4^+ concentrations, while *T. angustifolia* showed tolerance of high NH_4^+ concentrations.

Keywords: Ammonia; Developing country; Harvesting; Plant growth; *Scirpus grossus*; *Typha angustifolia*

1. Introduction

The use of constructed wetlands for wastewater treatment is becoming widespread throughout the world due to the demand for water-quality improvement and the increasing need for wastewater reclamation and reuse [1, 2]. The constructed wetland system is attractive due to its uncomplicated technology, low capital costs, and minimal maintenance requirements. This makes it ideal in resource-scarce developing countries where it is, currently used for domestic, non-toxic and also toxic wastewater treatment—for instance, in developing countries

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like Sri Lanka, Tanzania, Mexico, China, Kenya, Uganda, etc. [3–6]. In developed countries, constructed wetlands are mainly utilized for the improvement of water quality for preserving natural eco-systems. In these countries constructed wetlands are often used to treat wastewaters before release to natural water bodies like lakes and rivers. However, in the developing world, constructed wetlands would initially be more likely to be targeted towards better quality of water for human use. A secondary benefit is the possibility of sustainable harvesting by cropping biomass and utilizing this harvested plant material for cottage industries such as matting, weaving, and medicinal applications—a potential income source [7].

Although, most developing countries are located within tropical and sub-tropical climatic conditions, the adaptation of wetland treatment technology in these countries has been surprisingly slow. Tropical climatic conditions are conducive to rapid plant growth. Such conditions can support a continuous growing season and higher biological activity can be expected compared to temperate conditions [1, 7] resulting in more efficiently constructed wetlands for treatment of pollution. Although a number of studies have been conducted in tropical regions [4, 6, 8], further research on many design parameters is needed to optimize the treatment ability of these systems. While numerous plant species have been included in various wetland systems [2, 9, 10], few studies have produced comparative data [2, 10] on which to evaluate the relative effectiveness of different plant species in improving water quality and plant management (i.e. harvesting) in constructed wetlands.

The present study, conducted in Sri Lanka, is part of a larger investigation into the management options for enhancing municipal wastewater treatment in tropical regions using natural and constructed wetland technology. From the data presented here, we will extrapolate and speculate on the viability of two emergent macrophyte species in biological nutrient-removal processes and their potential application for on-site wastewater treatment and for small communities. The set of design guidelines derived from this experimental study will be of great relevance to Sri Lanka and other tropical developing-world contexts.

2. Materials and methods

The constructed wetland was built to treat wastewater from a student dormitory at the University of Peradeniya, Sri Lanka. The system, which was designed to function as a free water surface wetland, consisted of three units (see figure 1). Two of them were planted with similar initial wet weights of rhizomes (initial shoot density: 4 shoots m^{-2}) of *Typha angustifolia* L. (Typhaceae) or *Scirpus grossus* L. (Cyperaceae). The third, unplanted unit was used as the control. The units were rectangular (1 × 25 m), and the depth of the medium was 0.6 m where the top soil layer (0.1 m) supported vegetation and below this was the gravel-based medium (0.5 m). The primary-treated wastewater supply was fed into the units by gravity flow, and the inlet hydraulic retention time (HRT) was expected to be around 18 h (calculated based on [2, 9]). A layer of impervious Type 1000 polythene ground lining was installed to minimize flow loss due to seepage. The flow path through the operational systems was assumed to be horizontal.

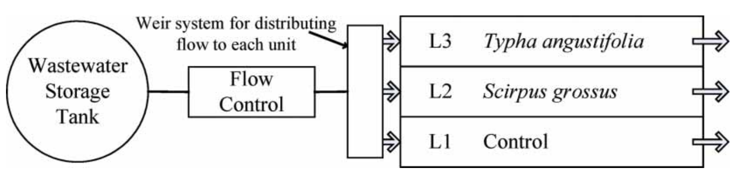

Figure 1. Schematic diagram of the treatment system.

The system was planted with *S. grossus* and *T. angustifolia* at the end of May 2004 and began running in early June 2004 with continuous wastewater feeding. Two quadrats were made near the inlet and outlet. The area of each quadrant was 1 m^2, and the quadrats were located 8 m and 16 m from the inlet. The locations were selected to calculate the average growth variation along the channel. Growth of the plants (shoot height, shoot density, number of leaves, and shoot diameter) within these two quadrats was measured once every two weeks. Influent and effluent flow rates were controlled by a valve system followed by a broad individual weir system. Flow rates were maintained after calibrating the weirs and were monitored weekly to achieve a constant flow rate for each unit. The average flow rate was maintained at around 13 m^3 d^{-1}, and the water depth of the free water surface was maintained at around 0.1 m throughout the study period. The average temperature and pH of influent wastewater were 24 ± 2.3 °C and 7.1 ± 0.31, respectively. The system was harvested by cutting shoots around 0.1 m above the water surface. Harvesting was carried out after 8 months (in January 2005) and 11 months (in April 2005) because it was assumed that the system was in a plateau condition – based on observations of plant growth height variation and start of inflorescence formation.

Monthly water-quality parameters were measured at the inlet and the outlet of each of the troughs from June 2004 to April 2005. Influent and effluent samples from each unit were collected in sterile 1 l Nalgene bottles. Approximately 200 mL of the sample was used to measure the temperature and pH at the time of collection using a multi-parameter water quality monitoring system (Horiba Instruments, U20XD Series) equipped with appropriate probes following standard methods [11]. The remaining portions of the samples were quickly transported to the laboratory and stored at 4 °C until processing. Samples were analysed for total suspended solids (TSS) and biological oxygen demand (BOD_5) following standard methods [11]. Samples were then filtered through a 0.45 μm membrane filter (Millipore) for the analysis of total dissolved phosphorus (ascorbic acid method), ammonia (salicylate method), and nitrate (UV-spectrophotometric screening method).

Soil samples were taken from the medium at a depth of around ~10 cm below the soil surface (root zone). The soil nitrogen content was determined using the total Kjeldahl nitrogen (TKN) method. The TKN method is based on the wet oxidation of soil organic matter using sulphuric acid as a digestion catalyst and conversion of organic nitrogen to the ammonium form. These parameters were determined following standard methods [11]. Water-quality data were analysed using repeated-measures ANOVA (SigmaStat version 3.11, Systat software 2004) for each unit to compare the effect of vegetation on water-quality parameters.

3. Results and discussion

3.1 *Wastewater treatment*

Removal efficiencies of BOD_5 (see table 1) were examined for the whole study period, and it was noted that the average BOD_5 removal efficiency after the first 3 months was higher and more stable than the BOD_5 removal efficiency during the first 3 month period. It can be assumed that it took around 3 months for the system to acclimatize and to develop a microbial ecosystem. Free water surface wetlands are efficient users of external carbon sources, as revealed by higher reductions in BOD_5. A fraction of the influent carbon compounds is dissolved in the influent, while the rest remains in the form of particulate matter. Particulate matter typically is found in the inlet zone of a wetland. The soluble carbon compounds are removed by microbial growth on the medium surfaces and attached to the plant roots and rhizomes penetrating the bed [12]. Tropical conditions with relatively constant high temperatures made the biological reactions faster. It was found that the effluent BOD_5 was significantly lower (table 1) than the

Table 1. Average removal of BOD_5, TSS, and TP.

	Influent	L1 effluent (control)	L2 effluent (*S. grossus*)	L3 effluent (*T. angustifolia*)
Average removal of BOD_5 during first 3 months (June 2004 to August 2004)				
BOD_5 (mg l^{-1}) during first 3 months	64.6 ± 7.2	44.9 ± 6.7	35.8 ± 12.4	34.4 ± 12.1
Removal efficiency (%)		30.50	44.60	46.70
Average removal of BOD_5 after establishment (September 2004 to April 2005)				
BOD_5 (mg l^{-1}) after establishment	60.4 ± 6.2	33.5 ± 4.8	19.2 ± 4.0	27.6 ± 5.4
Removal efficiency (%)		44.50	68.20	54.30
Average TSS and TP removal in different units (September 2004 to April 2005)				
Total suspended solids (mg l^{-1})	162.7 ± 31.4	57.4 ± 22.9	45.8 ± 22.8	39.1 ± 17.4
Removal efficiency (%)		64.70	71.90	76.00
Total phosphorus (mg l^{-1})	1.68 ± 0.51	1.54 ± 0.74	1.36 ± 0.69	1.43 ± 0.15
Removal efficiency (%)		8.30	19.00	14.90

Note: Concentration values are given as mean ± standard deviation (mg l^{-1}).

influent BOD_5 for all units after 3 months ($p < 0.001$). The L2 unit showed a significantly higher BOD_5 removal efficiency than L1 ($p < 0.001$) and L3 ($p < 0.01$). Therefore, it can be assumed that *S. grossus* performs better in terms of BOD_5 removal than *T. angustifolia.* This could be due to the higher root oxygen release potential (not measured in the present study) of *S. grossus* in contrast to *T. angustifolia* and hence higher microbial activity followed by better organic matter removal. Bavor *et al.* [13] reported that there was no difference in plant oxygen release for *Typha* and *Scirpus* in a gravel medium constructed wetland, while Szogi *et al.* [14] reported that *Scirpus* showed a higher nitrogen transfer rate, which is likely to be related to higher oxygen content in the root zone, compared with *Typha*, and which creates better conditions for efficient microbial processes.

Table 1 includes the results of removal of suspended solids and total phosphorus in the present free water surface wetland system. Although a higher removal rate of suspended solids was observed in the vegetated units (L2 and L3) than in the control, the difference between vegetated units and the control is not significant ($p > 0.05$). The combination of removal processes in a wetland can be generally referred to as filtration, although stem and litter densities are typically not high enough to act as a filter mat to remove suspended solids. The total phosphorus removal was low in all the units. It was noted that total phosphorus removal was not significantly high at the effluent compared with the influent in all the units ($p > 0.05$). It is assumed that the lower HRT (18 h) used in this study compared with other studies [2, 15] is another possible reason for the overall low level of phosphorus removal. Phosphorus removal in most constructed wetland systems is usually not very effective because of the limited opportunities for contact between wastewater and the soil. However, it is important to remove phosphorus concentrations before wastewater is discharged into water bodies because these nutrient accumulations can cause excessive algal growth in waterways (including blue-green algae), which can put natural ecosystems out of balance, harming water life and animals.

The average influent and effluent concentrations of NH_4-N and NO_3-N during the period of study are presented in table 2. It was assumed from the BOD_5 removal efficiencies that the first 3 months can be considered the establishment period for microbial activity, and hence the data for the first 3 months are not included in the analyses of other water-quality parameters (NO_3-N, NH_4-N, TP, and TSS) in this study. Wastewater generated from human waste can have significant levels of ammonia and organic nitrogen but not a considerable level of nitrate [16]. This was the case for the wastewater entering the present system. It was observed that ammonia removal was higher (table 2) in vegetated units than in the control unit. The statistical analysis

Table 2. Average removal of NH_4-N and NO_3-N (from September 2004 to April 2005).

	Influent	L1 effluent (control)	L2 effluent (*S. grossus*)	L3 effluent (*T. angustifolia*)
NH_4-N (mg l^{-1})	13.3 ± 1.8	7.1 ± 1.3	3.4 ± 1.7	5.5 ± 1.9
Removal efficiency (%)		46.6	74.4	58.6
NO_3-N (mg l^{-1})	1.8 ± 0.4	1.6 ± 0.3	0.9 ± 0.2	1.1 ± 0.3
Removal efficiency (%)		11.1	50.0	38.8

Note: Concentration values are given as mean $\pm$ standard deviation (mg l^{-1}).

showed that the NH_4-N removal efficiency of L2 was significantly higher compared with that of L1 ($p < 0.001$), supporting previous studies [5, 17] showing that unplanted wetlands remove less nitrogen than planted ones. However, there was no distinct difference in removal efficiencies between L2 and L3. It was also noted that the removal efficiency of L3 was not significantly higher than L1 ($p > 0.05$). This suggests that *S. grossus* has significantly more potential in removing NH_4-N in comparison with the control.

The NO_3^- concentration was significantly lower ($p < 0.001$) in the effluent (table 2) compared with the influent in all units, which suggests high removal of NO_3-N. However, statistical analysis showed that there was no distinct difference in removal efficiency between the control and vegetated units. Although wetlands may remove substantial quantities of nitrogen from water and subsequently store it in plant materials, they also potentially release a significant quantity of nitrogen to downstream ecosystems. A significant proportion of nitrogen in wetlands can be in organic form, contained in the vegetation (live plants), plant detritus, macrofauna, micro-organisms, or soil organic matter, or as dissolved organic compounds such as urea and amino acids [17]. It has been found that effective ammonium reduction and subsequent nitrification and different denitrification activities are also reasons for the difficulty in distinguishing the difference in NO_3-N removal between the control and vegetated units [18]. It was also observed that nitrate removal rates between *Typha* and *Scirpus* species differed significantly ($p < 0.001$), similar to the observations of Bachand and Horne [18]. The diverse findings described previously may be due to the different climatic conditions used in different experiments, suggesting that design parameters would differ significantly under tropical and temperate conditions.

The total nitrogen concentration (in soil) along the unit was examined after 11 months, and the observations are presented in figure 2. The trends observed in both the vegetated units (L2 and L3) are approximately the same, and the results presented here are the average values for the two units. A significantly high concentration of nitrogen was observed near the inlet region at a depth of 10–20 cm (*i.e.* root zone) below the soil surface. These concentrations decreased rapidly along the unit. As noted in table 2, NH_4^+ was the main form of nitrogen entering the system. Therefore, it is assumed that the continuous wastewater feed led to the accumulation of this higher concentration of nitrogen in the soil.

3.2 *Plant growth*

Plant growth was observed in the two marked quadrats in each unit, and the variation in shoot height is presented in figure 3. The maximum shoot height was 153 ± 5 cm and 288 ± 5 cm for *S. grossus* and *T. angustifolia*, respectively, just before the first harvesting (the first 8 months). The growth curves show that the shoots reached their maximum growth around 5 months after planting for *S. grossus* and around 8 months for *T. angustifolia.* These results (5 months and 8 months) indicate that these two species exhibit different growth patterns, and hence plant

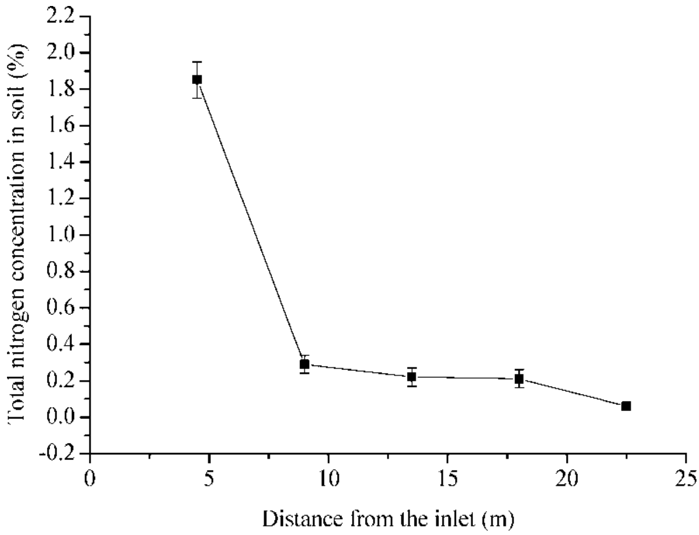

Figure 2. Variation in average total nitrogen concentration in soil along the L2 and L3 channels after 11 months. Concentration values are given as mean ± standard deviation (mg l^{-1}).

management in the systems by harvesting would require different timings (see figure 3). These results suggest that *S. grossus* is faster in establishment during the first months of the wetland system. However, it was noted that both species reached maximum shoot height within 3 months in the second phase, that is after the first harvest. Similar results were observed by Edwards *et al.* [19] who reported the difficulty of initial plant establishment in constructed wetlands, which could take even more than 5 months with *Scirpus* species.

The variation in shoot height along the channel after 11 months is presented in figure 4. The shoot height of *T. angustifolia* decreased along the channel, whereas the shoot height of *S. grossus* was lower near the inlet zone than in the middle and outlet zones. The reason for this growth difference along the channel could be due to a continuously high NH_4^+ concentration near the inlet that inhibited the growth of *S. grossus*. The higher nitrogen concentration accumulated near the inlet zone (figure 2) verified that this growth inhibition was due to constantly high NH_4^+ concentrations. It was also noted that the growth of *T. angustifolia* was not

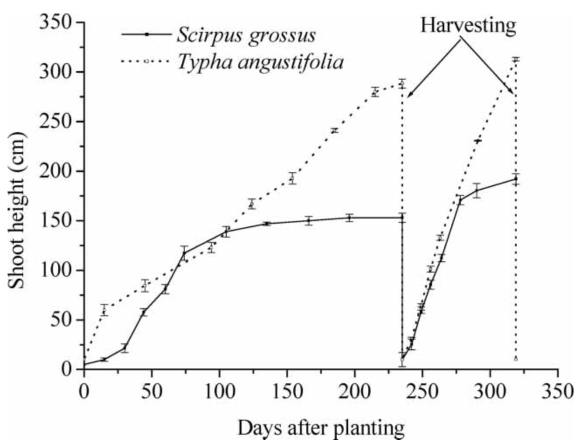

Figure 3. Seasonal change in shoot height of *S. grossus* and *T. angustifolia*.

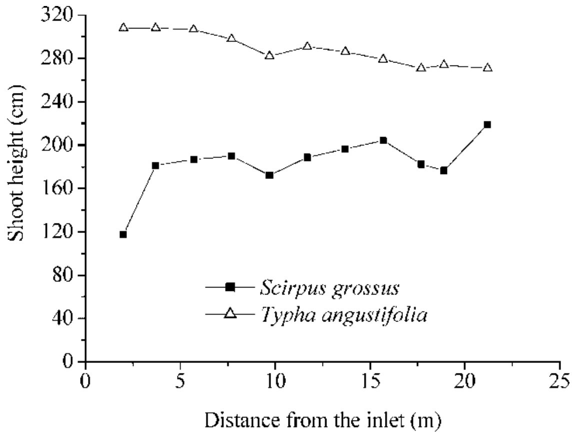

Figure 4. Variation in short height along the channels after 11 months.

identifiably affected by this phenomenon. This observation is in agreement with a previous study [20] that found that *T. angustifolia* has a higher tolerance for NH_4^+.

Variation in shoot density for both species was determined during harvesting (figure 5), which was done twice: 8 months and 11 months after planting. At both harvest times, it could be seen that the shoot density had not changed with time and that there was no identifiable change in shoot density along the channel for *T. angustifolia*, whereas for *S. grossus* there was a significant variation in shoot density. After the first 8 months, the *S. grossus* growth rate was higher near the inlet. However, after 11 months, the trend was different–the shoot density was lower compared with that after 8 months, and growth was inhibited near the inlet zone.

Figures 6(a) and 6(b) show the variations of above-ground biomass along the channel at different harvest times. A higher biomass production was noted for both species at harvesting after 11 months than at 8 months. The sluggishness in production during the first 8

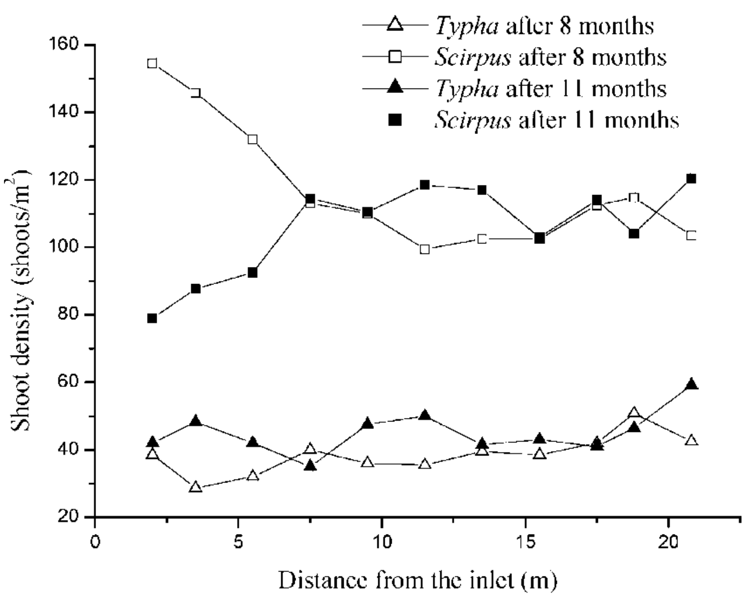

Figure 5. Variation in shoot density along the channel at different harvest times.

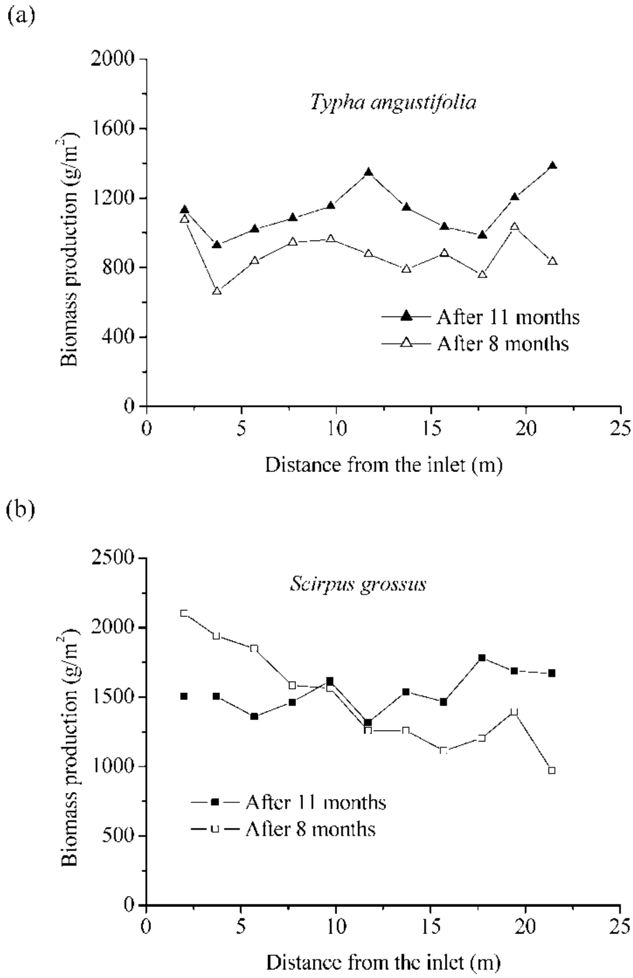

Figure 6. (a) Variation in above-ground biomass along the channel at different harvest times for *T. angustifolia*. (b) Variation in above-ground biomass along the channel at different harvest times for *S. grossus*.

months is because it takes a certain period for the initial establishment and due to the lower biomass reserves in the rhizomes that are mobilized for leaf growth. Although the above-ground biomass production (see figure 6(b)) was found to be higher after the first 11 months in the case of *S. grossus*, the production was lower near the inlet zone compared with biomass production at the first harvesting. It was surmised that continuous operation and nutrient accumulation affected the growth of *S. grossus* near the influent, which led to decreased productivity (figure 6(b)) and shoot density (figure 5) as well.

Table 3 shows the comparison of average above-ground biomass productivity in two different seasons: after 8 months and after 11 months. The productivity of *S. grossus* (1.3 kg/m^2) was higher than that of *T. angustifolia* and did not change significantly between the first and second harvests. The change in productivity in *T. angustifolia* was notably higher, 1.3 (table 3) than that of the first harvest time. Harvesting can affect nutrient storage in perennial plant tissues, depending on the time of harvest and the type of biomass (leaf, rhizome, or both) harvested, and it can also alter storage of rhizome carbohydrates needed for early season growth and stand strength [21]. Several studies have reported that repeated above-ground harvests adversely affect growth and biomass production, while total productivity can be considerably

Table 3. Comparison of changes of seasonal productivity.

	Average above-ground biomass production (kg m^{-2} growth period^{-1})		
	First harvest (growth period: May 2004 to January 2005)	Second harvest (growth period: January 2005 to April 2005)	Change in productivity (second harvest/first harvest)
S. grossus	1.2	1.3	1.1
T. angustifolia	0.73	0.96	1.3

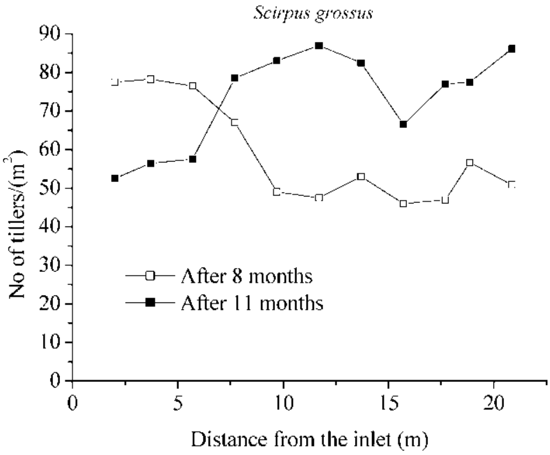

Figure 7. Variation in number of tillers along the channel (*S. grossus*).

increased if the shoots are removed repeatedly during the growth period [22, 23]. These productivity measures indicate that *S. grossus* was able to reach maximum productivity much faster (less than 8 months after planting) than *T. angustifolia*, suggesting that the former has a better potential in constructed wetlands due to its faster establishment and higher productivity.

We examined the number of tillers (terminal leaves) along the L2 unit after the 8 month and 11 month harvests. It can be seen from figure 7 that the number of tillers increased from 8 to 11 months. However, it was noted that the number of tillers was lower towards the inlet at 11 months. Figure 8 shows the variation of terminal leaf fraction for *S. grossus* along the L2 unit

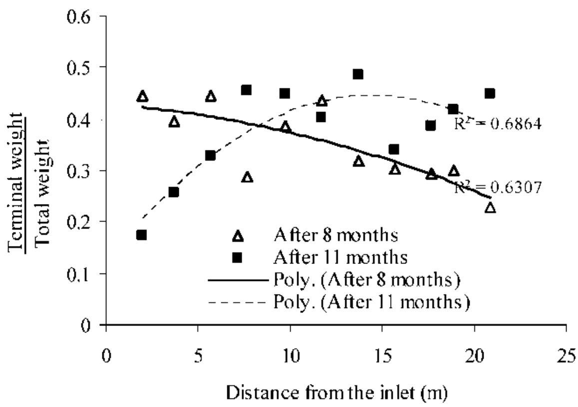

Figure 8. Variation in terminal leaf fraction along the channel (*S. grossus*).

at two different harvest times. Compared with *Typha*, an indirect advantage of *S. grossus* is that its tiller, which is the economically valuable part of the plant, comprises a greater fraction of its total biomass. These terminal leaves, which can be removed separately while harvesting, are used mainly to produce matting in rural communities. It was noted that the trend showed a clean difference at the first harvesting (8 months after planting) and at the second harvesting (11 months after planting). After 11 months, the terminal leaf fraction is lower at the inlet zone and higher towards the outlet zone. This supports the previous hypothesis (discussed with shoot height, shoot density, and above-ground biomass in the *S. grossus* unit) that high NH_4^+ concentrations inhibit plant growth of *S. grossus* and thereby delay the formation of terminal leaves and inflorescence. From figure 8, it can be seen that the area about 6 m from the inlet, which is around one fourth of the total wetland unit length (25 m), was most affected by NH_4^+. A possible reason is that nutrient availability along the channel varied with effective nitrification: less ammonium that could have been converted to nitrates and subsequently readily available for uptake by plants is available towards the outlet. It was also reported [24] that the availability of NH_4^+ in the rhizosphere suppresses the utilization of NO_3^- by wetland plants.

3.3 *Design considerations*

The present study suggests that *S. grossus* is a good choice for tropical free water surface constructed wetlands for domestic wastewater treatment. The biomass production was higher and consistent during the study period so that the biomass can provide additional revenue for the people who set up these constructed wetlands in isolated small communities. *S. grossus* took around 5 months for the initial establishment, whereas *T. angustifolia* took around 8 months to reach maximum shoot height before the first harvest. The optimum harvest time for *S. grossus* is suggested to be around 3 months after establishment. This timing will be marginally around 3 months for *T. angustifolia*. In the upstream area of the wetland, which is near the inlet, the growth of *S. grossus* was inhibited by NH_4^+, and it can be suggested that a quarter of the *S. grossus* unit could be planted with either mixed plants *T. angustifolia* and *S. grossus* together or only *T. angustifolia* to overcome this growth inhibition. The present system was operated at a comparably lower HRT (18 h), and the consistent performance suggests that the effluent of this emergent plant system can be reused for further water reclamation purposes while maintaining the same HRT. The idea is to have a multi-stage treatment where the effluent of this emergent system can be used more effectively for economic gain, for example, aquaculture. The findings of this study suggest that the design parameters need to be modified significantly in tropical conditions and that reliance on the guidelines derived from temperate climates would not be feasible for tropical conditions.

4. Conclusion

Constructed wetland systems have good pollutant-removal potential and are a viable option for wastewater treatment in developing countries with tropical climatic conditions. The study shows that the system has considerable potential for removing BOD_5 (44–68%), TSS (65–76%), TP (8–19%), NH_4-N (46–75%), and NO_3-N (11–50%). Of the three units, the *S. grossus* unit showed the best overall performance. The growth of *T. angustifolia* was found to be more robust with respect to NH_4^+ concentration, whereas the growth of *S. grossus* was inhibited by the continuous NH_4^+ feed. Further long-term research is necessary to examine the effects of continuous wastewater feeding and continual above-ground harvesting on the growth responses of plants. Such a long-term study will enable a more definitive understanding of the performance of such free water surface treatment wetlands under tropical conditions.

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