Performance evaluation of planted and unplanted subsurface-flow constructed wetlands for the post-treatment of UASB reactor effluents

Filipe Lima Dornelas, Matheus Boechat Machado and Marcos von Sperling

ABSTRACT

A system comprised by a UASB (Upflow Anaerobic Sludge Blanket) reactor followed by two horizontal subsurface-flow constructed wetlands in parallel was evaluated for the treatment of the wastewater generated in the city of Belo Horizonte, Brazil (50 inhabitants each unit). One unit was planted (*Typha latifolia*) and the other was unplanted. Influent and effluent samples were collected for a period of seven months. The systems were able to produce final effluents with low concentrations of organic matter and suspended solids, but showed not to be efficient in the removal of nutrients. Mean effluent concentrations for the planted and unplanted units were, respectively: BOD: 15 and 19 mg/L; COD: 42 and 64 mg/L; TSS: 3 and 5 mg/L; TN: 27 and 33 mg/L; N-NH_3: 25 and 29 mg/L; P Total: 1.2 and 1.5 mg/L. The planted wetland presented effluent concentrations and removal efficiencies significantly (Wilcoxon matched-pairs test, 5% significance level) better than the unplanted unit for most constituents. The study shows that horizontal subsurface-flow constructed wetlands can be effectively used as a post-treatment option for the effluent from UASB reactors.

Key words | horizontal subsurface-flow wetlands, UASB reactor, wastewater treatment

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INTRODUCTION

The upflow anaerobic sludge blanket (UASB) reactors are widely recognized as an appropriate option for the treatment of domestic wastewater in tropical developing countries. The main advantages include simplicity, no mechanization, low sludge production, sludge stabilization within the reactor, no energy consumption and production of biogas. However, UASB reactors show lower removal efficiencies compared with other secondary processes, which brings about the need for a post-treatment of their effluents, especially in terms of organic matter, nutrients and pathogenic microorganisms (Steen *et al.* 1999; Chernicharo 2007).

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One of the most promising technologies for the post-treatment of anaerobic effluents is constructed wetlands, which preserve the attributes of conceptual simplicity, no mechanization and no energy consumption. Since wetland systems have been more studied when they are integrated with other treatment processes, it is believed that their performance and behaviour as post-treatment options for UASB reactor effluents should be more investigated.

In this line, the current research aims at investigating the performance of two horizontal subsurface-flow constructed wetlands treating the effluent from a UASB reactor, one unit being planted (*Typha latifolia*) and the other unplanted.

METHODS

The system is located at the Experimental Wastewater Treatment Plant UFMG/COPASA (Federal University of Minas Gerais/Minas Gerais Water and Sanitation Company), that receives urban wastewater from the city of Belo Horizonte, Brazil (latitude 20°S). The study period was from July 2007 to April 2008 (268 days), involving two dry periods and one wet period (November to March).

The treatment system is composed of a UASB reactor with dimensions 1.20 m × 1.20 m × 5.0 m (width; length; height). This unit operated with a flow of 30 m^3/d and a hydraulic retention time around 6 hours. Part of the effluent flow from the UASB reactor was directed to the two wetland units, which operated in parallel, each receiving a flow of 7.5 m^3/d (population equivalent close to 50 inhabitants). One unit was planted with the macrophyte *Typha latifolia* and the other unit acted as an unplanted control. The support media in both units was steel slag with grain sizes with $d_{10} = 19$ mm and $d_{60}/d_{10} = 1.2$. The units were designed following the procedure given by Crites *et al.* (2006). The main characteristics are presented in Table 1. Figure 1 gives a view of the unplanted and planted units. It is believed that the size of the units and the population equivalents are representative of treatment systems for small communities, having similar hydraulic behaviour and operation and maintenance needs.

In both units, in the inlet and outlet areas, a coarse rock transition zone was included. The effluent was collected by a perforated pipe transversally located at the outlet end. For the planted units, adult *Typha latifolia* specimens were collected in a rural area, subjected to pruning with 0.8 m of aerial part and then planted following a density of 4 plants/m^2.

Table 1 | Physical and operating characteristics of each wetland unit

Parameter	Value	Unit
Bed height	0.4	m
Liquid height	0.3	m
Length	24.1	m
Width	3.0	m
Surface area	72.3	m^2
Wet volume	21.7	m^3
Flow	7.5	m^3/d
Surface hydraulic loading rate	0.1	m^3/m^2 d
Hydraulic retention time (V.porosity/Q)	1.2	d

Figure 1 | View of the unplanted and planted subsurface-flow wetland units.

Monitoring started in September 2007, two months after planting, lasting for 7 months. Samples were collected at the raw wastewater channel, effluent pipe from the UASB reactor and outlet manhole from each wetland. Samples were collected on a weekly basis, between 9 and 11 am. The total number of samples collected at each point during the experimental period was 25. Analyses were undertaken following the "Standard Methods for the Examination of Water and Wastewater" (AWWA/APHA/WEF 1998). Effluent flow was measured and adjusted on sampling days.

RESULTS AND DISCUSSION

Macrophytes growth and development

Planting was in July 2007. The planted specimens led to various buds that propagated via rhizomes and vegetated most of the unit. Growth was slow at the beginning, probably due to physiological stress brought about by the dry period and low air humidity. Nevertheless, with the onset of the rainy period in November, plant growth was steady, reaching heights in the order of 1.80 m.

During the experimental period, plant coverage by *Typha latifolia* was subjected to a single pruning (February 2008). In that occasion, plant heights varied between

2.1 and 2.5 m, and specimens were fully flowered. Pruning was undertaken through shallow cuts close to a stem height of 0.1 m.

Descriptive statistics of the performance

Table 2 presents the mean and standard deviation of the effluent concentrations of some of the investigated constituents. Based on the mean concentrations, mean removal efficiencies have been calculated and are presented in Table 3. The excellent performance in terms of organic matter and suspended solids removal can be readily seen. In terms of nutrients, no appreciable removals have been obtained. Regarding coliforms, even though removal efficiencies approached 3 log units, effluent concentrations were still high.

A comparison of the median effluent concentrations from the planted and unplanted units was carried out using the non-parametric Wilcoxon matched-pairs test. At the 5% significance level, there was a significant lower effluent concentration from the planted unit in terms of most constituents (BOD, COD, N total, N-ammonia, P-phosphate and *E. coli*). No significant difference was found only for effluent SS and P-total.

When comparing the performance of these wetland units with other wetlands integrated with different pre-treatment processes, the good performance of the UASB reactor must be taken into account. This reactor was able to produce an influent to the wetland systems with low concentrations of BOD, COD and SS, what may not be the case with other pre-treatment processes, such as those based on simple primary sedimentation tanks.

Organic matter removal

Figure 2 presents the box-and-whisker plot of COD concentrations along the system, together with the removal efficiency in each unit. The sequential decrease of concentrations is clear, and the contribution of each unit in the removal of COD can be easily seen. In terms of overall removal (UASB + wetland), the system with the planted unit showed a better performance and lower variability.

A detail of the performance of the wetland units alone in terms of BOD and COD can be seen in the box-and-whisker plots in Figure 3, which depict influent and effluent concentrations from both units, together with the removal efficiency in each unit, allowing a better comparison between the planted and unplanted units. This plot structure is adopted for other constituents in this paper.

The values obtained for BOD and COD removal are within those found by Solano *et al.* (2004), who studied subsurface flow units with hydraulic loading rates of 0.150 and 0.075 m^3/m^2 d and obtained removal efficiencies of 63% and 93% for BOD and 50% and 88% for COD in planted units. Mean efficiencies of COD removal of 80% (planted unit with *Typha*) and 65% for unplanted control unit were obtained in Tanzania (Mbuligwe 2004), values

Table 2 | Mean and standard deviation of the effluent concentrations

		Raw wastewater		UASB		Planted wetland		Unplanted wetland	
Constituent	Unit	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
COD	mg/l	528	473	145	44	42	18	64	35
BOD	mg/l	154	72	41	20	15	10	19	13
SS	mg/l	171	126	36	23	3	2	5	4
N Total	mg/l	29	8	36	5	27	7	33	8
N-Ammonia	mg/l	28	6	32	6	25	7	29	7
Nitrate	mg/l	0.10	0.10	0.08	0.13	0.48	0.32	0.29	0.36
P Total	mg/l	1.40	0.78	2.18	0.99	1.23	0.85	1.48	0.87
P-Phosphate	mg/l	1.20	0.76	1.05	0.55	0.57	0.36	0.91	0.67
Turbidity	NTU	121	64	64	30	3	2	5	3
E. coli	MPN/100 ml	1.0×10^8	1.0×10^8	5.2×10^6	2.1×10^6	1.3×10^5	1.1×10^5	4.6×10^5	4.3×10^5

Table 3 | Mean removal efficiencies (%) of each unit and of the system as a whole

Constituent	UASB	Planted wetland	Unplanted wetland	Global: UASB + planted wetland	Global: UASB + unplanted wetland
COD	73	71	56	92	88
BOD	73	63	54	90	88
SS	79	92	86	98	97
N Total	− 24	25	8	7	− 14
N-Ammonia	− 14	22	9	11	− 4
P Total	− 56	44	32	12	− 6
P-Phosphate	13	46	13	53	24
E. coli	94.8	97.5	91.2	99.9	99.5

Removal efficiencies (%) calculated based on the mean concentrations presented in Table 2.

that are similar to those obtained in the current research (71% and 56% for planted and unplanted units).

Typha is known for its capacity to transfer aerial oxygen to its roots and rhizomes. It is not clear whether this played an important role in the planted system, which could justify its better performance in terms of organic matter removal. The relative importance of this mechanism is controversial (USEPA 2000), and the current research had no elements that could allow any conclusion on this regard.

Figure 4 shows a plot of the effluent COD concentrations as a function of the applied surface organic loading rates in the planted and unplanted units. It is seen that higher influent loadings imply higher effluent concentrations, and also that the slope of the line of best fit in the unplanted unit is larger, suggesting that higher effluent concentrations are likely to be achieved for the same loading rate.

Assuming the plug-flow model ($C = C_o.e^{-K.t}$), values of the removal coefficient K (20°C) for BOD and COD were calculated using the mean influent (C_o) and effluent (C) concentrations (Table 2). The retention time t, already taking into account the porosity, was 1.2 d (Table 1). The temperature coefficient θ was adopted as 1.06 (Crites *et al.* 2006). The resulting K (20°C) values are shown in Table 4. It is seen that the K for BOD in the planted unit is lower than the value of 1.1 proposed by Crites *et al.* (2006), probably because the organic matter had been previously subjected to anaerobic treatment, which is more efficient in the removal of biodegradable matter than the typical primary treatment options usually applied upstream of wetland units. It is also noted that K values for the planted units are higher than those for the unplanted unit.

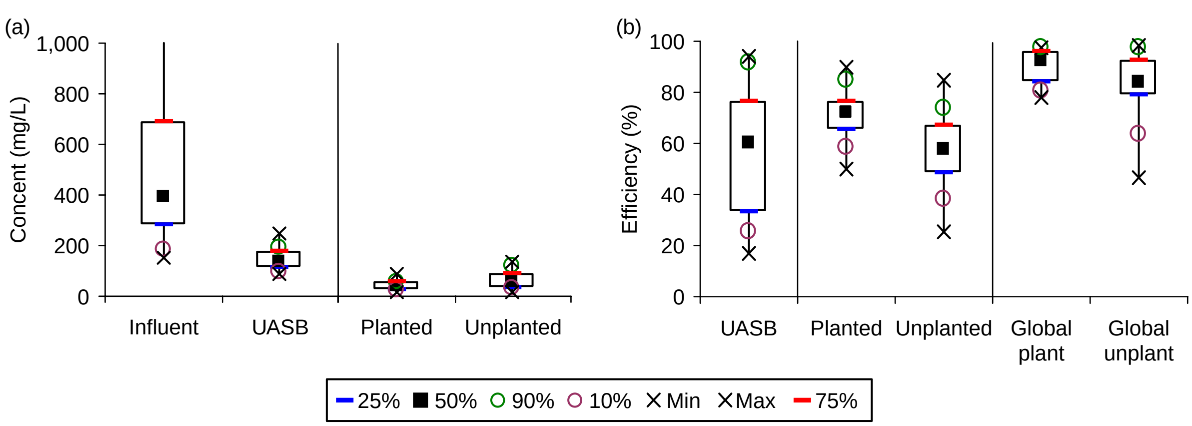

Figure 2 | (a) COD concentrations along the treatment line; (b) COD removal efficiencies in each unit and in the overall system (UASB + wetland).

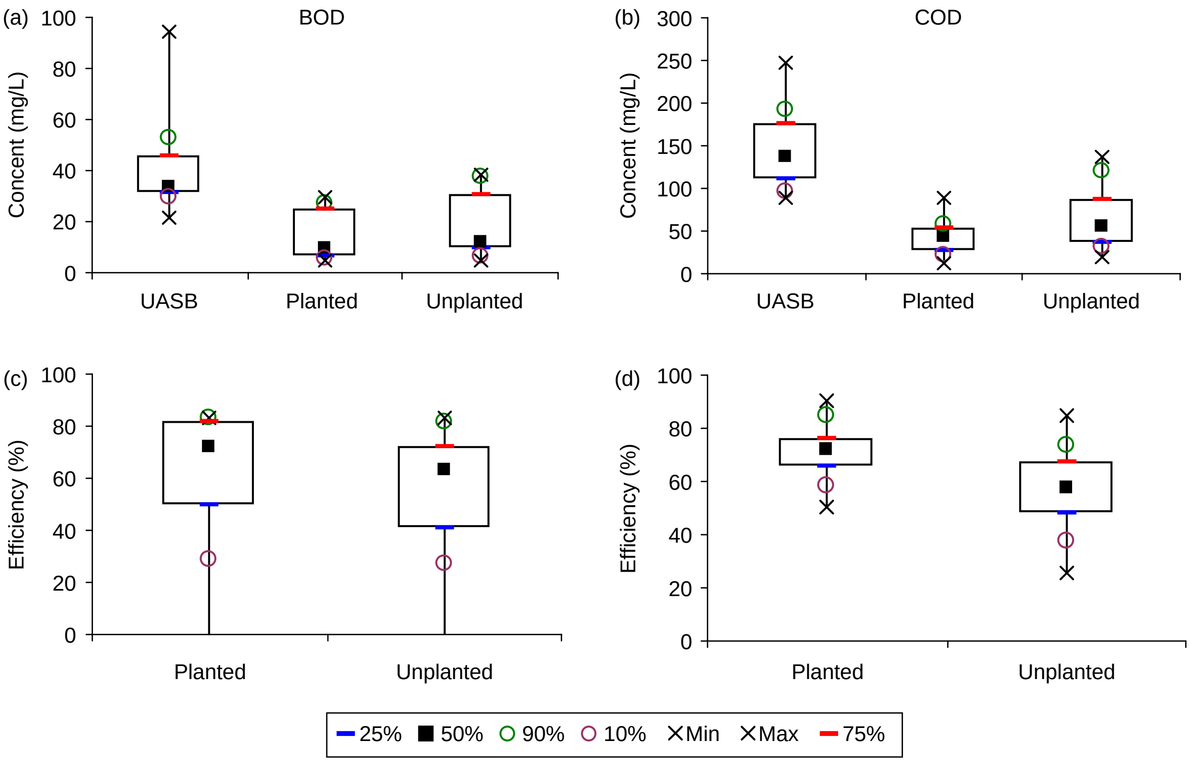

Figure 3 | BOD and COD concentrations and removal efficiencies in the planted and unplanted wetlands.

Solids removal

Suspended solids removal efficiencies were very good in both systems, with very low effluent concentrations and also turbidity values. Average values of SS removal efficiencies of 92% and 86% in the planted and unplanted units were obtained. Figure 5 presents the box plot of effluent concentrations and removal efficiencies, highlighting the good performance in both cases. Based on the Wilcoxon matched-pairs test, the median values of both units were not significantly different at the 5% significance level.

The substantial solids removal occurs through the filtering mechanisms that take place within the slag support media. This high solids retention capacity can cause clogging of the media, especially in the first meters in the vicinity of the inlet. To reduce this problem, adequate practices of sludge wastage in the UASB reactor are necessary in order to avoid solids loss with its effluent.

Assuming a ratio of 2.0 mg of effluent particulate COD per mg of effluent SS, the mean particulate COD in the effluent would amount to $2.0 \times 3 = 6$ mg/l for the planted

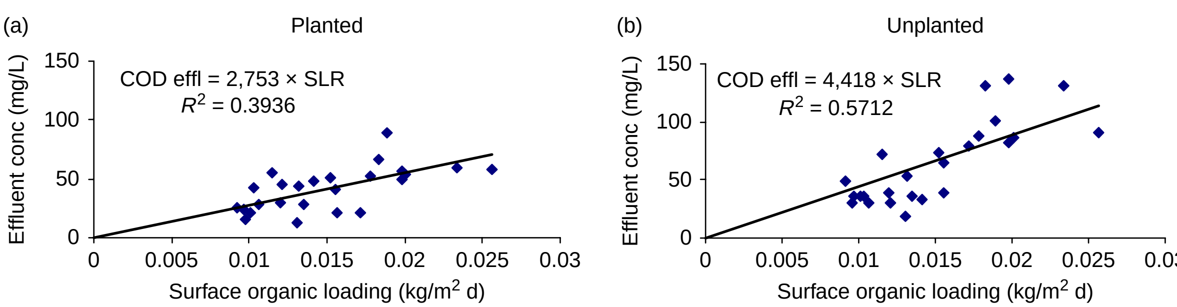

Figure 4 | Relationship between effluent COD concentration and surface organic loading rate (kgCOD/m^2 d). (a) Planted unit; (b) Unplanted unit.

Table 4 | BOD and COD removal coefficients (*K*) for the plug-flow model, expressed for a temperature of 20°C

K (20°C) (d^{-1})	Planted unit	Unplanted unit
K_{BOD}	0.59	0.45
K_{COD}	0.73	0.48

unit and 2.0 × 5 = 10 mg/l for the unplanned unit. Therefore, the particulate fraction of the total COD in the effluent would be only around 14% (planted) and 16% (unplanted), meaning that between 84% and 86% of the effluent COD is in the soluble form. This is a result of the excellent solids removal capacity of both units.

Nitrogen removal

Total nitrogen removal efficiencies were only modest in both units, with mean values of 25% for the planted wetland and 8% for the unplanted one, with the occurrence of occasional negative values. For ammonia, results are similar (22% planted and 9% unplanted). Figure 6 presents effluent concentrations of total nitrogen, ammonia and nitrate and also the removal efficiency of total nitrogen. The best performance of the planted unit (confirmed by the Wilcoxon matched-pairs test for median effluent concentrations) can be explained by the plant's life cycle and assimilation for growth.

Studies conducted by Mayo & Bigambo (2005) led to total N removal efficiencies of 49%, similar to those found by Gale *et al.* (1993), who reported values between 45% and 70%. Martin & Reddy (1997) obtained lower values (38%), but all these researches had higher efficiencies that those obtained in the current study.

Aquatic plants enhance nutrient removal through accumulation in the biomass, fixation of organic and inorganic particulates and, when oxygen is present, the creation of an oxidizing environment around the rizosphere (Brix 1994). Therefore, sites in the vicinity of the roots are susceptible to nitrification, what may explain the best performance of the planted unit. Besides that, wetland plants could allow nitrate removal by assimilation through the roots, but influent nitrate concentrations were, as expected, very low in the investigated system. Nitrification seemed to be very small, as indicated by the low effluent nitrate values, what is compatible with the low hydraulic retention time in the units (1.2 d). The possibility of having denitrification within the units was not investigated, but if this occurred, it is believed that it accounted for a small fraction, due to the presence of dissolved oxygen in the final effluents.

Phosphorus removal

Phosphorus removal took place in both wetlands, with mean removal efficiencies of 44% (planted) and 32% (unplanted). However, it should be taken into account that influent concentrations were already very small, in the range of 2 mg/L. The planted unit showed a better performance, but there was no significant difference between both units (Wilcoxon test) for effluent total

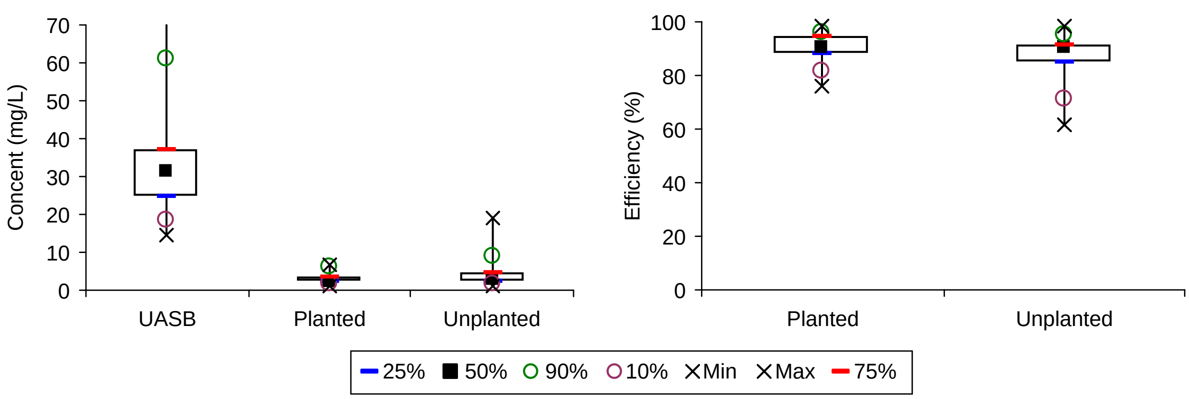

Figure 5 | SS concentrations and removal efficiencies in the planted and unplanted wetlands.

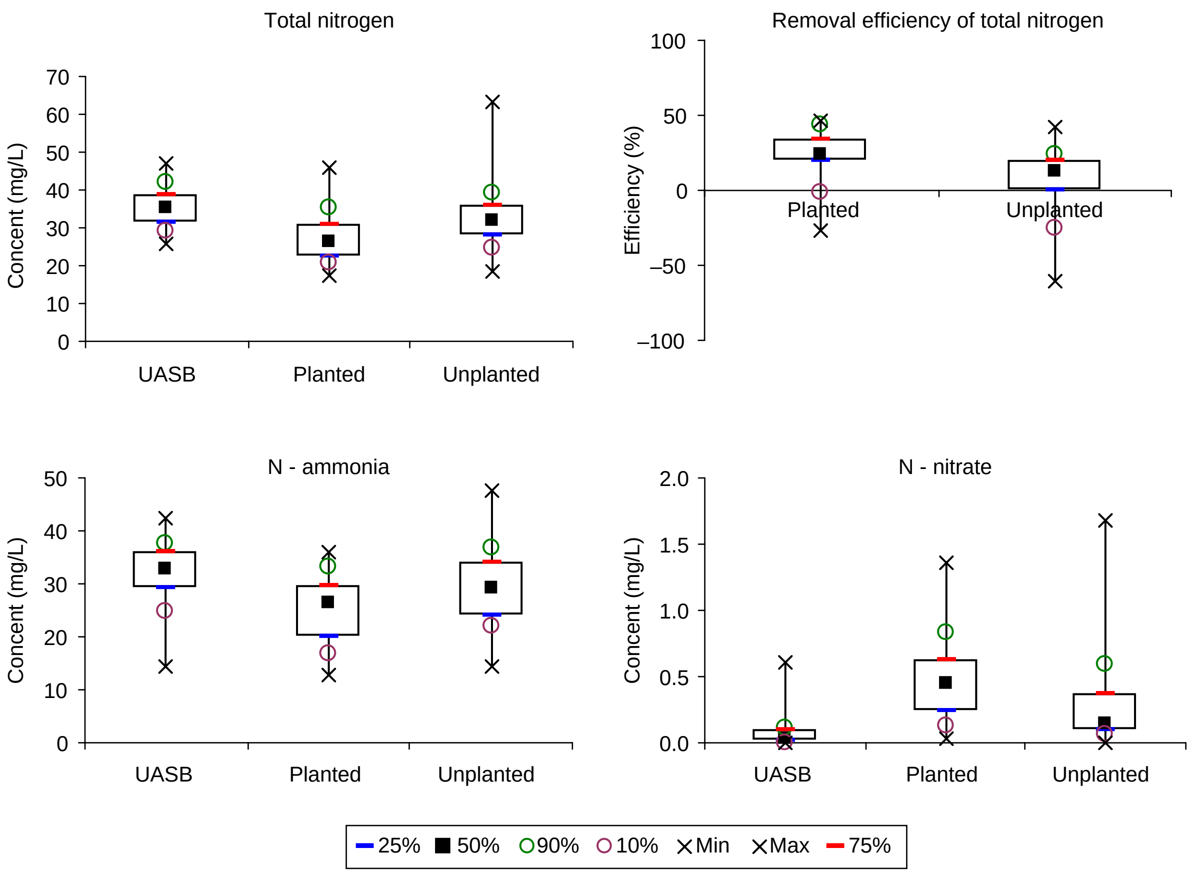

Figure 6 | Total-N, ammonia and nitrate concentrations, together with total-N removal efficiencies in the planted and unplanted wetlands.

P. However, for effluent phosphate there was a significant difference. The box plot for total P and phosphate concentrations can be seen in Figure 7.

For P removal, contact time plays an important role (Drizo *et al.* 2000), with evidences that the removal efficiency is positively correlated with the hydraulic retention time (Klomjek & Nitisoravut 2005). This could not be verified in the current research because the influent flow did not vary, leading to a stable retention time. The best performance of the planted unit, especially for phosphate,

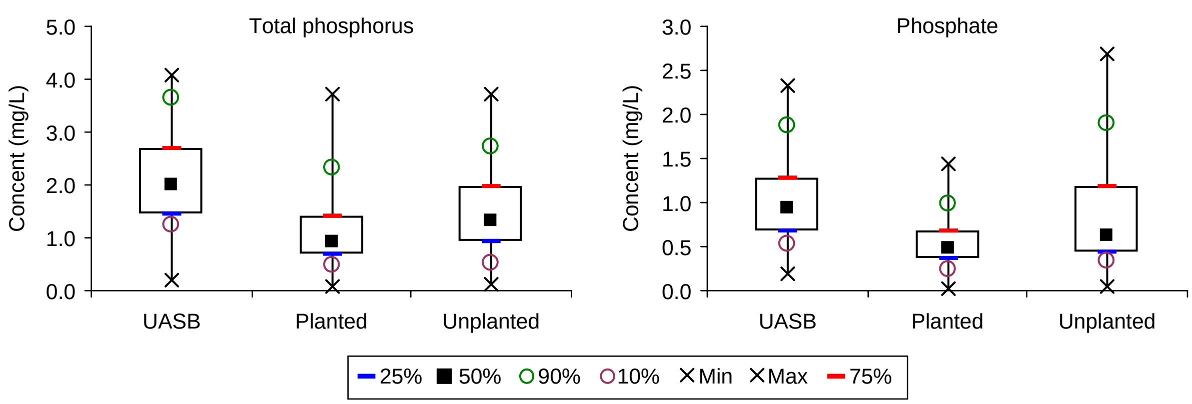

Figure 7 | Total phosphorus and phosphate concentrations in the planted and unplanted wetlands.

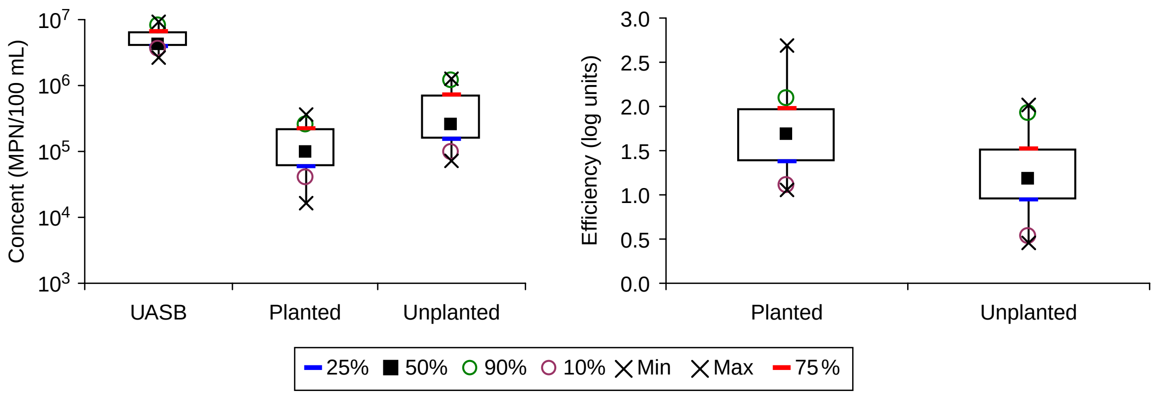

Figure 8 | *E. coli* concentrations and removal efficiencies (as log units removed) in the planted and unplanted wetlands.

can possibly be attributed to assimilation by *Typha*, especially during its growth stage. Presence of plants can effectively contribute to $P-PO_4^-$ removal, because this form is readily available for absorption (Chung *et al.* 2007).

Phosphorus removal associated with the support media used is also a possibility. In this research, steel slag was used, which has the capacity to retain phosphorus through adsorption and precipitation (Shilton *et al.* 2006).

Ahn & Mitsch (2002) reported removals from 24 to 52% for loading rates of 7–57 $mgP\,m^{-2}\,d^{-1}$ (lower rates than those applied in this research, which ranged from 100 to 400 $mgP\,m^{-2}\,d^{-1}$). Removal efficiencies between 27 and 65% were reported by Vymazal (2002), and were very influenced by the filter medium used. On the other hand, Mbuligwe (2004) reached high removals (69 to 75%) with a hydraulic retention time similar to the one applied in this research (1.2 d).

Coliform removal

E. coli removal can be seen in Figure 8. The planted unit led to lower effluent concentrations (significantly different, Wilcoxon matched pairs test at 5% significance level) and higher removal efficiencies. Removal efficiencies were typically between 1.5 and 2.0 log units (97–99%) for the planted wetland and 1.0 and 1.5 log units (90–97%) for the unplanted wetland. Taking into account the low retention time (1.2 days), the removal efficiencies can be considered good, although insufficient for many effluent discharge situations, since effluent concentrations were in the range of 10^4 and 10^6 MPN/100 ml.

Studies conducted by Decamp & Warren (2000) in four wetlands planted with *Phragmites australis* led to similar removal efficiencies (97% to 99%). However, four log units removal was obtained by Kefalla & Ghrabi (2005), without statistical difference between the planted and the unplanted units.

Coliform removal in wetlands is based on various physical (e.g. filtration through roots) and chemical (e.g. biocides secretion) mechanisms that are related with the presence of plants (Batchelor *et al.* 1990), what could explain the better performance of the planted unit. However, other factors may be considered, such as predation by nematodes, antibiotics, attacks from other bacteria and natural death (Decamp & Warren 2000).

CONCLUSIONS

Literature presents several publications in which planted and unplanted subsurface-flow wetlands have been compared, with conflicting conclusions as to the real contribution of the macrophytes. This research endorses the best performance achieved by the planted unit for most constituents of interest. In the present case, the major contribution lies in the application of the wetlands for the pos-treatment of the effluents from an anaerobic reactor of the UASB type.

In general, it can be said that the overall performance of the UASB – wetlands system was very good for organic matter and suspended solids removal, with a less important removal of nutrients. Given the simplicity of such systems, with no mechanization and energy consumption, it can be concluded that this is an important alternative for developing countries and warm climate regions. This overall conclusion matches those given by Souza *et al.* (2005), who investigated a similar system (UASB + wetland) and ascertained its potential for use of the effluent for restricted irrigation.

When comparing the planted and unplanted units, even though the performance of the planted one was better for most constituents, it is always a matter of careful consideration as to the real need of planting. Based on the results obtained, it is seen that there is no general answer to this question. Although the performance of the unplanted wetland was inferior, it was still very good for organic matter and solids removal, and its higher conceptual simplicity may indicate its application whenever a compatible effluent quality is required.

No conclusions on the influence of the loading rate on the treatment performance of both systems can be drawn, because they operated with a single hydraulic loading rate throughout the experimental period.

The filter media used (steel slag) seemed not to act differently from gravel or crushed stones of similar grain size, and no particular improvement in the removal of nitrogen and phosphorus due to chemical reactions was observed. This media, being a by-product of steel industries, is usually cheaper than crushed stones, especially when applied at the vicinity of a steel producing area, in order to benefit from low transportation costs.

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