Role of vegetation (*Typha latifolia*) on nutrient removal in a horizontal subsurface-flow constructed wetland treating UASB reactor–trickling filter effluent

Jocilene Ferreira da Costa, Weber Luiz Pinto Martins, Martin Seidl and Marcos von Sperling

ABSTRACT

The main objective of the work is to characterize the role of plants in a constructed wetland in the removal of nitrogen (N) and phosphorus (P). The experiments were carried out in a full-scale system in the city of Belo Horizonte, Brazil, with two parallel horizontal subsurface-flow constructed wetland units (one planted with *Typha latifolia* and one unplanted) treating the effluent from a system composed of an upflow anaerobic sludge blanket reactor and a trickling filter (TF). Each wetland unit received a mean flow of approximately 8.5 $m^3 d^{-1}$ (population equivalent around 60 inhabitants each), with a surface hydraulic loading rate 0.12 $m^3 m^{-2} d^{-1}$. The experiments were conducted from September 2011 to July 2013. Mean effluent concentrations from the wetlands were: (a) planted unit total nitrogen (TN) 22 mg L^{-1}, ammonia-N 19 mg L^{-1}, nitrite-N 0.10 mg L^{-1}, nitrate-N 0.25 mg L^{-1}, P-total 1.31 mg L^{-1}; and (b) unplanted unit TN 24 mg L^{-1}, ammonia-N 20 mg L^{-1}, nitrite-N 0.54 mg mL^{-1}, nitrate-N 0.15 mg L^{-1}, P-total 1.31 mg L^{-1}. The aerial part of the plant contained mean values of 24.1 gN (kg dry matter)$^{-1}$ and 4.4 gP (kg dry matter)$^{-1}$, and the plant root zone was composed of 16.5 gN (kg dry matter)$^{-1}$ and 4.1 gP (kg dry matter)$^{-1}$. The mean extraction of N by the plant biomass was 726 kgN $ha^{-1} y^{-1}$, corresponding to 17% of the N load removed. For P, the extraction by the plant biomass was 105 kgP $ha^{-1} y^{-1}$, corresponding to 9% of the P load removed. These results reinforce the reports that N and P removal due to plant uptake is a minor mechanism in horizontal subsurface-flow constructed wetlands operating under similar loading rates, typical for polishing of sanitary effluent.

Key words | cattail, domestic sewage, horizontal subsurface-flow, nitrogen, phosphorus, treatment wetlands

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INTRODUCTION

The role of plants in the performance of constructed wetlands treating domestic sewage is a matter of considerable debate among researchers because of the multiple angles that surround this analysis: physical influence of the roots in the hydraulic conductivity of the units, possibility of oxygen transfer through the root zone, release of exudates, contaminant adsorption in the biofilm zone around the roots, nutrient uptake from the plants, and other aspects. The degree of influence is dependent on several factors, such as plant species, influent composition, grain size distribution of the filter media, applied hydraulic and mass loading rates and geometric configuration of the wetland units.

The focus of this paper is nitrogen (N) and phosphorus (P) uptake from the plants and the relative role of plant uptake on the overall removal from the treatment unit. There is extensive literature on this subject, including, among others, Zhu & Sikora (1995), Kadlec & Knight (1996), Hamersley *et al.* (2001), Tanner *et al.* (2002), Brix (2003), Souza *et al.* (2003), DeBusk *et al.* (2004), Vymazal (2004, 2007, 2011), Edwards *et al.* (2006), Akratos & Tsihrintzis (2007), Brasil *et al.* (2007), Kadlec & Wallace (2009), Curia *et al.* (2011), Fia *et al.* (2011) and Soares (2012). Some conclusions from these studies are: (a) the rate of nutrient removal has been reported to be higher during the growth phase of the plant and lower

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during its senescence; (b) both ammonia and nitrate can be used by the plants; (c) nutrient removal efficiencies vary widely; and (d) the relative contribution of the nutrient removal via plant uptake to the overall removal is usually independent of the applied loading rates. This last point is explained by the fact that, for the common utilization of constructed wetlands in domestic sewage treatment practice, usually the input load of N and P is higher than the extraction capacity by the plants, given the typical surface loading rates for which the wetlands are designed.

This study aims to contribute to the above knowledge, by comparing two horizontal subsurface constructed wetlands operating in parallel, one with plants (*Typha latifolia*) and the other unplanted, both treating the effluent from units not frequently covered in the wetland literature: upflow anaerobic sludge blanket (UASB) reactor followed by trickling filter (TF). The objective is to: investigate the removal efficiencies of N fractions and P compare the planted and unplanted units, determine how much of the removed nutrient load has been due to plant uptake and characterize the amount of nutrients in the aerial and root parts of the plants. The other removal routes of N and P are not within the scope of this work, which concentrates on removal by plant uptake.

METHODS

The experiments were conducted at the Centre for Research and Training on Sanitation UFMG/COPASA, located in the Arrudas wastewater treatment plant, in the city of Belo Horizonte, Brazil (latitude 19 °53′ S). Belo Horizonte is located in a Cfa or Cwa humid subtropical climate according to Köppen classification, with a mean annual air temperature of 22.1 °C and mean annual rainfall of 1,540 mm/year. The UASB reactor received municipal wastewater after preliminary treatment (screening and grit removal). The effluent from the UASB reactor was directed to a TF, whose effluent was split into the two horizontal subsurface flow wetland units. Each wetland unit received a mean flow of 8.5 $m^3\ d^{-1}$, corresponding to approximately 60 inhabitants each and a mean surface hydraulic loading rate of 0.12 $m^3\ m^{-2}\ d^{-1}$ and a mean chemical oxygen demand (COD) mass loading rate of 12.3 gCOD $m^{-2}\ d^{-1}$. The medium was steel slag with $d_{10} = 19$ mm, non-uniformity coefficient $d_{60}/d_{10} = 1.2$ and porosity = 0.40. The height of the bed was 0.40 m, and the design water depth was 0.30 m (the actual operating liquid depth was higher, due to progressive clogging). One bed was cultivated with cattail (*Typha latifolia*). The dimensions of each unit were: length L = 24.1 m; width B = 3.0 m; length/width ratio = 8.0; surface area = 72.3 m^2. The system started operation in 2007, but the experiments described here were conducted from September 2011 to July 2013. More information about the treatment system can be obtained in Costa *et al.* (2013). Figure 1 shows a view of the two wetland units and the schematics of the treatment flowsheet.

Routine monitoring was done through weekly or fortnightly sampling of raw wastewater, effluent from the UASB reactor and TF, and effluent from the wetlands. The parameters monitored were the usual physicochemical parameters. Those of special interest here are total Kjeldahl nitrogen (TKN), N-ammonia (N-NH_4^+), N-nitrite (N-NO_2^-), N-nitrate (N-NO_3^-) and total phosphorus (TP). The physicochemical analyses were undertaken at the Department of Sanitary and Environmental Engineering of the Federal University of Minas Gerais, Brazil, following the procedures of *Standard Methods for the Examination of Water and Wastewater* (APHA/AWWA/WEF 2005). In addition, periodical longitudinal profiles of bed liquor were done, with sampling at 0% (inlet), 25, 50, 75 and 100% (outlet) of the bed length.

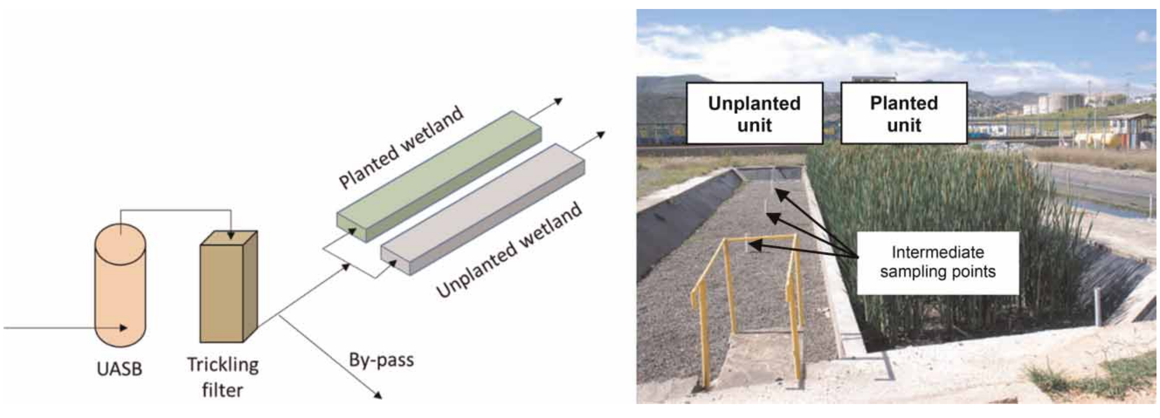

Figure 1 | Flowsheet of the treatment system (left) and view of the two wetland units (right).

Each sample from the three intermediate points was made up of 0.5 L collected from sampling columns inserted in the filter bed (see detail in Figure 1). Each sampling column was made of a fixed 100 mm diameter PVC pipe, which covered the full depth of the filter bed, with perforations over the full lateral of the pipe in order to allow the entrance of the surrounding liquid. Each sample was collected from inside the pipe, after discarding the original content, and represented the content of the full liquid column (0.30 m). Redox potential was measured *in situ* from the collected samples and the other parameters were analysed in the laboratory.

Plant growth was analysed based on samples from the aerial parts. The planted unit was divided into four plots along the bed length. From each plot, 10 plants were randomly selected and collected. The height of each plant was measured and the number of leaves was counted. The biomass analyses were undertaken in the Veterinary Department of the Federal University of Minas Gerais.

To characterize the plant biomass composition (dry matter, N and P), plant samples were collected at three different stages of their cycle: phase 1 – regeneration; phase 2 – growth phase; phase 3 – stationary. Each cycle, as measured by the intervals between cuttings, had typical durations between 3 and 4 months. Sampling was in three different areas (3 m^2 each) along the bed length. Productivity in terms of dry matter (P_{DM}), expressed in $g\,m^{-2}\,d^{-1}$, was obtained from Equation (1), while the capacity of the plants to extract nutrients was obtained from the product of the nutrient concentration and the dry matter productivity (Equations (2) and (3)):

$$P_{DM} = (M_W * DM)/(A.t) \quad (1)$$

$$R = P_{DM} * (NC/100) \quad (2)$$

$$E = (R * A_{CW} * 100)/(Q_{infl} * C_{infl}) \quad (3)$$

where P_{DM} = productivity in terms of dry matter ($g\,m^{-2}\,d^{-1}$); M_W = mass of the sample, in wet weight (kg); DM = dry matter content of the sample ($g\,kg^{-1}$); A = bed area of the sample (m^2); t = growth time (d); R = capacity to remove nutrients ($g\,m^{-2}\,d^{-1}$); NC = nutrient concentration in the plant biomass (%); E = efficiency in the removal of nutrients (%); A_{CW} = area of the constructed wetland unit; Q_{infl} = influent flow to the treatment unit ($m^3\,d^{-1}$); C_{infl} = nutrient concentration in the influent to the treatment unit ($g\,m^{-3}$).

To compare performance between the planted and unplanted horizontal subsurface flow wetlands units, statistical analysis of the data was performed using the nonparametric Wilcoxon matched pairs test for dependent variables at the 5% significance level using Statistica® software.

RESULTS AND DISCUSSION

Nutrient concentrations in the treatment system

Table 1 presents the mean and standard deviation of the nutrient concentrations in the treatment system, together with the mean removal efficiencies, based on loads. A water balance (Costa 2013) was undertaken over a period of 1 year (May 2012–May 2013), leading to the values of 5% water loss by evapotranspiration in the planted unit (1,677 mm/year) and 2% water loss by evaporation in the unplanted unit (671 mm/year). Therefore, the removal efficiencies were calculated based on the removed loads, knowing that the outlet flows were 95% and 98% of the influent flows in the planted and unplanted units, respectively. COD values are also presented in Table 1, in order to allow a better interpretation of the behavior of the system.

The performance of the system in terms of organic matter removal was very good, as shown by the overall COD removal efficiencies (94 and 93% for the systems with the planted and unplanted units), with a good contribution from both wetland units. It can be seen that the prevailing N form is ammonia, and the concentrations of the oxidized forms (nitrite and nitrate) are very small. The TF allowed only partial nitrification, and the low nitrite and nitrate influent concentrations to the wetland units were decreased due to the reducing conditions inside the wetland units (redox potential around –100 mV in the planted unit and between 0 and –100 in the unplanted unit; see Figure 3). The removal efficiencies of TKN and ammonia were small in both wetland units (around 25 and 18% in the planted and unplanted units). However, P removal was high, with a mean value of 70%.

Statistical analysis (Mann–Whitney test) comparing the median values of the effluent concentrations of the planted and unplanted units indicated a significant difference (at 5% significance level) for total N ($p = 0.0000$) and no significant difference for total P ($p = 0.114$). However, if the same test is applied for removal efficiency in terms of effluent loads (flow x concentration), the planted and unplanted units are significantly different for both total N ($p = 0.0000$) and

Table 1 | Mean and standard deviation of the nutrient concentrations and mean removal efficiencies (September 2011 to July 2013)

Constituent	Concentrations (mg/L) Raw sewage	UASB	TF	Planted CW	Unplanted CW	Wetlands removal efficiencies (%) Planted CW	Unplanted CW	Overall (whole system) removal efficiencies UASB + TF + planted CW	UASB + TF + unplanted CW
COD	400 (159)	145 (56)	105 (54)	26 (15)	31 (18)	76	71	94	93
TKN	–	35 (8)	28 (7)	22 (8)	23 (8)	25	18	40	34
N-ammonia	26 (6)	30 (7)	24 (6)	19 (7)	20 (7)	25	17	31	23
N-nitrite	0.03 (0.11)	0.01 (0.01)	1.15 (0.77)	0.10 (0.26)	0.54 (0.45)	–	–	–	–
N-nitrate	0.06 (0.05)	0.07 (0.10)	2.49 (1.88)	0.25 (0.75)	0.15 (0.27)	–	–	–	–
Phosphorus	4.21 (2.25)	4.06 (1.55)	4.04 (1.56)	1.31 (0.99)	1.31 (1.15)	69	68	70	70

Mean values (standard deviations inside parentheses).
Mean removal efficiencies were calculated based on the mean influent and effluent loads (mean concentrations *x* mean flows).
UASB: upflow anaerobic sludge blanket reactor; TF: trickling filter.

total P ($p = 0.0287$), due to the fact that the planted unit had a higher water loss, generating a lower effluent flow and, consequently, load.

Figure 2 presents the box-plot of ammonia (which was the main N fraction) and total P concentrations in the units in the treatment system. As expected, ammonia concentration increases in the UASB reactor due to ammonification and decreases in the TF due to partial nitrification. There is a further decrease in both wetland units, but the values are still high. Regarding P, the UASB reactor and TF do not contribute to its removal, but the wetland units are responsible for a substantial decrease.

Figure 3 shows the box-plot of the longitudinal profile of ammonia and P concentrations and redox potential along the length of both wetland units. Ammonia decreased at approximately the same low rate along the length. Phosphorus decreased at a faster rate, with most of the removal taking place in the first half of the units. The redox profile indicated that, inside the filter medium, there was a predominance of reducing conditions inadequate for supporting some conversion mechanisms, such as nitrification. It is interesting to observe that redox potential values in the first half of the unplanted unit were higher than those in the planted unit. This fact is now the subject of further in-depth research in the same treatment units.

Nutrient uptake by the plant biomass

The measured samples of *Typha latifolia* reached a height between 70 and 100 cm (without taking into account the part in contact with the support medium (pseudo-stem)), showing an average growth rate (during the growth phase) of 1.03 cm per day. During three sampling campaigns, the mean values of plant density in the filter bed ranged from 12.0 to 13.4 plants per m^2. Determination of N and P content in the aerial part (leaves) and in the root zone led to the following average results, expressed in terms of dry matter: (a) N, leaves $= 24.1$ g kg^{-1}, roots $= 16.5$ g kg^{-1}; (b) P, leaves $= 4.4$ g kg^{-1}, roots $= 4.1$ g kg^{-1}.

Figure 4 shows the mass balances for N and P obtained during the period of 1 year (July 2012–July 2013). The values presented are expressed in terms of kg ha^{-1} $year^{-1}$, and also in relative terms, based on an influent load of 100%. The influent and effluent loads were computed based on the

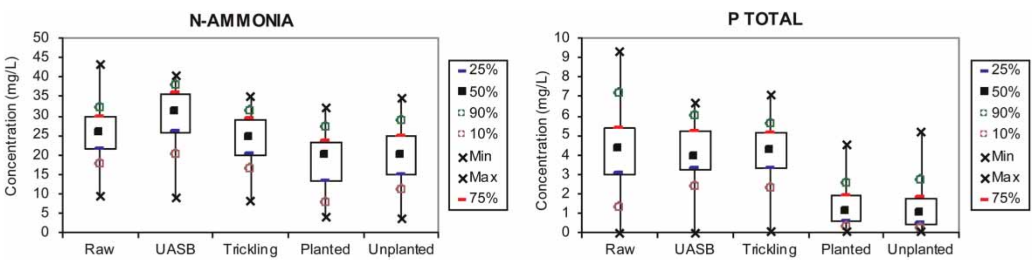

Figure 2 | Box-plots of ammonia and total P concentrations in the units along the treatment system.

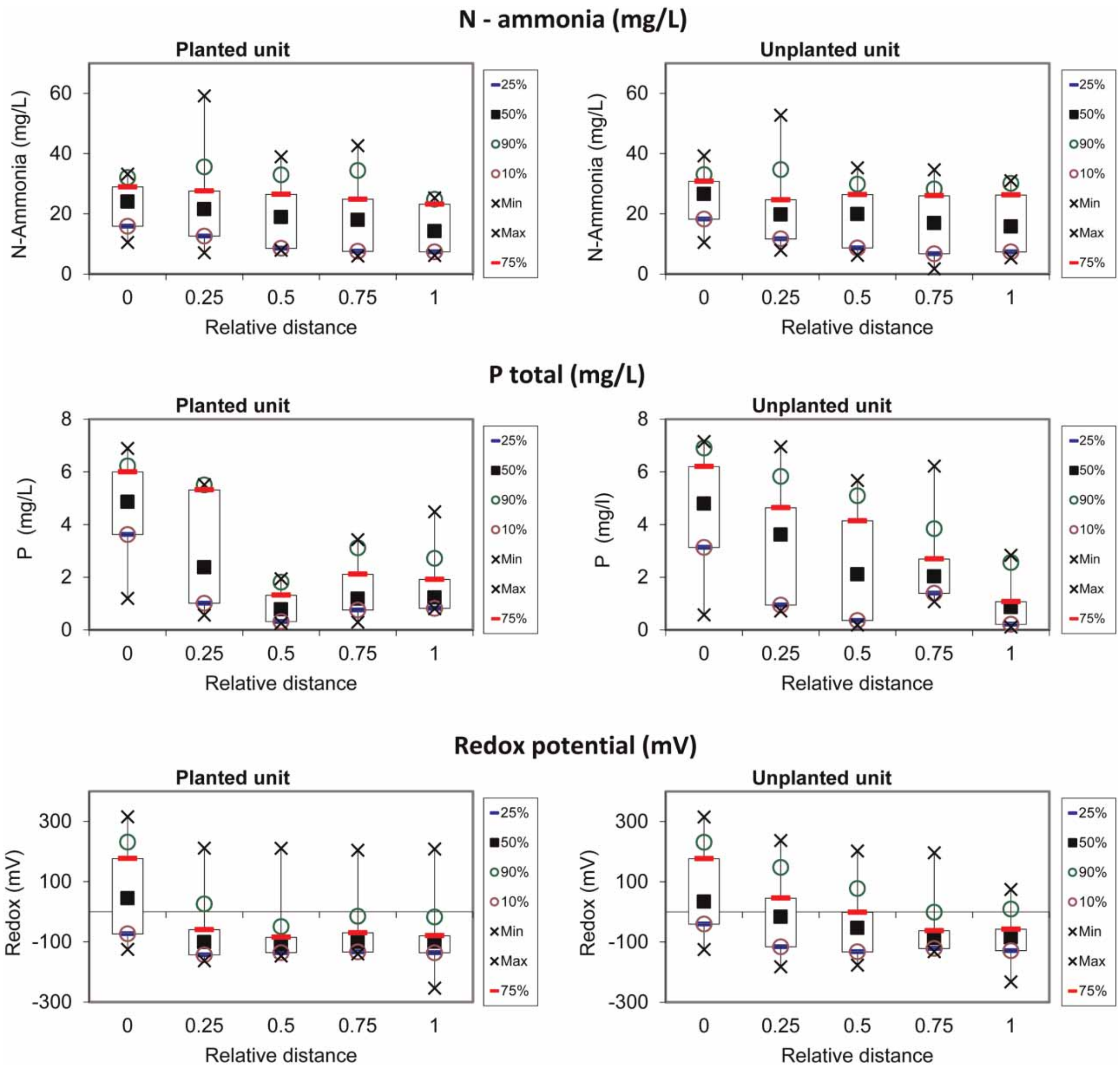

Figure 3 | Box-plots of the longitudinal profile of N-ammonia (top), phosphorus (middle) and redox potential (bottom) along the length of both wetland units.

measurements of influent and effluent flows and concentrations. The uptake by plant biomass was calculated based on Equations (1)–(3). Losses were estimated by a water balance, which indicated losses of water through seepage from the wetlands bottom, which had been lined with compacted clay during construction. Losses by seepage were estimated at 18% of the applied flow, and were calculated based on measurements of precipitation, evaporation and transpiration rates carried out in separate planted and unplanted tanks (evaporimeters and lysimeters) reproducing the same operating conditions as the full-scale units (details in Costa 2013). N and P removal by other mechanisms was computed as the difference between the sources and sinks. As mentioned in the Introduction, it is not the objective of this paper to discuss the mechanisms related to other removal routes of N and P. However, it should be remembered that the support medium utilized here is steel slag, which may explain a higher removal of P.

The most important point of this mass balance is that only 7% of the applied N load was removed by plant uptake, which accounted for 17% of the removed load ($= 7/(35 + 7)$). Similarly, for P, only 6% of the applied load was removed by plant uptake, which accounted for 9% of the removed load ($= 6/(60 + 6)$).

Reddy & DeBusk (1985) reported absorption values by emergent macrophytes in the range of 120–1,200 kgN ha^{-1} $year^{-1}$ for N and 18–180 kgP ha^{-1} $year^{-1}$ for P. Fia *et al.* (2011) obtained N uptake rates between 443 and 540 kgN ha^{-1} $year^{-1}$. For P, Vymazal (2004) reported plant uptakes between 60 and 98 kgP ha^{-1} $year^{-1}$ for *Phragmites australis*

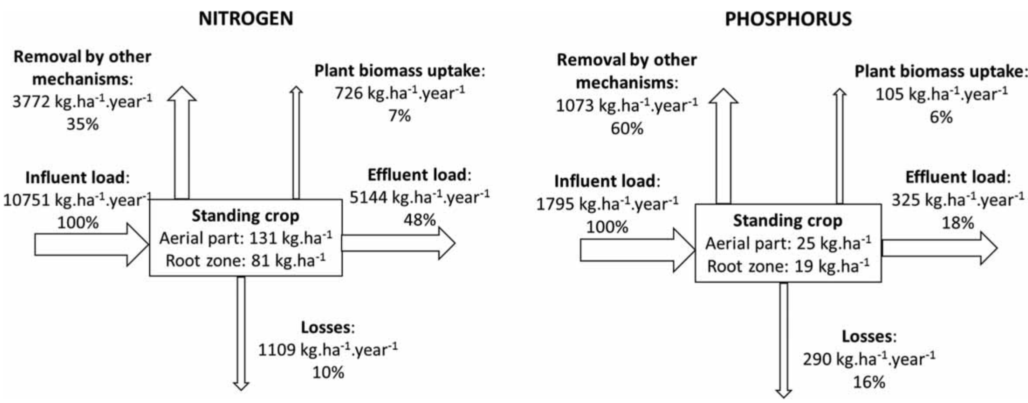

Figure 4 | Mass balance of nitrogen and phosphorus in the planted wetland.

and 20–65 kgPmha^{-1} year^{-1} for *Typha* sp. Brix (1994) stated that emergent macrophytes, such as *Typha latifolia*, are capable of absorbing from 50 to 150 kgP ha^{-1} year^{-1}. The values obtained here (726 and 105 kgP ha^{-1} year^{-1}) are within these ranges.

Summing up the removal by plant uptake and the other mechanisms, it can be seen that the overall removal efficiency of N and P, expressed in terms of loads, was 42% for N and 66% for P (these values are different from those in Table 1, because they apply to the period of only 1 year). The overall removal was 4,498 kgN ha^{-1} year^{-1} and 1,178 kgP ha^{-1} year^{-1}. Vymazal *et al.* (2006) reported values of N removal from 2,500 to 6,300 kgN ha^{-1} year^{-1}, which encompass the mean values obtained here.

CONCLUSIONS

The system comprised of a UASB reactor and a TF in series, followed by two parallel horizontal subsurface-flow constructed wetlands (one planted and one unplanted) was able to achieve a very good performance in terms of organic matter removal (mean removal efficiencies of 94 and 93% for the planted and unplanted units, respectively), a good removal of P (mean efficiencies of 70% for both units) and a fair removal of N (40 and 34%).

Both constructed wetlands contributed substantially to the removal of COD, and were responsible for most of the N and P removal in the treatment system. However, the actual contribution of the plants in terms of nutrient extraction was small. The mean extraction of N by the plant biomass was 726 kgN ha^{-1} y^{-1}, corresponding to 17% of the N load removed. For P the extraction by the plant biomass was 105 kgP ha^{-1} y^{-1}, corresponding to 9% of the P load removed. The results obtained here reinforce the reports that N and P removal due to plant uptake is a minor mechanism in horizontal subsurface-flow constructed wetlands operating under similar surface loading rates, typical for polishing of sanitary effluent.

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