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Performance and behaviour of planted and unplanted units of a horizontal subsurface flow constructed wetland system treating municipal effluent from a UASB reactor

Jocilene Ferreira da Costa, André Cordeiro de Paoli, Martin Seidl and Marcos von Sperling

ABSTRACT

A system composed of two horizontal subsurface flow constructed wetlands operating in parallel was evaluated for the post-treatment of UASB (upflow anaerobic sludge blanket) reactor effluent, for a population equivalent of 50 inhabitants per unit. One unit was planted with cattail (*Typha latifolia*) and the other was unplanted. The study was undertaken over a period of 4 years, comprising monitoring of influent and effluent constituents together with a full characterization of the behaviour of the units (tracer studies, mathematical modelling of chemical oxygen demand (COD) decay, characterization of solids in the filter medium). The mean value of the surface hydraulic load was 0.11 $m^3 m^{-2} d^{-1}$, and the theoretical hydraulic retention time was 1.1 d in each unit. Using tracer tests with ^{82}Br, dispersion number (d) values of 0.084 and 0.079 for the planted and unplanted units were obtained, indicating low to moderate dispersion. The final effluent had excellent quality in terms of organic matter and suspended solids, but the system showed low capacity for nitrogen removal. Four-year mean effluent concentration values from the planted and unplanted units were, respectively: biochemical oxygen demand (BOD_5): 25 and 23 mg L^{-1}; COD: 50 and 55 mg L^{-1}; total suspended solids (TSS): 9 and 9 mg L^{-1}; N-ammonia: 27 and 28 mg L^{-1}. The COD decay coefficient K for the traditional plug-flow model was 0.81 and 0.84 d^{-1} for the planted and unplanted units. Around 80% of the total solids present in the filter medium were inorganic, and most of them were present in the interstices rather than attached to the support medium. As an overall conclusion, horizontal subsurface flow wetlands can be a very suitable post-treatment method for municipal effluents from anaerobic reactors.

Key words | domestic sewage, horizontal subsurface flow constructed wetlands, nitrogen, organic matter, *Typha latifolia*, UASB reactor

Jocilene Ferreira da Costa
André Cordeiro de Paoli
Martin Seidl
Marcos von Sperling (corresponding author)
Departamento de Engenharia Sanitária e Ambiental – UFMG,
Av. Antônio Carlos,
6627 – Escola de Engenharia - Bloco 1,
4° andar, Postal Code –31270-901,
Belo Horizonte,
Brazil
E-mail: *marcos@desa.ufmg.br*

INTRODUCTION

Horizontal subsurface flow constructed wetlands (HSSFW) are generally used as a polishing stage for the effluent from various biological wastewater treatment processes. However, there are relatively few studies in the literature related to the use of subsurface flow wetlands as post-treatment of effluents from upflow anaerobic sludge blanket (UASB) reactors, despite the importance of this anaerobic process for treating sewage in regions with a warm climate (von Sperling & Chernicharo 2005). UASB reactors usually remove around 70% of the influent biochemical oxygen demand (BOD), which usually requires a polishing stage in order to enhance organic matter removal. While this removal may be insufficient for complying with discharge standards in most countries, it does provide an important contribution, reducing land requirements for the post-treatment stage. An important feature of anaerobic reactors is the fact that nitrogen removal is almost negligible, which brings another important role for the post-treatment, in case nitrogen removal is important due to requirements in the receiving water body (Chernicharo 2007).

Sousa *et al.* (2004) evaluated during 3 years the performance of HSSFW receiving effluent from a UASB reactor, obtaining chemical oxygen demand (COD) removal efficiencies varying from 70 to 86%. For total Kjeldahl nitrogen

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(TKN) and P-total, the system was more efficient during the first year of operation, reaching 66 and 86% removal, respectively. Bastos *et al.* (2010), also investigating wetland units for post-treatment of UASB reactor effluents subjected to different loading rates, obtained BOD_5 and SS effluent concentrations lower than 25 mg L^{-1} under all operating conditions. Results obtained by Mbuligwe (2004) showed that horizontal subsurface flow wetlands planted with *Typha* can effectively remove phosphorus, sulfate, ammonia and COD from pre-treated domestic sewage in UASB reactors.

The aim of the present study was to evaluate long term performance based on approximately 4 years of operation of a HSSFW system, comparing one unit planted with *Typha latifolia* and one unplanted unit, treating sanitary sewage originated from a UASB reactor. The relevance is associated with the need to increase research on post-treatment of anaerobic effluents. Moreover, it deals with a long-term detailed evaluation, especially considering that most studies with wetlands are done in the short term, which does not allow a solid performance evaluation (Kadlec & Wallace 2009).

METHODS

The experimental set-up (Figure 1) is located in the Centre for Research and Training on Sanitation – CePTS UFMG/COPASA, located in the Arrudas Wastewater Treatment Plant, in the city of Belo Horizonte, Brazil. The UASB/HSSFW system received wastewater after preliminary treatment (screening and grit removal).

The treatment system consisted of a UASB reactor followed by two horizontal subsurface flow wetland units designed for a population equivalent of 50 inhabitants each and a flow of 8.0 m^3 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. 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; wet volume $V = 21.7$ m^3; flow $Q = 8.0$ m^3/d; surface hydraulic loading rate = 0.11 m^3/m^2 d; hydraulic retention time (HRT) (V.porosity/Q) = 1.1 d.

Routine monitoring was done through weekly sampling of raw wastewater, effluent from the UASB reactor and effluent from the wetlands over a period of 4 years. To determine the longitudinal profile of filtered COD, additional samples were collected along the length of the wetlands (at 25, 50 and 75% of the wetland length, plus inlet and outlet). The physico-chemical analyses were undertaken at the Department of Sanitary and Environmental Engineering of the Federal University of Minas Gerais, Brazil, following the procedures of the *Standard Methods for the Examination of Water and Wastewater* (APHA/AWWA/WEF 2005).

In order to investigate further the COD decay along the longitudinal profile of the wetlands, traditional kinetic models of organic matter decay were used to simulate filtered COD concentration. The specific data for this analysis were obtained when the wetlands were operating for 2 years, covering a 6-month dry period with no significant rainfall, with a total of 16 samples for each sampling point along the wetlands length, as mentioned above.

Traditional kinetic models have been applied to the experimental data. Two categories of models have been

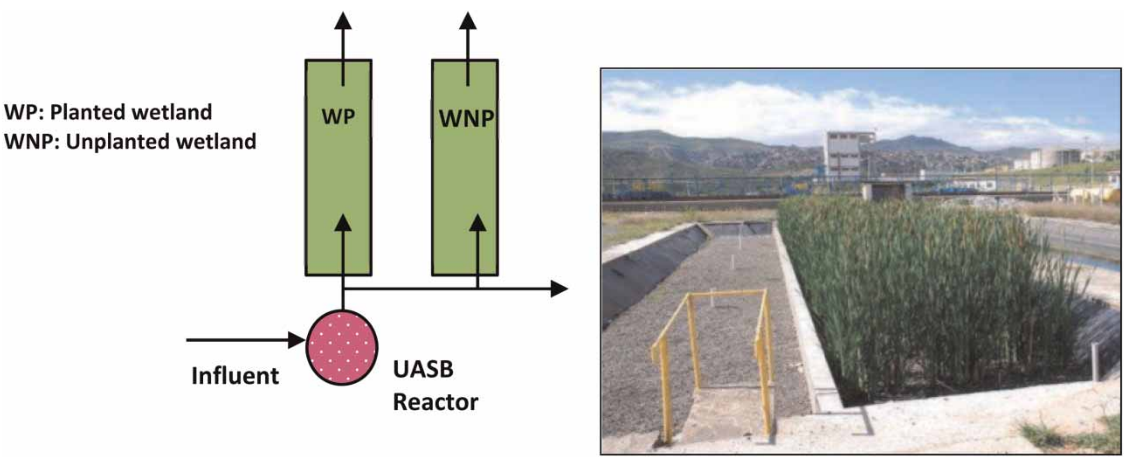

Figure 1 | Schematics and view of the wetland units studied (planted and unplanted).

used: without and with residual soluble COD concentration (C^*). The model equations are presented in Table 1 (further details on the wetlands modelling can be obtained in von Sperling & de Paoli (2013)).

The estimated values of the filtered COD concentrations were fitted against the observed values of the filtered COD concentrations (mean values of the 16 samples at each sampling point). The values of the coefficient K were obtained by minimizing the sum of the squared errors using the Solver tool in Excel™ (error = mean of observed COD concentrations – estimated COD concentration at each of the sampling points). The evaluation of the goodness of fit was done using the coefficient of determination CD (CD values varying from $-\infty$ to $+1$, where $+1$ indicates perfect fitting).

Tracer tests with pulse addition of ^{82}Br were performed, to characterize the flow patterns in the two units. The mean HRT and dispersion number using the variance method and assuming dispersion of great intensity ($d > 0.01$) were calculated according to Levenspiel (1999).

Determination of total nutrient content (N, P) of the plant biomass was performed at three different stages of the plant growth between two cuttings. Representative samples were collected at four different areas along the planted unit.

After 2 years and 4 months of operation, solids inside the filter medium were characterized. Eight paired sampling points were used, at distances of 3, 6, 12 and 18 m from the inlet of the bed, and located on both the left- and right-hand sides of the central axis. At each point, 0.5 L of the support medium was collected together with its liquid content, to include attached and suspended biomass. The slag sample was first passed through a sieve (opening = 2.38 mm) and gently washed twice, using the local effluent. This liquid was characterized as containing interstitial solids. Distilled water was added to the beaker containing the pre-washed slag sample and, to detach the adhered biomass, ultrasound equipment was used for a 15-min period. The sample was sieved again, now with the distilled water containing the loosened biomass. This liquid was characterized as containing solids of the attached biomass. Quantification and characterization of solids were carried out using the method described in AWWA/APHA/WEF (2005) for analysis of total, fixed and volatile solids.

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

Performance evaluation

Table 2 shows the results of the mean influent and effluent flow rates obtained during the 4-year operating period of the system. It can be observed that the effluent flow rates are lower than the influent ones, and that the planted system showed higher water losses. The water losses are due to the evaporation that occurs in the two units and the transpiration that only occurs in the planted unit.

Table 3 shows the descriptive statistics (mean and standard deviation) of the concentrations of the main constituents during the experimental period. The excellent quality of the final effluent, in terms of organic matter and suspended solids in both wetlands units, can be clearly noted.

Table 1 | Kinetic models applied to the experimental data

Model	Traditional equations	Equations with residual C^*
Plug-flow	$C = C_0.e^{(-K.t)}$	$C - C^* = (C_0 - C^*) \cdot e^{(-K.t)}$
Dispersed-flow	$C = C_0 \cdot \dfrac{4ae^{1/2d}}{(1+a)^2 e^{a/2d} - (1-a)^2 e^{-a/2d}}$ $a = \sqrt{1 + 4K.t.d}$	$C - C^* = (C_0 - C^*) \cdot \dfrac{4ae^{1/2d}}{(1+a)^2 e^{a/2d} - (1-a)^2 e^{-a/2d}}$ $a = \sqrt{1 + 4K.t.d}$
Complete-mix tanks-in-series	$C = \dfrac{C_0}{\left(1 + K \cdot \dfrac{t}{N}\right)^N}$	$C - C^* = \dfrac{C_0 - C^*}{\left(1 + K.\dfrac{t}{N}\right)^N}$

C = filtered COD concentration at different points along the wetland unit (mg/L); C_0 = influent COD concentration (mg/L); C^* = residual effluent filtered COD concentration (mg/L); K = COD decay coefficient (d^{-1}); t = hydraulic retention time HRT (=V.porosity/Q) (d); d = dispersion number (–); N = number of equivalent complete-mix tanks-in-series.

Table 2 | Means of the influent and effluent flow rates for each wetland unit

Unit	Mean influent flow rate (m^3/d)	Mean effluent flow rate (m^3/d)	Mean water loss (%)
Planted unit	8.2	6.6	19.5
Unplanted unit	8.0	6.8	15.0

Table 4 shows the averages of the removal efficiencies in the planted and unplanted units, calculated in terms of concentration (traditional way of expressing removal efficiencies) and, because of the water loss in the system, also in terms of load (concentration × flow). As expected, the determination of efficiency based on load leads to higher values than the efficiency based on concentration, thus better representing the actual participation of the system in removing pollutants. The excellent performance of the system as well as the important contribution of the wetlands to the polishing of the UASB reactor effluent are clearly seen, complementing the evaluation based on effluent concentrations.

The large contribution of the wetlands in reducing organic matter from the effluent of the UASB reactor is noted and an important reduction of BOD and COD concentrations in the final effluent can be observed.

The removal of ammonia was small in both units, but the performance in the planted unit was better. Although the full mechanisms associated with nitrogen conversions in the wetlands have not been investigated in this research, incorporation of nitrogen in the plant biomass was evaluated. The following results have been obtained at a different time and under different operating conditions, in which the pretreatment was carried out by the UASB reactor and a trickling filter in series (instead of only the UASB reactor), but can still be useful here, since the influent concentrations to the wetlands were approximately the same, because nitrification in the trickling filter was very small. Nitrogen uptake by the plants had mean values of nitrogen mass per kg of plant dry matter (DM) of 33.0 gN/kgDM (growth phase, 1.5 months after cutting), 21.0 gN/kgDM (intermediate phase) and 13.0 gN/kgDM (senescence phase, 4 months after cutting). It can be observed that at the beginning of plant growth nitrogen uptake was much higher than in the senescence period. However, only 1.06% of the total nitrogen load applied to the wetland was incorporated by the plant biomass. These values of nitrogen uptake are similar to those found by Brasil *et al.* (2007) in HSSF wetlands planted with cattail treating domestic sewage, who reported average values of 15.0 gN/kgDM. From these comments, it is believed that the better performance of the planted unit in the removal of TKN and ammonia is due to other mechanisms, not directly related to N uptake by the plants.

The comparison between the performance of the planted and unplanted units was done applying the nonparametric Wilcoxon test for dependent variables (matched pairs) at the 5% significance level, for the two following

Table 3 | Mean concentration and standard deviation of the quality parameters

	Raw wastewater		UASB reactor		Planted wetland		Unplanted wetland	
Parameters	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
COD	414	195	179	75	50	19	55	25
BOD	293	223	83	58	25	19	23	17
TSS	296	115	51	53	9	8	6	7
VSS	227	86	36	37	4	4	3	3
TKN	29	10	32	8	30	9	31	9
Ammonia	24	6	29	8	27	10	28	10
Nitrite	0.02	0.06	0.02	0.06	0.02	0.11	0.006	0.01
Nitrate	0.03	0.08	0.05	0.09	0.16	0.25	0.12	0.23
DO	1.03	0.7	0.74	0.8	0.68	0.6	1.32	0.9
P-total	–	–	3.2	2	2.3	2	2.3	2
pH	7.1	0.2	6.8	0.2	7.2	0.1	7.3	0.4
Alkalinity	207	46	217	35	255	60	249	57
Electr. cond.	721	71	672	78	801	84	803	79

The unit adopted for all parameters is mg L^{-1}, except pH (dimensionless) and electrical conductivity (μScm^{-1}). TSS: total suspended solids; VSS: volatile suspended solids; DO: dissolved oxygen.

Table 4 | Mean removal efficiencies of the treatment units

Parameters	Efficiency (%) UASB	Wetlands efficiency based on the concentration removed (%) Planted	Unplanted	Wetlands efficiency based on the load removed (%) Planted	Unplanted	Overall system efficiency based on the concentration removed (%) UASB + planted	UASB + unplanted
COD	57	72	69	78	74	88	87
BOD_5	72	70	72	76	76	91	92
TSS	83	82	88	86	90	97	98
TKN	–	6	3	25	18	–	–
Ammonia	–	7	3	25	18	–	–

Efficiencies calculated based on the mean concentrations (Table 3) and mean influent and effluent flow rates (Table 2).
Efficiency expressed in concentration: (mean influent concentration–mean effluent concentration)/mean influent concentration.
Efficiency expressed in load: (mean influent load–mean effluent load)/mean influent load.

results: (i) median values of measured effluent concentrations and (ii) median values of removal efficiency based on load (Table 5). It can be observed that, in general, a significant difference between each unit was obtained for COD, TKN and ammonia, and no significant difference was found for BOD, TSS, nitrate and phosphorus.

Table 5 | Comparison between planted and unplanted units. Results of the Wilcoxon test for the medians of the measured effluent concentrations and medians of removal efficiency based on load

Parameters	*p*-value for effluent concentration	*p*-value for efficiency based on load
BOD	0.985	0.184
COD	0.056	0.007
TSS	0.953	0.990
TKN	0.051	0.000
Ammonia	0.001	0.002
Nitrate	0.069	0.578
P-total	0.111	0.304

$p \leq 0.05$: medians of the planted and unplanted units are significantly different.
$p > 0.05$: medians of the planted and unplanted units are not significantly different.

COD decay along the length of the units

Figure 2 shows the mean values observed for the decay in the concentration of organic matter (filtered COD; $n = 22$ data for each point) along the longitudinal axis of the units. The decay trend follows the traditional format of first order kinetics.

Tracer tests (^{82}Br) were performed in order to characterize the hydraulic behaviour of the units and to obtain information for the mathematical modelling of COD decay. From the tracer tests, the following values of the dispersion number were obtained: planted unit, $d = 0.084$; unplanted unit, $d = 0.079$. These values indicate low to moderate dispersion. For the tanks-in-series models, the estimated number of tanks in series was 6.50 (planted unit) and 6.87 (unplanted unit). The tracer experiments indicated non-substantial differences between the actual HRT, with mean values of 1.30 and 1.43 d for the planted unit

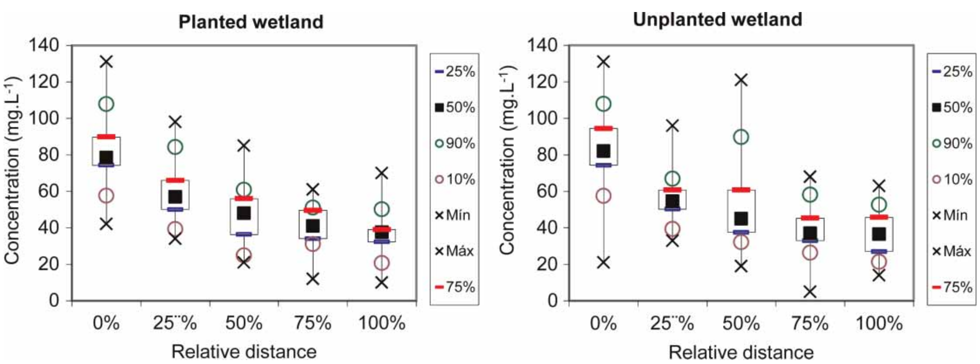

Figure 2 | Box-plot for the decay of the concentration of organic matter (filtered COD) along the wetlands.

and unplanted unit, respectively (de Paoli & von Sperling 2010). Under the test conditions, the theoretical HRT calculated on the basis of the real water volume (average length = 24.1 m; average width = 3.0 m; average height of liquid in the bed, taking into account clogging during the test period = 0.35 m; porosity = 0.4) and the average inflow during the test period (7.15 m^3/d, without considering water gains or losses) was 1.42 d.

Table 6 presents a summary of the *K* values obtained for each of the three conventional COD decay models, without and with residual *C**. All models represented well the mean values of COD decay along the units, resulting in very good coefficients of determination, which ranged from 0.940 to 0.992, with the best fittings associated with the dispersed-flow and tanks in series models with residual *C**. As expected, the performance of the dispersed-flow and tanks in series models were equivalent, and the resulting *K* coefficient is virtually the same (apart from rounding errors).

Since the conventional plug-flow model ($C = C_0.e^{-K.t}$) is the one more frequently used for the design of horizontal subsurface flow wetlands, it is interesting to compare the values of the coefficient *K* obtained (0.81 d^{-1} for the planted unit without residual *C**) with those reported in the literature: 0.8–1.1 d^{-1} (Reed *et al.* 1988); 0.7 $d^{-1} \pm 0.2$ (Conley *et al.* 1991); 0.86–1.84 d^{-1} (Metcalf & Eddy 1991); 0.17–6.11 d^{-1} (Rousseau *et al.* 2004); 0.44 d^{-1} (Brasil 2005); 0.31–2.65 d^{-1} (Stein *et al.* 2006); 0.46–0.75 d^{-1} (Sandoval-Cobo & Peña 2007); 0.56–1.37 d^{-1} (Fia 2009). It can be seen that the values obtained are within the range reported in the literature, but loading rates and the existence and type of biological pre-treatment are likely to influence the decay coefficient. It should also be noted that the values obtained in the present study are for COD removal, whereas most of the values reported in the literature are for BOD_5 removal.

Characterization of solids in the filter medium

Figure 3 shows the proportion of volatile solids as percentage of the total solids along the bed of each wetland. The

Table 6 | Values of the coefficient *K* for the three models (without and with residual *C**) for the planted and unplanted wetlands

Item	Conventional model		Model with residual *C**	
	Planted	Unplanted	Planted	Unplanted
Plug flow	0.81	0.84	1.15	1.12
Dispersed flow	0.85	0.88	1.24	1.21
Tanks in series	0.86	0.89	1.25	1.21

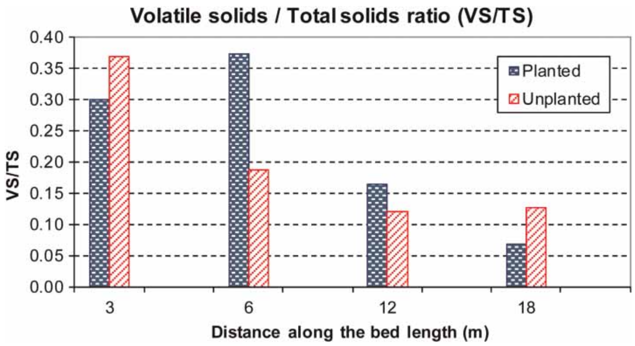

Figure 3 | Ratio of volatile to total solids (VS/TS) in the filter medium along the planted and unplanted units.

data are an average of the left and right profiles. Along the longitudinal axis of the beds, solids tended to be mineralized, thereby reducing the volatile fraction. Similarly to the results from Tanner *et al.* (1998) and Caselles-Osorio *et al.* (2007), most of the accumulated solids in the bed consisted of inorganic solids. For these authors, the fixed solids fraction was 90 and 85% of the total solids, for the planted and unplanted units, respectively. In the present research, these values were 78 and 80% respectively.

Figure 4 shows the proportion of interstitial and attached solids for each wetland (average of the left and right profiles). The planted unit had a larger amount of solids, especially at the bed inlet. These solids were probably formed largely by the development of bacterial biomass that grew in the interstices of the filter medium. In both wetlands, and at all sampling points, most of the solids were interstitial (around 80% at the inlet and 60% at the outlet of both units), with the attached biomass representing a lower fraction. More details can be found in de Paoli & von Sperling (2013).

After 4 years of operation, occurrence and evolution of unwanted surface runoff were observed in the initial portions of both units due to the accumulation of solids. A larger amount of surface runoff occurred in the planted unit, which showed a greater mass of accumulated solids in the initial zone.

CONCLUSION

The planted and unplanted wetlands treating the effluent from a UASB reactor showed an excellent performance of organic matter and suspended solids removal during the 4 years of operation. However, the removal of nitrogen and phosphorus was low. From the statistical tests undertaken, it was observed that the planted unit had a better

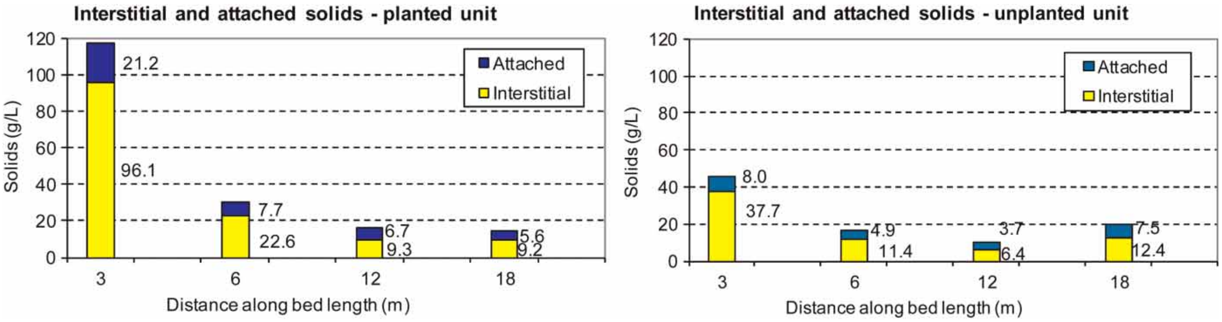

Figure 4 | Proportion of interstitial and attached solids along the beds of the planted and unplanted units.

performance in terms of COD, TKN and ammonia removal. Nitrogen uptake by the plant biomass was a minor mechanism in nitrogen removal.

Longitudinal profile measurements of the COD concentration indicated continuous decay along the length. The mean decay could be well simulated by traditional models from the literature, such as plug flow, dispersed flow and tanks in series.

The water flow in the wetlands, which have a length/width ratio equal to 8, indicated small to moderate dispersion as a function of the dispersion number and the equivalent number of tanks in series obtained from the tracer tests.

The planted wetland accumulated more solids in the filter media than did the unplanted wetland. Of the accumulated solids, most of them were inorganic. In terms of distribution between interstitial and attached solids, the interstitial fraction was the highest.

Based on the results obtained over this long-term and detailed monitoring study it may be concluded that horizontal subsurface flow wetlands constitute a good alternative for the post-treatment of effluents from UASB reactors, especially for complementary organic matter and suspended solids removal.

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