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UPGRADING POND EFFLUENT WITH VERTICAL FLOW CONSTRUCTED WETLANDS AND INTERMITTENT SAND FILTERS: COMPARISON OF PERFORMANCES AND HYDRAULIC BEHAVIOUR

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ABSTRACT

With the aim of improving the WSP effluent quality, different types of Vertical Flow Constructed Wetlands and Intermittent Sand Filters were tested in a pilot plant in Aurignac (France). The effectiveness of each design for upgrading the effluent from the pond was studied over a period of two years. Physicochemical parameters were monitored by taking composite samples over 24 hours and weekly punctual samples. The hydraulic behaviour of the filters was studied by tracing methods (using NaCl) and monitoring the infiltration rate. This paper describes the influence of: (a) the characteristics of the medium (presence of *Phragmites*, depth, type of sand), (b) feeding modes and (c) the presence of an algae clogging layer on the performance of the beds. Overall, both Vertical Flow Constructed Wetlands and Intermittent Sand Filters are appropriate systems for retaining algae, completing organic matter degradation and nitrifying the WSP influent. The design and operation bases, the hydraulic behavior and the advantages and disadvantages (in terms of efficiency and maintenance) of the different configurations were determined.

KEYWORDS

Clogging; hydraulics; intermittent sand filters; pond effluent; vertical flow constructed wetlands.

INTRODUCTION

Waste Stabilization Ponds (WSPs) are appropriate wastewater treatment technologies for small communities, although the presence of algae in the effluent can limit their implementation when high quality effluent is required. In the case of fragile receiving bodies, the WSP effluent quality is not always sufficient according to the limits set out in certain regulations: e.g. French Quality Level D4: <125 mg/L COD; <25 mg/L BOD_5 (Racault and Boutin, 2005). For this reason, a complementary treatment is required. Several methods for upgrading the quality of WSP effluent have been studied (Johnson and Mara, 2005; Kimwaga *et al.,* 2006). The implementation of Vertical Flow Constructed Wetlands (VFCWs) and Intermittent Sand Filters (ISFs) as polishing treatments can solve the problem of effluent quality due to their capability for retaining algae (Neder *et* al. 2002; Kayser *et al.* 2002), remove organic matter and nitrify the filter influent. Although there is a lot of experience with VFCW and ISF treatment of "algae-free" effluent, the optimal design and operation of these technologies for treating a WSP effluent is not completely developed. In this context, an experimental plant using the combinations WSP+ISFs and WSP+VFCWs was built in Aurignac (France) as part of an European LIFE programme. One of the aims of the project was to define the most appropriate system for upgrading WSPs. This paper presents the study of the effectiveness of 4 different designs of ISFs and 2 of VFCWs in improving pond effluent over a period of 2 years. A description is given of the influence of*: (a) characteristics of the medium (presence of Phragmites, depth, type of sand), (b) feeding/operation modes and (c) presence of an algae clogging layer* on the hydraulic and the performance of beds.

MATERIAL AND METHODS

Experimental plant description The Aurignac wastewater treatment plant is designed for 300 PE (PE=People Equivalent) and consists of one facultative pond ($7m^2$/PE) followed by six independent filters in parallel with a surface of $50m^2$ each ($1m^2$/PE). The filters have three different types of media (river sand, river sand with *Phragmites australis* and crushed sand). The granulometry of the sands was chosen according to the recommendations set up in France (Liénard *et al*., 2001). Two filter heights were used for each kind of medium: 25 and 65 cm. The main characteristics of the filters are shown in Table 1.

Table 1. Main characteristics of the filters

Filter	Depth (cm)	Support media	Sand Characteristics			
			d_{10}[2]	CU[3]	Fines content (% by weight)	Porosity (%)
M25	25	Planted[1] River sand	0.25	4.7	2.1	0.42
M65	65	Planted[1] river sand				
R65	25	River sand	0.25	4.7	2.1	0.42
R25	65	River sand				
C65	25	Crushed sand	0.19	9.3	4.0	0.44
C25	65	Crushed sand				

[1] Reeds: *Phragmites australis* (4 plants/m^2), [2] d_{10}: Mesh diameter allowing 10% of the sand mass to go through (mm), [3] CU: Coefficient of uniformity: ratio d60/ d10

Operation The filters were alternately fed with a feed/rest period of 3-4/7 days. Different hydraulic loads and feeding frequencies were tested for each filter (Table 2) in order to establish the impact of the operational mode on the hydraulics and treatment performance.

Table 2. Operation stages

Stage	Duration (months)	Hydraulic Load (HL) (cm/day)	Organic Load ($COD/m^2·d$)	Feeding modes	
				Height of batch (cm)	Number of batches per day (f)
1	4	20	17-21	5	4
2	10	40	42-68	5	8
3	5	80	104-140	5	15
4	5	80	119-170	2.5	30

Monitoring *(a) Hydraulic measurements.* Inlet and outlet flows were measured using pump functioning time and Venturi channels. Infiltration rates (IR) were quantified by measuring the level of the surface water with 2 ultrasound probes per filter. All these data were recorded on a data logger minute by minute. Periodic experiments with flow tracer impulse were carried out in all the filters using sodium chloride (NaCl) which can be easily monitored by conductimetric sensors. All tracer tests were done after adequately moistening the filter (a minimum of 4 batches preceded all the tracing batches). *(b) Physico-chemical analyses.* A two-year monitoring program consisting of the analysis of 24-hours composite-samples (40 tests) and grab samples (collected weekly) were performed from September 2003 to October 2005. Physicochemical parameters were evaluated in the WSP outlet (=filters inlet) and the ISFs outlet. pH, EC, COD, BOD_5, SS, KN, $N\text{-}NH_4$, $N\text{-}NO_3$, $P\text{-}PO_4$ and TP were analyzed according to standard French methods (AFNOR, 2005). Laser granulometry (particle counter Hiac Royco Pacific Scientific 8000) was applied to study the filtration capacity of the beds. Temperature inside the filters was also monitored by sensors located at 15 cm depth.

RESULTS AND DISCUSSION

The characterization of the water entering the filters is presented in Table 3.

Table 3. Characterization of the WSP effluent: average (mg/L) and standard deviation (SD)

Parameter	COD	dCOD	BOD_5	SS	KN	$N\text{-}NH_4$	$N\text{-}NO_3$	TP	$P\text{-}PO_4$
Average	140	93	60	44	19	12	< 0.5	3.5	2.4
SD	45	56	34	22	5.4	5.2	-	0.5	0.5

During the monitoring all filters achieved the quality fixed by French regulations for discharge in sensitive areas, with effluent concentrations lower than 100 mg/L for COD and 20 mg/L for BOD_5 (Torrens *et al.*, 2006). VFCWs and ISFs were effective removing TSS (59-78 % depending on the design) confirming their capability for retaining algae. The pond effluent was nitrified, even in winter periods, with KN concentrations <8 mg/L and $N\text{-}NH_4$ concentrations ≤4mg/L. The TP outlet concentrations ranged from 1.9 to 3.4 mg/L. Retention of phosphorus was low and in one year the removals diminished drastically in all beds (from 80% to 20 % for planted filters). Although all filters performed efficiently during the two years of monitoring, differences in the performances were evident depending on the studied configurations and conditions.

Effect of the presence of *Phragmites*.

Planted and unplanted beds presented similar IR and Detention Time Distribution (DTD) curves (Figure 1). However, it is to note for the first batches that a fraction of the water flowed through the planted beds more quickly than trough the unplanted filters, possibly due to the presence of rhizomes creating preferential ways.

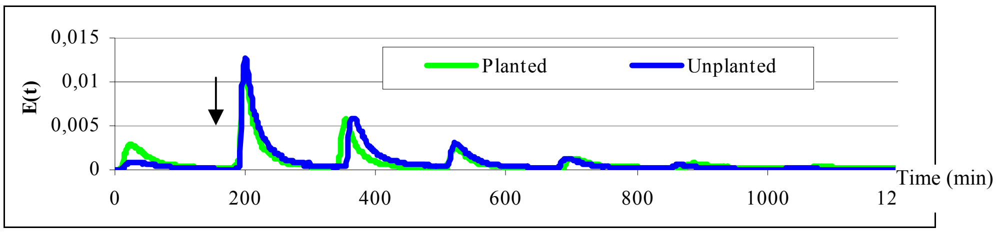

Figure 1. DTD curves for planted and unplanted filters of 65 cm cm (HL=40 cm/day, f=8)

Planted filters presented slightly better performances (Table 4), but not significant. In relation to KN and N-NH_4, both filters had similar average removal performances (Table 4). This suggests that ammonia assimilation by plants, as well as their role in rhyzosphere oxygenation, is of minor importance in vertical filters, which is in concordance with Reed (1993) and Kefalla (2005).

Table 4. Performance of planted and unplanted filters: average outlet pollutant concentration (SD) and % removal

	COD		BOD_5		SS		KN		N-NH_4		N-NO_3	
	mg/L	%	mg/L	%	mg/L	%	mg/L	%	Mg/L	%	mg/L	%
Planted river sand 65 cm	57.7 (15)	62	6.2 (2.5)	89	9.8 (6.3)	78	4.3 (3.9)	79	1.6 (2.6)	93	10.4 (6.3)	(1)
Unplanted river sand 65 cm	59.3 (18)	57	7.9 (3.5)	85	11.5 (5.9)	75	4.9 (4.1)	78	1.7 (3.7)	90	18.5 (11)	(1)
Planted river sand 25 cm	79.0 (16)	44	13.5 (4.2)	76	17.1 (8.6)	63	6.9 (5.4)	70	2.7 (4.2)	83	11.1 (4.8)	(1)
Unplanted river 25 cm	79.8 (18)	42	13.6 (5.7)	76	17.8 (8.2)	63	6.5 (4.1)	69	3.0 (4.3)	82	14.3 (8.8)	(1)

(1) Inlet N-NO_3 concentrations <0.5 mg/L

Nonetheless, the average N-NH_4 reduction by the planted filters was slightly higher than that of the unplanted in the colder periods (Figure 2). Two principal parameters are stated to affect microbial nitrification: temperature and oxygen availability. The redox curves in the effluent of the filters, in aerobic conditions, did not show any difference between the beds. Then, the differences could be explained by the different temperatures inside the filters (Figure 3). As noticed by Brix (1994) air temperature variations are attenuated in the planted filters due to the vegetation, and therefore the temperatures inside the filters with macrophytes were warmer.

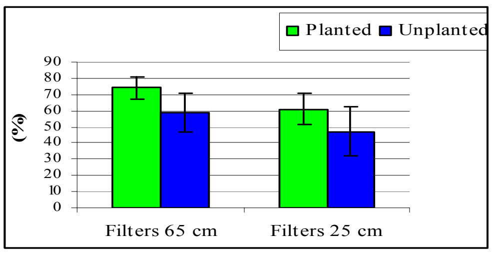

Figure 2. N-NH_4 removal in winter (HL=40 cm/day, f=8)

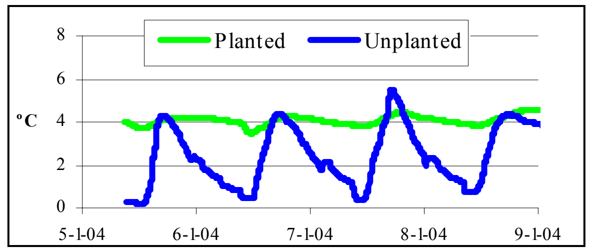

Figure 3. Temperature at 15 cm inside the filters M65 and R65

The removal of TP and P-PO_4 was not important in any case (<5 % for unplanted and around 20% for planted filters the second year of operation). The better performance of the planted filters was probably due to the assimilation of phosphorous by the plants. In order to mantain the planted filters, the faded part of the reeds was cut and removed once a year. For the unplanted beds, maintenance was more frequent and complicated due to the continuous growth of heterogeneous weeds.

Effect of the depth of the filter.

As expected, tracer results showed that water flowing out through the filter was faster for the 25cm filters than for the 65cm filters (Figure 4). This can be explained by the flow resistance increasing with filter depth. Then it is remarkable that with an increase of 40 cm depth, the residence times are much higher (3 to 5 hours more).

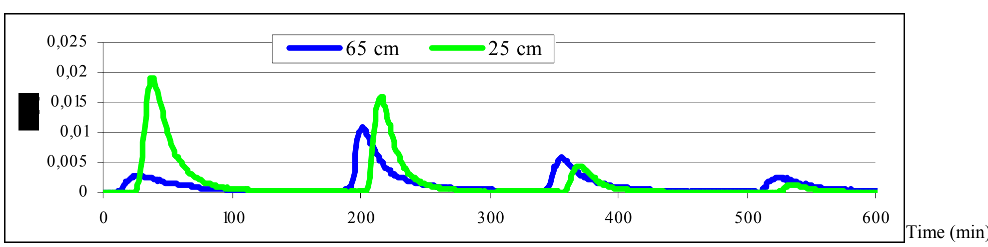

Figure 4. DTD curves for river sand filters 65 cm and 25 cm (HL=40 cm/day, f=8)

The 65cm filters showed better performances for all physicochemical parameters (Figure 5), especially for the removal of organic matter. Probably the short HRTs of the shallow beds do not allow for better performances. It should be noted that the effluent quality from 25cm filters presented COD and BOD_5 concentrations close to the required discharge limits (Figure 5a).. Filter depth also had a significant effect on algae removal, as demonstrated by the granulo-laser analyses and SS removal. Microscopic and biological analyses of the sand showed that algae retention, especially in the case of round and small algae (e.g. *Chlorella*), not only occurs at the surface of the filter but troughout the media. For the tested granulometries the depth of the filter also played a role in algae filtration.

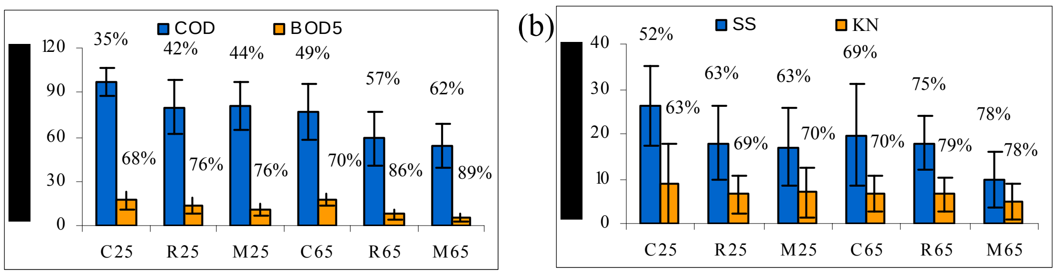

Figure 5. Concentration of filter's effluent and percentage removal for (a) BOD_5-COD (b) SS-KN

The effect of different sand types.

From the IRs and the tracer tests no consistent conclusion can be drawn in relation to the hydraulic behavior depending on the type of sand. Pilot tests under more controlled conditions must be performed in order to compare the hydraulic patterns of the two media. Regarding the performance of filters (Table 5), statistical analysis indicated that the type of sand had a significant effect on the removal of all contaminants. Crushed sand filters performed worse than river sand filters in all the tested conditions.

Table 5. Performance of crushed sand and river sand filters: average outlet pollutant concentration (SD) and % removal

	COD		dCOD		BOD_5		SS		KN		$N-NH_4$	
	mg/L	%	mg/L	%	mg/L	%	mg/L	%	mg/L	%	mg/L	%
Crushed Sand 65 cm	76.4 (18)	49	67.1 (18)	27	17.0 (4.1)	70	19.7 (11)	69	6.7 (3.9)	70	4.0 (3.1)	73
River Sand 65cm	59.3 (18)	57	49.1 (21)	47	7.9 (3.5)	86	11.5 (5.9)	75	4.9 (4.1)	78	1.7 (3.7)	92
Crushed Sand 25 cm	96.9 (17)	35	69.2 (15)	23	18.1 (6.2)	68	26.3 (10)	52	8.7 (5.5)	63	4.3 (4.5)	71
River Sand 25cm	79.8 (18)	42	55.3 (17)	35	13.6 (5.7)	76	17.8 (8.2)	63	6.5 (4.1)	69	2.7 (4.2)	82

The effect of the dosing regime.

DTD was strongly influenced by the fractionation of the daily hydraulic load (f) (Figure 6), as observed by Brissaud (1999) and Molle (2006). For the same HL (80 cm/day), when f was lower than 15 an important part of the applied water spent only a very short time in the bed. Tracer breakthrough occurred for less than one hour when f=15. Figure 7 shows the proportion of water from the tracing batch that went out directly from the filter in the first batch. For the deeper beds, water exchanges inside the filters were worse with greater batch volumes. For the 25cm filters, f did not significantly influence hydraulic behaviour.

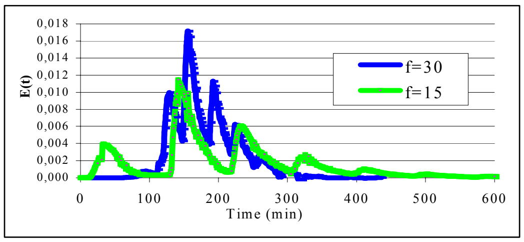

Figure 6. DTD curves for f=15 and f=30 and f=30

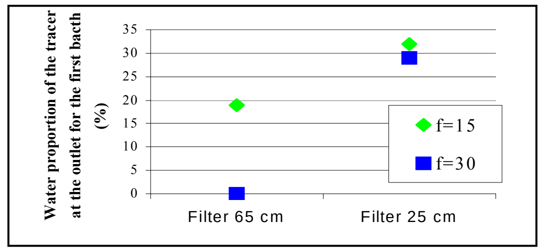

Figure 7. Dilution of the tracer batch for f=15

The dosing regime also played an important role in determining the level of treatment in the filters (Table 6). In the first days of feeding, COD, SS and KN performances were significantly better at higher f values, for all of the 65cm filters. These results are in accordance with Folch (1999) results. COD removal and oxidation of nitrogen appeared to be highly dependent on f.

Table 6. Removal efficiency in the first two days of feeding (HL=80 cm/d)

Parameter	COD		SS		KN	
Daily doses / Filter	f=15	f=30	f=15	f=30	f=15	f=30
C25	33.0	34.6	41.8	44.4	65.7	70.6
R25	24.9	27.0	46.1	49.0	71.2	78.7
M25	33.3	38.2	51.1	52.0	71.0	78.8
C65	45.9	53.8	63.6	66.0	64.0	77.1
R65	40.8	58.7	66.5	81.8	68.2	87.3
M65	42.9	60.9	68.0	82.2	72.0	88.4

Folch (1999) and Bancolé (2004) showed that the more daily feed was divided, the greater the removal of organic matter and nitrogen. Nevertheless batch frequency has a different impact on the evolution of COD removal and nitrification efficiency. As it was shown by Molle *et al*., (2006) we observed that while COD removal remains constant with time when f is 30, nitrification further decreases (Table 7). Nitrification is happening mainly between batches. Therefore, when the fractionation is higher HRT is also higher but oxygenation is lower due to a lower oxygen diffusion into the system. When f=30 a higher feeding period than the established (3-4 days) could thus limit the oxygenation and the nitrification capacity especially for the 65cm filters.

Table 7. Removal efficiency for the the first and fourth day of feeding (HL=80 cm/d)

Filter	R65				C65				M65			
Daily doses	f=15		f=30		f=15		f=30		f=15		f=30	
Day of feeding	1st	4th	1st	4th	1st	4th	1st	4th	1st	4th	1st	4th
Nitrification (%)	68	69	88	67	64	60	77	58	73	71	87	64

Effect of deposit on the surface of the filters.

In autumn 2003, surface clogging of the filters appeared. Failure to respect the recommended feeding and resting periods (3-4/7 days) coupled with the presence of potentially clogging algae (*Scenedesmus)* in the WSP effluent enhanced the build-up of a surface organic clogging mat. On the surface of the 25cm river sand filter (R25) a 7mm deposit was formed and then manually removed. Two tracer tests and performance analysis (HL 20 cm/day) were done on the R25 filter, once with the deposit present and a second time after the deposit had been removed. The hydraulic behavior and treatment performance in the two cases were markedly different despite the small height of the deposit. The outflow was much faster after the clogging layer had been removed and thus the stocked water was lower as shown by the DTD curves (Figure 8). The average retention time was much shorter when there was no algae deposit. This was also demonstrated by the continuing monitoring of IR. The IRs values were very different: between 10^{-6} and $10^{-7} m.s^{-1}$ with the deposit presence and greater than $1.5.10^{-4} m.s^{-1}$ after the surface deposit had been removed. Clogging by algae strongly decreased IR because almost all the algae and SS were filtered at the surface (Figure 10a) if the particles were bigger than 20-30 µm. Ponded water at the surface hindered oxygenation, anoxic state appeared (Figure 9) and performances decreased. Moreover, ponded water favoured rapid algae development and increased clogging. Controlling the feeding and restings period is thus of great importance for the durability and the reliability of the system.

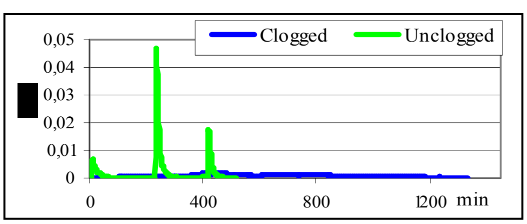

Figure 8. DTD curves for R25

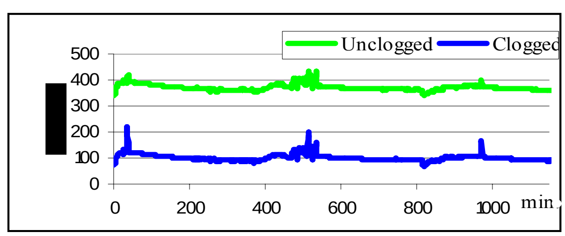

Figure 9. Redox conditions for R25

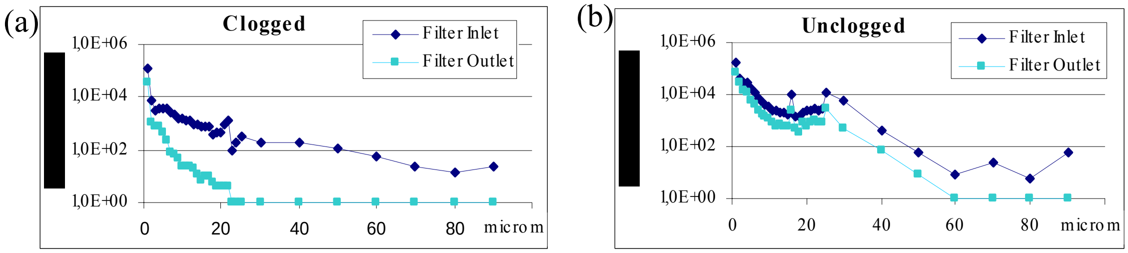

Figure 10. Particle count analysis at the inlet and outlet of the filter R25 for (a) clogged (b) unclogged conditions

CONCLUSIONS

The study has proved the viability of VFCWs and ISFs for upgrading effluent from WSPs. Both technologies have demonstrated their effectiveness for retaining algae, for completing organic matter degradation and for nitrifying the pond effluent; even in winter periods and for HL up to 80cm/day. The presence of plants does not significantly affect the performance of filters. However, the presence of *Phragmites* is important in terms of maintenance and robustness of the systems due to their thermal effect among others. The deeper filters presented better removals for all parameters, especially the elimination of organic matter, due to their higher HRTs. The outlet quality of the 25cm filters was very close to the required limits of quality and so, for safety reasons, it is recommended to use deeper filters. Crushed sand filters presented lower removals for all parameters. Crushed sand is not to be discarded but more studies in relation to its hydraulic behavior and performances are needed. For the same HL an increase in the number of daily doses resulted in higher HRTs and better percentage removal for almost all parameters. Following the recommended feeding/resting periods was of a great importance for avoiding surface clogging by algae. Such clogging drastically reduced the capacity for both infiltration and oxidation. For the studied conditions the recommended configuration is: river sand filters planted with *Phragmites* ($1m^2$/PE; >25 cm depth) divided in 3 beds with feeding/resting periods of 3-4/7 days. These dimensioning bases can be useful for upgrading existing WSPs and for the design of new WSPs, allowing a reduction of the total necessary surface compared to the classical WSPs configurations and increase water quality.

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