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Distribution and biodegradability of sludge accumulated in a full-scale horizontal subsurface-flow constructed wetland

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ABSTRACT

Sludge accumulated in the inlet and outlet zones of a full-scale horizontal subsurface-flow constructed wetland was analysed in order to assess its distribution pattern and biodegradability characteristics. The amount of sludge was very variable (4.6–20.2 g TSS·kg gravel^{-1}) depending on sample location and it was mainly composed by mineral fractions (ca. 90% of the total solids content). Sludge accumulated at the inlet zone was more easily biodegraded by both aerobic and anaerobic pathways than that accumulated at the outlet zone. Specific methanogenic activities of the sludge at the inlet and outlet zones expressed as BOD equivalents were 7.8 mg BOD·g VSS^{-1}·d^{-1}, and 1.7 mg BOD·g VSS^{-1}·d^{-1}, respectively. Specific aerobic biodegradability of the sludge at the inlet and outlet zones were 23 mg BOD·g VSS^{-1}·d^{-1}, and 3.8 mg BOD·g VSS^{-1}·d^{-1}, respectively. Only around a 5% of the organic matter of the tested sludges could be degraded through aerobic pathways, and therefore it was rather refractory. Results of this study indicate that density and packing properties of the sludge are so important as the amount of sludge in relation to clogging processes.

Keywords: Wastewater; Small communities; Reed beds; Hydraulic conductivity; Methane

1. Introduction

The application of natural wastewater treatment systems, specifically horizontal subsurface-flow constructed wetlands (HSSF CWs), for the sanitation of small communities has recently increased in Spain [1]. HSSF CWs offer several advantages over conventional wastewater treatment systems. Some of the most important advantages of HSSF CWs are low sludge production, not specialised staff needed, good landscape integration, and low operation and maintenance costs [2].

Although HSSF CWs have been proved to be a very efficient technology for the removal of a wide range of domestic sewage contaminants [3], the progressive clogging of the granular medium can affect to a great extent its treatment capacity [4]. In fact, clogging is the worst operational problem described for this technology [5]. It is a complex phenomenon in which biological and physico-chemical processes — such as sedimentation, chemical precipitation, biofilm growth and solids entrapment — are involved [4]. Therefore, the study of this phenomenon has aroused the interest of both technical and scientific communities.

Several recommendations have been provided by practitioners and researchers in order to avoid a quick clogging of the granular medium and thus increase the lifespan of HSSF CWs [6]. As example, one of these recommendations consists in the use of intensive pretreatments with the aim of reducing the amount of solids that get into the wetland [7]. These solids accumulate in the form of sludge and avoid maintaining a permanent high hydraulic conductivity [8].

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There have been few efforts to quantify the different sort of solids accumulated within the granular medium of HSSF CWs. Refractory compounds (mainly lignocelulose) have been reported to be quite important [9,10]. More scientific knowledge on distribution and biodegradability of sludge accumulated in HSSF CWs is needed. This information will contribute to the development of appropriate management and operational strategies for mitigating clogging processes. The main objective of the present work is to evaluate the amount and distribution of sludge accumulated in the granular medium of a full-scale HSSF CW, and its biodegradability.

2. Material and methods

2.1. Wastewater treatment plant

Sludges were obtained from an urban wastewater treatment plant (WWTP) located in Verdú (Lleida, Catalonia, northeastern Spain). This WWTP started operation in 2002 and treats an average flow of 177 $m^3 \cdot d^{-1}$ (2000 persons equivalent). The set up of the plant consists in screening, three septic tanks in parallel, four HSSF CWs of 976.5 m^2 each one in parallel, two aerobic polishing ponds of 2000 m^2 each one in parallel, and two polishing HSSF CWs of 518 m^2 each one in parallel. The first four wetlands have a length-to-width ratio of 1:1.1 while in the polishing wetlands is 1:2. The first four wetlands have signs of clogging near the inlet zone due to the presence of puddles. All wetlands were planted with *Phragmites australis* and filled with the same gravel (D_{60} = 9 mm, C_u = 1.8, initial porosity = 40%). Average wetted depth ranged from 0.4 to 0.5 m. Additional information about these facilities can be found in [11]. The mean concentrations (± SD) of some water quality parameters measured at the influent of the WWTP during the years 2003-2005 are 201 ± 48.5 mg $TSS \cdot L^{-1}$, 295 ± 143.9 mg $COD \cdot L^{-1}$ and 144.3 ± 71.7 mg $BOD_5 \cdot L^{-1}$. Mean concentrations in the effluent of WWTP are 17 ± 6.2 mg $TSS \cdot L^{-1}$, 32 ± 7 mg $COD \cdot L^{-1}$ and 10 ± 5.6 mg $BOD_5 \cdot L^{-1}$.

2.2. Sludge sampling procedure

Four sludge sampling points were considered within one of the first four HSSF CWs. Two sampling points equally distributed along the width were located at the inlet zone of the wetland, where there was ponding (numbers 1 and 2). The other two were also equally distributed along the width and located at the outlet zone (numbers 3 and 4). These sampling points were considered to be representative of the first third of the length (inlet zone) and the last third of the length (outlet zone).

Gravel samples ranging from 1.5 to 4 kg (including sludge and interstitial water contained in such gravel) were taken once at each sampling point in spring 2007. Gravel was taken out with a shovel and stored at 4°C until it was processed at the laboratory. All samples were taken at ca. 30 cm below the water surface. Quantification of sludge accumulated at this depth only gives an approximate measure of the actual amount of sludge; however, for the purposes of this study it was considered to be pragmatic approach for sludge quantification and study.

Sample processing started by removing recognisable live and dead rhizomes and roots, cleaning the gravel by hand shaking with distilled water, and filtering the resulting water (containing sludge and interstitial water) through a 1 mm metal mesh to further remove any fine material [12]. Therefore, debris greater than 1 mm has not been considered in this study neither the solids strongly adhered to the gravel (which are clearly linked to the gravel particles and are not easily released). Water collected during the whole cleaning process was settled in a graduated cylinder of 6 L of total volume in order to concentrate the sludge. Supernatant water was removed after 1 day and solids were again settled over 3 days. This procedure allows the settleable fraction to be separated from the rest of solid fractions (mostly colloidal and macrocolloidal). The final supernatant water was left out and the volume of the sludge remaining was quantified and processed for TSS, VSS and COD analyses, which were carried out using standard methods [13]. Biodegradability of this sludge was also evaluated.

2.3. Aerobic and anaerobic biodegradability tests

Aerobic and anaerobic biodegradabilities at 20°C were evaluated from sludges of sampling points 1 and 3 (near inlet and outlet, respectively). Biodegradability under aerobic conditions was evaluated by means the BOD test using commercial respirometric WTW Oxitops. Aerobic tests lasted 40 days. Anaerobic biodegradability was evaluated through the use of glass vials of 45 mL (reactors) equipped with a valve [14]. These reactors were filled with sludge and bubbled with helium. Gas samples were taken out from the headspace of these reactors using a syringe and then methane production was measured by means a thermo Finnigan gas cromatographer (model Trace GC) equipped with a thermal conductivity detector (TCD). The chromatographic separation was performed by a capillary column using helium as carrier gas. Anaerobic tests lasted approximately 70 days and 2–3 gas samples were taken weekly from each reactor.

In order to compare aerobic and anaerobic biodegradation results, methane was converted into BOD equivalent assuming that all methane was produced from acidogenic methanogenesis (1 mg CH_4 is equivalent to 4 mg O_2).

3. Results and discussion

3.1. Amount and distribution of sludge

Table 1 shows sludge characteristics. There is not a

Table 1
Characteristics of the sludges obtained from each sampling point of the HSSF CW

		Inlet zone		Outlet zone	
		Point 1	Point 2	Point 3	Point 4
Volume of sludge settled (mL)		400	300	135	72
Gravel weight sampled (g)		4030	2157	2469	1480
TSS$^{(1)}$ (g TSS·kg gravel^{-1})		8.8	4.6	20.3	5.3
VSS$^{(1)}$ (g VSS·kg gravel^{-1})		1.1	0.2	1.3	0.5
Ash$^{(1)}$ (g ash·kg gravel^{-1})		7.7	4.4	19.0	4.6
VSS (%)		12	4.3	6.4	9.4
Ash (%)		88	96	94	91
Total COD$^{(1)}$ (g·L^{-1})		84.7	31.3	59.6	23.0
BOD$_5$$^{(1)}$ (g·L^{-1})		8.0	2.0	1.6	0.8
Ratio COD/ BOD$_5$		10.6	15.7	37.3	28.8
		Inlet zone values $^{(2)}$		Outlet zone values $^{(2)}$	
Solids content related to volume of gravel	kg TSS·m^{-3} gravel	10.2–19.4		11.3–44.5	
	kg VSS·m^{-3} gravel	0.37–2.4		1.16–2.77	
	kg ash·m^{-3} gravel	9.8–17.0		10.2–41.7	
Solids content related to gravel surface	kg TSS·m^{-2} gravel	5.1–9.7		5.7–22.3	
	kg VSS·m^{-2} gravel	0.2–1.2		0.6–1.4	
	kg ash·m^{-2} gravel	4.9–8.5		5.1–20.9	

$^{(1)}$ Referred to volume of settled sludge.
$^{(2)}$ Inlet and outlet zone values are the min/max values of samples taken at points 1 and 2 and points 3 and 4, respectively.

clear pattern in the amount of accumulated TSS and VSS due to the high variability and heterogeneity of the data. The results obtained for solids are not related to the visual observation of ponding in the inlet zone (and therefore, more clogging). In fact, point 3 (outlet) had the highest TSS content. These results suggest that clogging is not directly linked to the amount of solids in sludge, but to its nature (density and packing properties). The density of sludge in the inlet zone was lower (approximately 5 times) than that of the sludge in the outlet zone. Thus, the higher content of mineral material in the sludge near the outlet (10.2–41.7 kg ash·m^{-3} gravel) might fill the interstitial spaces of the granular media to a lesser extent than the sludge near the inlet (9.8–17 kg ash·m^{-3} gravel). All these results are in accordance with those reported by [9] and [11], in which a clear inverse relationship between the amount accumulated solids of neither hydraulic conductivity nor retention time was found.

The mineral fraction of the analysed sludges is higher than that reported by [10] (ca. 20%) and very similar to that reported by [12] and [15], who found that up to 90% of the organics solids were composed of refractory fractions. Results of the mineral fraction are also similar to those reported by [11] (ca. 60–90%) and that were obtained in the same HSSF CW studied in the present work. In this former study, colloidal and macrocolloidal fractions were considered together with settleable solids. This fact could explain the slightly higher mineral values (87–96%) found in the present study. Comparing the results of the present work with those of the previous investigation in the same wetland it is concluded that the settleable fraction is of major importance in the whole solid content of the sludge accumulated within the gravel media.

The predominance of mineral material in the sludge of the studied might be related to a partial disintegration of the gravel media, since X-ray diffraction studies revealed that the mineral composition of the sludge coincided with that of the gravel (mostly quartz and calcite) [16].

3.2. *Aerobic and anaerobic biodegradability*

Figs. 1 and 2 show the results of the aerobic and anaerobic tests of sludges taken out from sampling points 1 and 3. Note that both curves of anaerobic tests do not show a trend towards an asymptote which suggests that a certain amount of biodegradable organic matter still remained in the reactors after 67 days. However, these curves can be compared between them. Sludge of the inlet zone was more aerobically and anaerobically biodegradable than sludge of the outlet zone. In Fig. 1 it can be observed that the BOD (per g of VSS) after 40 days was ca. 8 times higher in the sludge of the inlet zone. In Fig. 2 it can be observed that methane production (expressed

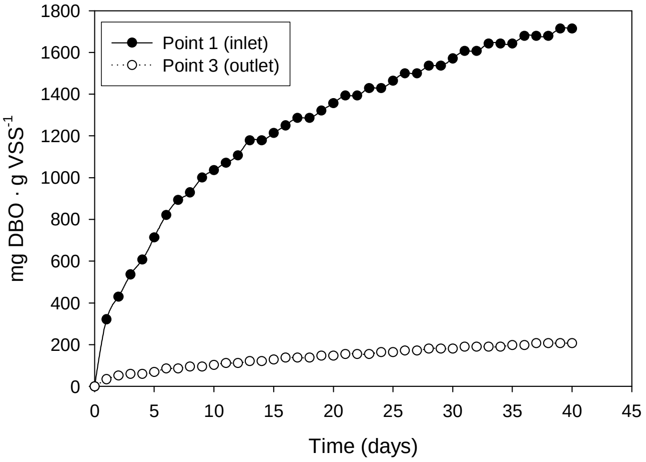

Fig. 1. Changes of BOD throughout the aerobic biodegradability tests conducted on sludge samples obtained at the inlet and the outlet of the wetland evaluated.

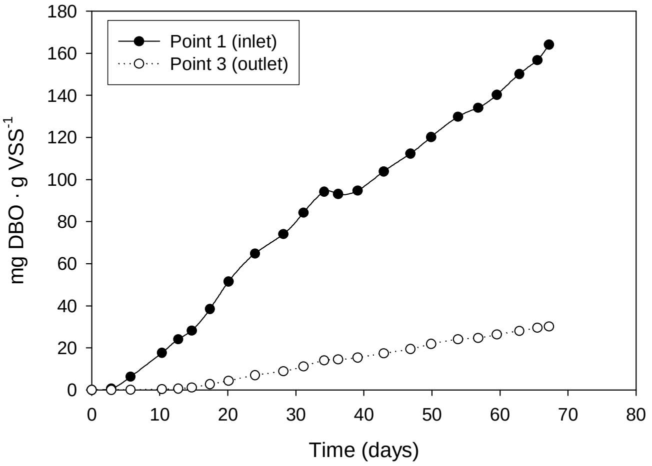

Fig. 2. Changes of BOD equivalent throughout the anaerobic biodegradability tests conducted on the sludge samples obtained at the inlet and the outlet of the wetland evaluated.

in terms of BOD equivalents per g of VSS) after 67 days was ca. 5 times higher in the sludge of the inlet zone.

According to the results of the aerobic tests only around 5% of the total organic matter (measured as COD) accumulated in the granular medium could be removed after 40 days. This low biodegradability might be linked to a great degree of mineralisation of the sludge. [4] and [17] reported that the degree of sludge organic matter mineralisation may increase with depth. Also it could be related to the presence of refractory vegetal material (as lignocellulose or humic-type substances) [10,15]. In this sense, [12] observed that the predominance of stable organic matter was due to the refractory nature of the organic matter inputs (lignocellulose and humic compounds) from wetland plant litter and the applied wastewater.

Table 2 shows the values of the specific aerobic and anaerobic biodegradability activities of the sludges analysed in this work as well as values from other sludges reported in literature. Sludge samples from the inlet zone presented a specific methanogenic activity similar to that reported for refractory substrates like sludges from septic tanks, river mud or fresh manure. Concerning to the aerobic biodegradability, results are in the low part of the range of values described for secondary sludges. The aerobic biodegradability of the sludge of the outlet zone presents lower values than those reported for primary or secondary sludges.

Table 2
Specific aerobic and anaerobic activities of sludges analysed in this study and values reported in literature from other sludges

		Specific methanogenic activity (mg COD·g VSS^{-1}·d^{-1}) (*)	Specific aerobic activity (mg BOD·g VSS^{-1}·d^{-1})
Domestic sludge(1)		20–200	—
Digested manure(1)		20–80	—
Septic tank(1)		10–70	—
Aerobic ponds(1)		30	—
Fresh manure(1)		1–20	—
River mud (1)		2–5	—
Cheese whey permeate(2)		22–150	—
Secondary sludge(3)		—	14.4–75.3
Primary sludge(3)		—	36–120
This study	Inlet zone	7.7	23
	Outlet zone	1.8	3.8

(*) Methane production is expressed as COD equivalents according to [18]. In the case of this study BOD equivalent values are transformed directly in COD equivalents.
(1) [18]; (2) [19]; (3) [20]

3.3. Management and operational strategies recommended

The results of this investigation indicate that the mineral fraction has a major importance within the sludges evaluated. Despite that this importance could have been slightly overestimated due to the fact that colloidal and macrocolloidal solids were not considered during sample processing, it is quite clear that interstitial spaces of the granular media of the wetland are filled with a variable amount of mineral particles. These particles could come off the granular media as a result of disintegration mediated by acid attack as reported by [16]. Thus, it is of capital importance to choose granular media with good resistance properties to acid attack. The wetland evaluated in this study has a granular media that is highly susceptible to acids because is constituted by gravel with a high content of calcareous minerals.

The results of this study also show that the amount of sludge (measured as TSS, for example) is very variable depending on the location that samples are taken. In the inlet zone, this variability is linked to (at least partially) a non-uniform distribution of the wastewater along the width of the wetland. Thus, a homogeneous discharge of the wastewater along the width has to be guaranteed.

Moreover, it seems that refractory organic compounds may have a vegetal origin [10,15]. This refractory organic fraction is of relevant importance within the whole organic fraction of the sludge accumulated, and presents a very low biodegradability. Therefore, an adequate management of the biomass of the macrophytes has to be implemented to reduce the amount of this fraction. Yearly removal of dead plant biomass might constitute an adequate management.

4. Conclusions

The amount of sludge accumulated within the granular medium of the horizontal subsurface flow constructed wetlands studied in this investigation is very variable and mainly composed by mineral fractions (ca. 90% of the total solids content). This great variability suggests new samplings for further experiments.

Specific anaerobic biodegradability of the sludge accumulated in the wetland is similar to those of river mud, fresh manure and septic tank sludge. In terms of specific aerobic biodegradability is similar to that of secondary sludge. The organic fraction of the sludge accumulated in the wetland is considered to be rather refractory.

Density and packing properties of the sludge are so important as the amount of sludge in relation to clogging processes.

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