Vertical-flow constructed wetlands as an emerging solution for faecal sludge dewatering in developing countries

I. M. Kengne, E. Soh Kengne, Amougou Akoa, N. Bemmo, P.-H. Dodane and D. Koné

ABSTRACT

Yard-scale experiments aiming at assessing the suitability of vertical-flow constructed wetlands to dewater faecal sludge (FS) were conducted in Yaoundé (Cameroon). During 6 months, beds vegetated either with *Cyperus papyrus* L. or *Echinochloa pyramidalis* (Lam.) Hitchc. & Chase were fed under constant solids loading rates (SLR) of 100, 200 and 300 kg TS (total solids) m^{-2}/year. Physicochemical parameters of raw FS and percolate as well as the dewatering efficiency of each bed unit were monitored weekly. Results showed that, despite the high loading rates, the beds' pollutant removal efficiencies were more than 78% for the parameters considered and were not affected by the SLR or the macrophyte types. Beds loaded at 100 kg TS m^{-2}/year rarely clogged with an average dry matter content ≥ 30%. However at SLR ≥ 200 kg TS m^{-2}/year, the occurrence of clogging was higher in the papyrus beds than those of *E. pyramidalis*. Approximately 30–40 cm/year of sludge will be accumulated in beds loaded at the lowest SLR against 50–70 cm/year at 200 kg TS m^{-2}/year and more than 80 cm/year at 300 kg TS m^{-2}/year. These promising findings suggest the system as adequate for further investigation at real scale for FS dewatering in the context of developing countries.

Key words | biosolid accumulation, *Cyperus papyrus*, *Echinochloa pyramidalis*, faecal sludge dewatering, pollutant removal efficiencies, vertical-flow constructed wetlands

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INTRODUCTION

In developing countries, a high percentage (65–100%) of households relies on on-site sanitation systems for excreta disposal (Bemmo *et al.* 1998). These will continue for decades to play an important role for excreta disposal, since most of the sanitation supply programmes are latrine-based. When full, these facilities are emptied, if not manually, then mechanically using trucks. Paradoxically, very little research has been conducted to identify suitable treatment schemes for faecal sludge (FS) once emptied, despite its high pollutant and pathogen concentrations (Koné & Strauss 2004). This gap in knowledge on low-cost and efficient treatment options is one of the main factors leading to the uncontrolled discharge of untreated FS into the environment. This improper practice of excreta disposal is a growing environmental and sanitary concern since many waterborne diseases are transmitted from faeces to humans through water and soil pollution. According to UNICEF, water-related diseases caused by insufficient safe water supplies coupled with poor sanitation and hygiene cause 3.4 million deaths a year, mostly among children (UNICEF 2008). Based on a survey conducted by Esrey *et al.* (1991), a stronger impact on morbidity due to diarrhoea and helminth eggs could be observed by improving excreta disposal.

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In recent years, growing interest has been exhibited in the use of sludge drying beds vegetated with macrophytes (also known as vertical-flow constructed wetlands) as a cost-effective and technically feasible approach for sludge dewatering, stabilisation and humification in Western countries and Asia (Kim & Smith 1997; Koottatep *et al.* 2005; Nielsen 2003). The basic principle of the system is simple: sludges are applied on the beds, thus allowing the solid phase to be retained on the surface of the filtering matrix where it undergoes mineralisation, while the liquid phase drains out of the system for further treatment. The system relies on emergent plants playing a major role in sludge dewatering, thus allowing long-term functioning without desludging (Kadlec & Knight 1996; Randall 2003; Rulkens 2004).

This ecotechnology could therefore be viewed as an emerging solution to tackle the lack of affordable dewatering technology for faecal sludge in sub-Saharan countries, as most of the systems commonly used, such as activated sludge or waste stabilization ponds, suffer from the high solids concentration, leading to rapid overloading of the beds (Strauss *et al.* 1997). Furthermore, the technology has several advantages: (i) low investment and running costs compared with conventional sludge treatment systems; (ii) its harmonious fit into the landscape and therefore environmentally sensitive approach that is viewed with favour by the general public; (iii) several options of resource recovery are offered in addition, as the sludge residues from septage or from latrines may become a well-composted soil after few years that could be beneficially used as soil amendment or landfill cover and the macrophytes used as fodder for sheep and goats if a forage plant is used as support for the system (Kengne *et al.* 2008).

The dewatering performance of such a system depends on a variety of factors related to the design (substrate type and size, type of plants), the maturity of beds, the climatic factors, the sludge characteristics, as well as operational factors (hydraulic loading rates, solids loading rates, frequency of beds feeding, etc.) (Breen 1997; Prochaska *et al.* 2007).

This paper reports on the comparative pollutant removal efficiencies and the dewatering performance of two indigenous macrophytes (*Echinochloa pyramidalis* and *Cyperus papyrus*) used as the support for FS dewatering in yard-scale trials at the University of Yaoundé I (Cameroon). The system was run under three different nominal loading rates (100, 200 and 300 kg TS m^{-2}/year). Based on the results obtained, the paper also speculates about the future role that this ecotechnology could play as an emerging solution for faecal sludge dewatering in the region.

METHODS

Experimental design and operational procedures

Six vertical-flow constructed wetlands (VFCW) bed units (1 × 1 × 1 m) vegetated half with *Cyperus papyrus* and half with *Echinochloa pyramidalis* were set up at the wastewater treatment plant of the University of Yaoundé I (Figure 1) from June 2005 to July 2006. In order to investigate the potential of these macrophytes to support dewatering, FS was stirred prior to each loading and then the loads were gradually increased for six months to ensure that the macrophytes did not wither as a result of the rapid and large applications of pollutants, and to overcome any adverse conditions that could hamper the experiments. The beds were subsequently fed at nominal solids loading rates of 100, 200 and 300 kg TS (total solids) m^{-2}/year for another six months at one application per week (Figure 2). Additional details on planting, starting phase and operational procedures are given in Kengne *et al.* (2008).

Assessment of the pollutant removal efficiencies

Raw sludges and percolate samples obtained were analysed for pH, conductivity, ORP (oxydo-reduction potential), TS (total

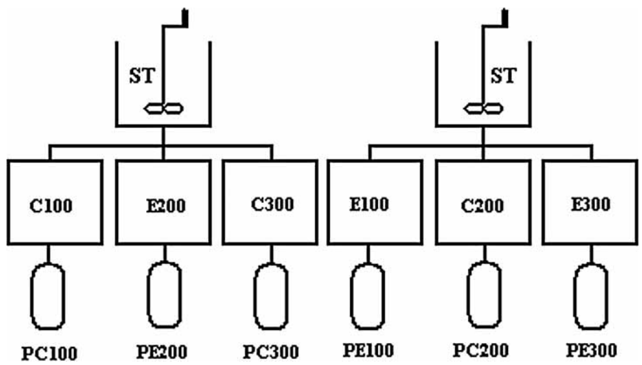

Figure 1 | Layout of the Yaoundé yard-scale plant for faecal sludge dewatering. ST: storage tank; C: beds vegetated with *C. papyrus*; E: beds vegetated with *E. pyramidalis*; PC, PE: percolate tanks; 100, 200 and 300: nominal solids loading rates of 100, 200 and 300 (kg TS m^{-2}/year).

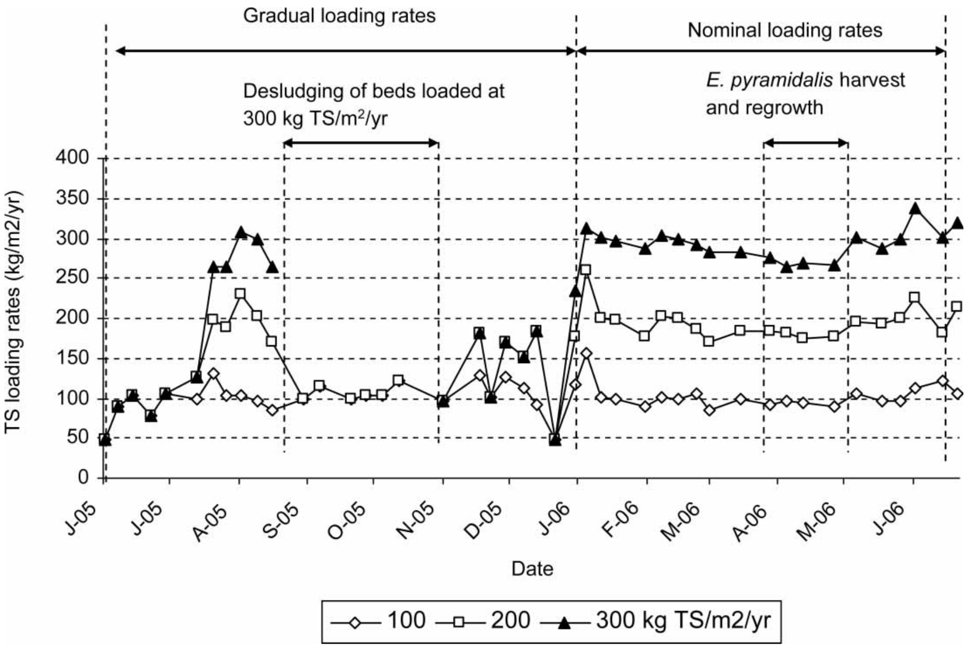

Figure 2 | Loading rates applied to the pilot beds during the period of investigation.

solids), TSS (total suspended solids), TVS (total volatile solids), COD (chemical oxygen demand), colour and TKN (total kjedahl nitrogen), NH_4^+ as outlined in American Public Health Association/American Water Works Association/Water Environment Federation (2005). A CG Schott Gerate pH meter was used for pH and ORP, an oven and muffle furnace for TSS and TVS, respectively, a Hach CO150 conductimeter for conductivity and Hach DR 2010 spectrophotometer for COD, colour and NH_4^+. TKN was determined after a wet acid digestion followed by distillation in Butchi K-350 distiller and titration with H_2SO_4 0.01 N (AOAC 1980). Removal efficiencies were calculated taking into consideration the inflow and outflow loads.

Assessment of the frequency of clogging

A simple and quick way was developed to assess clogging based on the infiltration time. Field investigations showed that the liquid fraction infiltrates within a few minutes to not more than two days for beds that are well drained (rank 0), while it remained standing on the top of the beds after this period if the beds are slightly clogged (rank 1). Beds were considered severely clogged if the amount of water retained on the top of the beds did not allow a full application of the subsequent volume of sludge to be applied (rank 3).

Assessment of the dry matter content of biosolids

Dry matter content of biosolids accumulated in the top of the pilot beds was determined at the end of each period of sludge application (generally after one week), prior to each new cycle of sludge application in accordance with the procedures described in American Public Health Association/American Water Works Association/Water Environment Federation (2005). Samples of biosolids (25 to 50 g) from different locations in each bed were evaporated in a weighed dish and dried to constant weight in an oven at 103–105°C (generally overnight). In addition, the probable period of beds emptying for the defined solids loading rates, were assessed by measuring at monthly intervals the height of the dewatered sludge accumulated on top of each bed with the aid of a graduated ruler.

RESULTS AND DISCUSSION

Raw sludge characteristics

The quality of raw sludge produced in Yaoundé was characterised by a high concentration and a great variability as

Table 1 | Characteristics of the raw sludge applied to the planted sludge drying bed units

Parameters	*n*	Mean	Median	Coefficient of variation	Minimum	Maximum
pH	44	7.50	7.5	9.2	6.55	9.34
Conductivity (mS cm^{-1})	44	2.79	2.10	101.7	714	15.1
ORP (mV)	41	−54.2	−45.0	−61.0	−150.0	−7.0
Apparent colour (PtCo)	23	87,703	72,000	98.6	4,500	402,500
TSS ($g\,l^{-1}$)	41	27.6	22.6	83.8	2.5	124.4
TS (%)	44	3.7	2.9	76.2	0.3	12.7
TVS (%)	43	65.4	68.9	20.6	31.0	90.7
NH_4^+ ($g\,l^{-1}$)	42	0.6	0.4	96.8	0.08	3.3
TKN ($g\,l^{-1}$)	42	1.1	0.9	69.3	0.3	3.9
CODt ($g\,l^{-1}$)	42	31.1	30.5	46.4	7.4.8	72.5
CODf ($g\,l^{-1}$)	42	3.3	2.3	90.7	2.3	12.2

n: number of samples; CODt: total chemical oxygen demand; CODf: filtered chemical oxygen demand; ORP: oxydo-reduction potential; TKN: total Kjeldahl nitrogen; TVS: total volatile solids; TS: total solids; TSS: total suspended solids.

expressed by the coefficient of variation which, except for pH, generally ranged from 21 to 102% (Table 1).

As expressed by the PCA (principal component analysis), the FS of Yaoundé was highly influenced by its solid fraction, then the nutrients and organics contents (Figure 3). Indeed, the first component, which exhibits the highest variability of sludge quality, encoded the solid contents of the sludge. The parameter with the strongest loadings on this component was TVS (−0.456) which was negatively correlated with TSS (0.437) and TS (0.421). The second component, which also expressed the variability of the sludge quality after the parameters of the first component, could be interpreted as its nutrient contents. The parameters with the strongest loadings were NH_4^+ (0.557), conductivity (0.462) and NTK (0.454). The third component (not

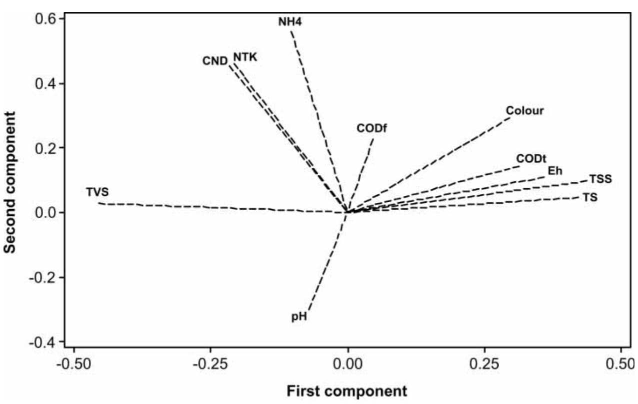

Figure 3 | PCA of the sludge quality of Yaoundé.

represented in Figure 3) was the organic content of raw sludge, with CODt (total chemical oxygen demand), CODf (filtered chemical oxygen demand) and ORP (Eh) having the strongest loadings (0.495, 0.442 and 0.403, respectively). These first three components accounted respectively for 37.3, 21.9 and 12.0% of the variability observed, giving a cumulative total of 71.2%. The other parameters accounted to a lesser extent for the variability observed.

Removal efficiencies

The removal efficiencies of pollutants based on differences in input and output fluxes showed a great variation within the same pilot beds (Table 2). On an average basis, beds vegetated either with *C. papyrus* or *E. pyramidalis* performed relatively well for solids, nutrients and organics, irrespective of the solid loadings rate applied ($P > 0.05$). Pollutant removal rates of the beds were more than 78% for NH_4^+, 88% for TS, 92% for TSS and 98% for COD. These removal efficiencies were in the same range as those obtained for septage dewatering in Bangkok using *Typha angustifolia* (Koottatep *et al.* 2005). Nevertheless, the percolate remained of relatively poor quality, with concentrations close to those of raw domestic wastewater and therefore necessitate additional treatment before discharge into the environment. This could be done using waste stabilization ponds or even constructed wetlands.

Table 2 | Average (mean) removal efficiencies of the different bed units (minimum–maximum)

	C. papyrus			***E. pyramidalis***		
	Loading rates (kg TS m^{-2}/year)			**Loading rates (kg TS m^{-2}/year)**		
Parameters	**SLR$_1$**	**SLR$_2$**	**SLR$_3$**	**SLR$_1$**	**SLR$_2$**	**SLR$_3$**
TVS	97.1 (80.4–99.9)	98.4 (92.1–99.9)	98.9 (94.7–99.9)	97.8 (90.0–99.9)	96.6 (73.4–99.7)	95.4 (68.0–99.8)
TS	90.2 (61.5–99.8)	95.8 (79.0–99.8)	95.1 (62.6–99.9)	92.0 (64.9–99.6)	94.5 (70.6–99.9)	94.6 (71.1–99.7)
TSS	86.0 (61.5–99.8)	93.7 (56.9–99.8)	93.4 (62.3–99.9)	98.9 (95.2–99.9)	97.9 (78.5–99.9)	95.8 (61.8–99.9)
NTK	92.6 (66.2–99.9)	95.7 (83.9–99.9)	93.4 (72.1–99.9)	91.5 (77.8–99.6)	90.1 (69.2–99.3)	89.5 (78.7–98.3)
NH4	85.4 (41.2–99.9)	90.9 (65.8–99.9)	85.0 (33.8–99.8)	87.2 (45.1–99.2)	77.6 (8.2–99.7)	79.9 (29.1–99.9)
Colour	93.5 (68.3–99.8)	94.1 (74.1–99.6)	94.9 (48.6–99.8)	95.0 (74.2–99.8)	89.1 (96.9–99.8)	85.1 (98.1–99.9)
COD	97.8 (82.2–99.9)	98.7 (92.1–99.9)	99.2 (98.0–99.9)	98.7 (96.7–99.9)	97.9 (73.4–99.9)	97.8 (78.0–99.9)

Occurrence of clogging and dry matter content of sludge

Beds loaded at 100 kg TS m^{-2}/year, corresponding to the lowest hydraulic loading rate (HLR), rarely clogged (Figure 4). However, at solids loading rates (SLR) $\geq$ 200 kg TS m^{-2}/year, the frequency of slight clogging was higher in *C. papyrus* beds than in *E. pyramidalis* beds. Severe clogging most often occurred at 300 kg TS m^{-2}/year: water remained on the surface of the beds for more than a week, thus allowing development of algae, fly larvae and sometimes odours (especially with FS from public toilets or traditional pit latrines).

Bed clogging is influenced by high solid and hydraulic load, the ability of the different FS to dewater, the low resting period after sludge application as well as insufficient development of roots. Nielsen (2005) suggested the absence of capillary connection between the different layers of the sludge as a factor leading to clogging in sludge-drying reed beds in Denmark. Though the present findings suggest the

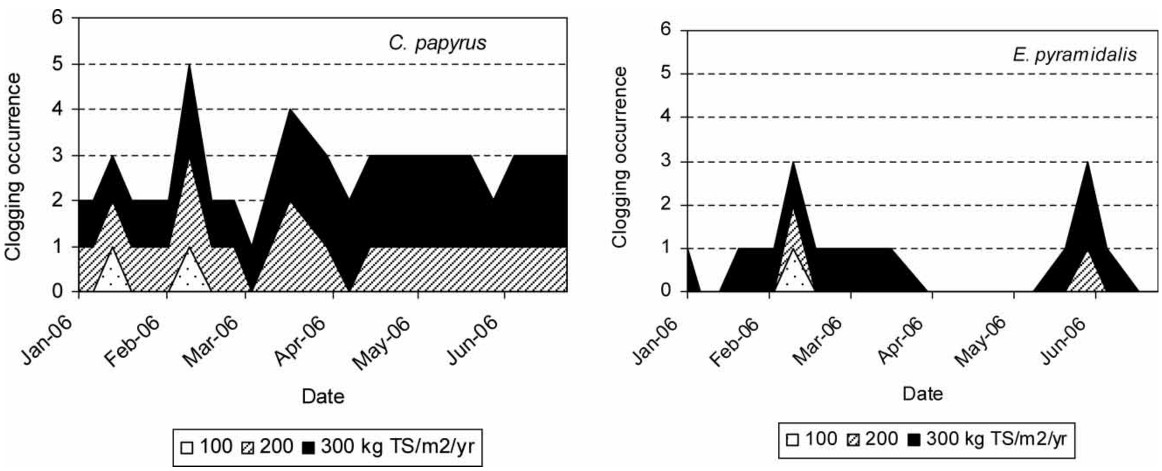

Figure 4 | Occurrence of clogging events in the different beds with respect to SLRs.

inadaptability of the system to run at 300 kg TS m^{-2}/year, the solids loading rate is far higher compared with the 40–60 kg TS m^{-2}/year frequently applied in Europe and North America (Nielsen 2005). Experiments carried out in Thailand revealed that the optimum solids loading rate was 250 TS m^{-2}/year (Koottatep *et al.* 2005).

Sludge dewatering was high in beds loaded at 100 kg TS m^{-2}/year, with an average dry matter content calculated prior to each application of > 30% (Table 3). At SLR ≥ 200 kg TS m^{-2}/year, the dewatering process was best achieved in beds vegetated with *E. pyramidalis* compared with beds vegetated with *C. papyrus*.

The lesser clogging observed for *E. pyramidalis* beds may be attributed to its growth and morphological characteristics (Kengne *et al.* 2008). Indeed, it was shown that this plant grows luxuriously, with a higher density of shoots per m^2 and a dense mat of roots and rhizomes colonizing the whole beds, thus allowing a higher evapotranspiration rate and therefore a better dewatering of sludge. In contrast, the *C. papyrus* growth pattern allows only one umbel per shoot and a lower density per m^2. Furthermore, the latter macrophyte develops large rhizomes at higher loading rates, which may potentially limit the infiltration of water within the beds (Kengne *et al.* 2008).

Sludge accumulation with respect to SLRs applied

Beds vegetated with *E. pyramidalis* presented lower sludge accumulation than those with *C. papyrus*. Based on the equation derived from the observation, approximately 30–40 cm/year of sludge would be accumulated in beds loaded at 100 kg TS m^{-2}/year, against 50–70 cm/year and 80–113 cm if loaded at 200 and 300 kg TS m^{-2}/year, respectively (Figure 5). In terms of operation, these results suggest that *C. papyrus* used as support for FS treatment combined with high solids loading rates (200 and 300 kg TS m^{-2}/year) will lead to just a few years of operation before desludging if the free board is only 1.5 to 2 m as found in most sludge dewatering reed bed plants (Nielsen 2003; Koottatep *et al.* 2005).

Table 3 | Average (median) dry matter (DM) contents of the sludge accumulated in the different bed units (minimum–maximum)

	C. papyrus			***E. pyramidalis***		
Loading rate (kg TS m^{-2}/year)	**100**	**200**	**300**	**100**	**200**	**300**
DM (%) before each application	30.8 (13.6–76.8)	16.1 (8.2–30)	15.6 (11.5–22.3)	33.5 (16.2–70.0)	21.7 (10.7–49.7)	25.6 (11.0–40.7)

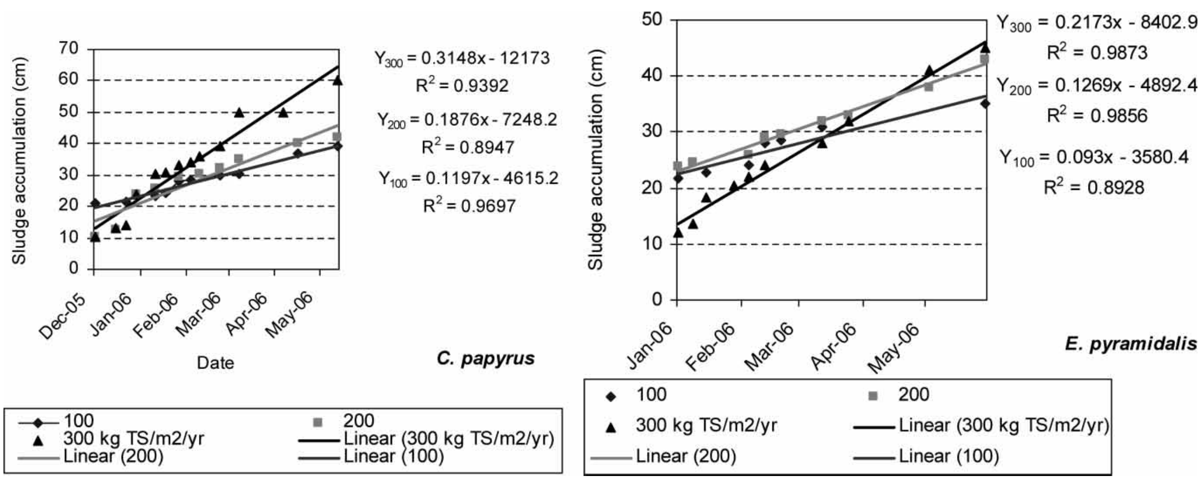

Figure 5 | Sludge accumulation in the top of beds with respect to time and solids loading rates.

CONCLUSION

This study showed that *C. papyrus* and *E. pyramidalis* can be used as support in vertical-flow constructed wetlands for highly concentrated FS dewatering in tropical regions at solids loading rates of ≤ 100 and ≤ 200 kg TS m^{-2}/year, respectively. FS treatment was effective, with removal efficiency $\geq 78\%$ for most of the parameters considered and did not differ significantly with respect to the solids loading rates applied or the types of macrophyte used. As expected, the quality of the percolates remained relatively poor with regard to most discharge guidelines and necessitated further appraisal before release into the environment. Based on the accumulation of sludge, at least 1.5–2 m of free board is required for at least 3 years of functioning without desludging.

When considering the anarchic discharge of FS prevailing in most developing countries, findings from this work suggest vertical-flow constructed wetlands as an emerging technology that could be used to tackle the lack of affordable FS treatment options in developing countries. Scaling up these results, as it is the case in Dakar (Senegal) by the Senegalese National Sanitation utilities (ONAS), may contribute to confirm or refute some of the findings of the present work.

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