# Effect of hydraulic loading frequency on performance of planted drying beds for the treatment of faecal sludge

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## ABSTRACT

This study was conducted to evaluate the effect of loading frequency on treatment performance of faecal sludge (FS) with drying beds planted with *Echinochloa pyramidalis*. Beds were loaded at a constant total solids (TS) loading rate of 200 kg TS/m$^2$*year, at a frequency of 1X, 2X or 3X per week. The FS was highly variable, with a range of 2,600–21,492 mg/L TS, which resulted in variable hydraulic loadings. Weekly monitoring was conducted 23 times over a period of nine months. Increased loading frequency resulted in increased plant growth with 211, 265 and 268 plants/m$^2$, respectively, for the 1X, 2X and 3X, and the 2X and 3X loadings had 12–13% more liquid lost due to evapotranspiration versus percolation. Even with high removals that were resistant to variable hydraulic loadings, leachate had 883–5,228 mg/L TS, 49–727 mg/L total suspended solids and 92–1,853 mg/L chemical oxygen demand due to the high initial concentrations. Increased loading frequency resulted in greater nitrification, with 7–28, 18–43 and 28–51 mg/L $NO_3^-$ for 1X, 2X and 3X, respectively. FS requires a longer storage time than three months for stabilization and pathogen reduction. These results provide valuable information for FS planted drying bed operation.

**Key words** | biosolids, *Echinochloa pyramidalis*, fodder, leachate, low- and middle-income countries, wastewater

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## INTRODUCTION

Faecal sludge (FS) is the sludge that accumulates in onsite sanitation technologies (e.g., septic tanks, pit latrines). There are few technological options for the reliable treatment of FS, and this represents an important research need as globally 2.7 billion people are served by onsite sanitation technologies (Boston Consulting Group 2013). The need is especially urgent in low-income countries, where the vast majority of people in urban areas are served by onsite technologies, but for the most part a FS management infrastructure is not in place. Planted drying beds have had limited but increasing use in Europe for the dewatering and stabilization of wastewater sludge over the last 30 years (Uggetti *et al.* 2010), and there have been a few attempts to transfer this technology to the treatment of FS in low-income countries (Koottatep *et al.* 2005; Kengne *et al.* 2008). However, this limited information is not adequate to transfer the technology from treatment of wastewater in temperate climates to FS in southern climates, as FS is more concentrated and less stabilized than wastewater sludge.

Planted drying beds appear to be a very promising technology for FS treatment in low-income countries. They can be loaded directly with untreated sludge (Molle *et al.* 2005) and produce treatment end products that can be sold to offset operation costs, including animal fodder and organic

doi: 10.2166/washdev.2014.024

soil amendments. For wastewater sludge, the operation of planted drying beds is currently based on empirical experience and prescribed guidelines, for example annual loading rates based on total solids (TS) concentrations (Dominiak *et al.* 2011b). Before planted drying beds can be reliably implemented for the treatment of FS in low-income countries, research needs to be conducted to develop the same type of empirical guidelines, and gain a scientific understanding of the effect of operating parameters.

Of the operating parameters, loading frequency is one of the most important, as it has a direct impact on clogging of beds, available oxygen for treatment and plant growth. Clogging results in anaerobic conditions, and reduced treatment performance (Langergraber *et al.* 2003; Molle *et al.* 2006), but intermittent feeding has the potential to increase available oxygen (Langergraber *et al.* 2003). This also has an effect on the growth of plants and attached biomass, and hence rates of mineralization (Molle *et al.* 2006; Stefanakis & Tsihrintzis 2011). Examples of studies on the effect of loading rates in temperate climates include: beds treating wastewater two or three times per week with 20–40 litres (0.08–0.17 $m^3/m^2$ hydraulic load, or 0.02–0.04 kg $BOD_5/m^2$) for beds planted with *Phragmites australis* (Prochaska *et al.* 2007); in Mediterranean climates, beds planted with *Typha latifolia* and *Phragmites australis* treating wastewater loaded once a week (Stefanakis & Tsihrintzis 2011); and in humid tropical climates, beds treating FS fed once a week with a resting period of 1 week for high loadings (200 kg $TS/m^2$*an) with beds planted with *Echinochloa pyramidalis* (Kengne *et al.* 2008). Results of loading rates have been variable based on types of plants, location and characteristics of wastewater or sludge (Prochaska *et al.* 2007; Kengne *et al.* 2008; Stefanakis & Tsihrintzis 2011). No studies have been conducted for loading frequencies of FS in semi-arid climates, conditions that are prevalent throughout sub-Saharan Africa.

The objective of this study was to determine optimal loading frequencies of FS for treatment with planted drying beds, and to gain an understanding of how loading frequency affects clogging, plant growth, stabilization and leachate quality. This study was conducted with *E. pyramidalis* due to its ability to grow in drying beds and potential value as animal fodder.

## MATERIALS AND METHODS

### Study location

This study was conducted at a pilot-scale research facility at the Cambérène FS and wastewater treatment plant in Dakar, Senegal. Dakar has a semi-arid climate with rainy periods during July to October (500–600 mm per year). The average temperature varies between 22 °C and 25 °C from December to April and from 27 °C to 32 °C from May to November. The FS used in this study was obtained from a storage tank with a mechanical mixer at the treatment plant, where vacuum trucks that collect FS from septic tanks discharge.

### Experimental design

The pilot-scale planted drying beds consisted of 200 litre barrels (90 cm tall and 50 cm diameter) filled with a 10 cm layer of coarse gravel (10–40 mm), a 10 cm layer of fine gravel (5–10 mm) and a 15 cm layer of sand with a $d_{10}$ of 0.35 mm, a $d_{60}$ of 0.75 mm and a uniformity coefficient of 2.14. A 4 cm diameter perforated PVC pipe was placed at the bottom for drainage, with a slope of 2.5°. The barrels were then planted with nine cuttings/$m^2$ with at least two inter-nodes of *E. pyramidalis*.

The study was conducted over a 15 month period, including three months for acclimatization, nine months for loading the beds 23 times, and three months for stabilization of the accumulated sludge layer. The acclimatization period consisted of watering first with tap water for 15 days and then effluent from FS settling tanks for 15 days. The sludge load was then gradually increased to 50, 100 and 150 kg $TS/m^2$*year over a two month period to allow the plants to adapt to FS loadings. At the end of the study period, the sludge was left for three months with no loading for stabilization.

During the study period, the barrels were loaded weekly at a rate of 200 kg $TS/m^2$*year from August 2011 to April 2012. The load was broken up into feedings of 1X, 2X or 3X times per week, and each loading frequency was conducted in triplicate for a total of nine drying beds. Leachate was collected in 100 liter barrels. A resting period with no loading was instituted if any of the nine beds experienced ponding of surface liquid ('clogging'). No sludge from the accumulated layer was removed during the study. Accumulated sludge was sampled and analysed after the maturation phase.

## Analyses

Plant development was measured by density and average stem diameter. The density was measured by counting all stems in one quarter of each bed. Plant density was given by dividing the total number of stems by the surface of the bed. Stem diameter was measured using an electronic callipper at 5 cm above the surface of the sludge layer.

Influent FS and leachate samples were collected in 1 liter bottles, kept in a cooler with ice and transported to the lab within 1 hour for analysis. The samples were analysed in the Cambérène laboratory. pH, ORP (oxidation/reduction potential), conductivity and salinity were measured directly in the samples with Hach HQ 40 d multi pH-conductivity meter probes. TS, total volatile solids (TVS), total suspended solids (TSS), chemical oxygen demand (COD), total Kjeldahl nitrogen (TKN), ammonia ($NH_3$), nitrate ($NO_3^-$) and total phosphorus (TP) were analysed following Standard Methods (APHA *et al.* 2005). TS were measured gravimetrically by drying in an oven at 105 °C, and TVS at 550 °C. TSS were quantified by filtering a well-mixed sample of sludge or leachate through a 1.2 μm ashless filter. COD was measured with Hach kits according to the manufacturer's directions. Samples were processed with a Hach DRB 200 Heating Block and quantified with a DR 5000 Spectrophotometer. TKN was measured with the macro-Kjeldahl digestion method, nitrates were determined with the nitrate cadmium reduction method. Ammonia was analysed with the Nessler method, and TP was analysed with the vanadomolybdophosphoric acid colorimetric method after sulphuric acid-nitric acid digestion.

Accumulated sludge samples were taken at three different points of each bed through the entire thickness of the sludge layer using a hand auger. Samples from each bed were mixed and dried at room temperature, and crushed and sieved through a 2 mm mesh sieve, prior to analysis. *Ascaris* analyses were done at the Cambérène laboratory, heavy metals at the Mineral Analysis Center of the University of Lausanne (Switzerland), and agronomic characteristics at the Laboratory of Analytical Methods of the French Research Institute for Development (Dakar). The cation exchange capacity (CEC) and exchangeable cations were determined by extraction with ammonium acetate (1 N) at pH 7. Exchange capacity was done by colorimetry of ammonium, while the exchangeable cations were determined by atomic absorption spectrophotometry. Mineral nitrogen ($NO_3^-$ and $NH_4^+$) was determined by colorimetry after extraction with a solution of KCl (1 N). The C:N was measured using a self-elemental analyser. TP was determined by colorimetry after aqua regia digestion and available phosphorus (as $PO_4^{3-}$) after extraction by Olson/Dabin method. Metals were quantified by inductively coupled plasma atomic emission spectrometry (ICP-AES). *Ascaris* total and viable eggs analyses were done according to Moodley *et al.* (2008). 10 g were collected and suspended in ammonium bicarbonate, filtered and then placed in centrifuge tubes. The tubes were centrifuged at 3,000 rpm, the supernatant was removed and the pellet resuspended. The tubes were centrifuged again at 2,000 rpm and then filtered with 20 μm, the amount remaining on the filter was placed in centrifuge tubes. The tubes were centrifuged again at 3,000 rpm for 3 minutes. The supernatant was removed and eggs were counted on glass microscope slides.

## Statistical analyses

Statistical analysis was performed with a Kruskal–Wallis one-way analysis of variance test, followed by a multiple pairwise comparison procedure of each treatment with a Tukey test. All statistical analyses were performed with SigmaPlot 12.0 for Windows. Results of statistical analyses are presented in the Supplementary Information (found online at http://www.iwaponline.com/washdev/004/024.pdf).

## RESULTS AND DISCUSSION

### FS characteristics

The characteristics of the incoming FS are reported in Table 1. The sludge was collected from individual households and transported to Cambérène, and was hence highly variable. Similar results were observed in Yaounde Cameroon with TS from 3,000 to 127,000 mg/L (Kengne *et al.* 2008). In this study, the high variation of TS

**Table 1** | Characteristics of untreated FS applied to planted drying beds over 23 loading periods

| Loading | TS (mg/L) | TSS (mg/L) | TVS % TS | COD (mg/L) | TKN (mg/L) | $NH_3$ (mg/L) | $NO_3^-$ (mg/L) | TP (mg/L) |
|---|---|---|---|---|---|---|---|---|
| 1 | 6,896 | 6,508 | – | 6,032 | 134.7 | – | – | – |
| 2 | 13,692 | 13,448 | – | 16,104 | 303.5 | – | – | – |
| 3 | 13,684 | 11,680 | 59.3 | 14,112 | – | – | – | – |
| 4 | 4,320 | 2,720 | 52.7 | 3,144 | – | – | – | – |
| 5 | 10,256 | 11,680 | 58.5 | 14,480 | – | – | – | – |
| 6 | 5,084 | 5,212 | 59.1 | 6,400 | – | – | – | – |
| 7 | 7,375 | 6,824 | 55.5 | 5,240 | – | – | – | – |
| 8 | 5,832 | 4,540 | 56.3 | 2,480 | – | – | – | – |
| 9 | 9,584 | 2,984 | 53.7 | 19,500 | – | – | – | – |
| 10 | 8,940 | 8,698 | 55.5 | 12,360 | – | – | – | – |
| 11 | 21,492 | 19,873 | – | 21,260 | – | – | – | – |
| 12 | 8,984 | 9,676 | 58.4 | 14,040 | – | – | – | – |
| 13 | 12,256 | 12,182 | 61.6 | 10,120 | 918.0 | 269.0 | – | 208.0 |
| 14 | 12,092 | 9,828 | 54.4 | 10,980 | 840.8 | 423.0 | 430.6 | 90.9 |
| 15 | 6,600 | 4,988 | 52.5 | 5,820 | 377.5 | 192.5 | 280.0 | 100.3 |
| 16 | 5,760 | 4,872 | 52.9 | 4,913 | 313.3 | 212.0 | 74.4 | 49.0 |
| 17 | 4,948 | 4,073 | 55.8 | 5,122 | 129.8 | 95.6 | 61.7 | 42.1 |
| 18 | 11,625 | 10,508 | 44.6 | 11,640 | 274.3 | 72.2 | 103.6 | 70.4 |
| 19 | 2,105 | 2,127 | 49.7 | 4,387 | 303.4 | 63.5 | 200.7 | 31.1 |
| 20 | 2,804 | 1,504 | 47.5 | 1,760 | 213.1 | 56.7 | 100.0 | 51.3 |
| 21 | 2,600 | 1,308 | 55.5 | 2,360 | 138.7 | 154.7 | 120.6 | 32.6 |
| 22 | 3,004 | 2,504 | 58.7 | 2,233 | 219.8 | 42.5 | 180.2 | 19.8 |
| 23 | 8,228 | 6,507 | 56.1 | 7,378 | 248.5 | 78.3 | 120.6 | 99.1 |

concentration (2,100–21,400 mg/L) resulted in quite variable hydraulic loadings of 0.2–1.8 m, or 36–369 litres total volume applied, as the rates were based on TS loading rates. This variability can be assumed to be reflective of operating conditions at FS treatment facilities without a large equalization basin, and is unique due to the high variability of FS (e.g., in contrast to wastewater, which is not as variable) (Strande *et al.* 2014). However, Kengne *et al.* (2009a) did not observe any differences in measured parameters with loading rates of 100, 200 or 300 kg/m$^2$*year.

## Effect of loading frequency on plant growth

As shown in Figure 1, 2X or 3X loading frequencies increased plant density and stem diameter. At the end of the study, plant densities were 211, 265 and 268 plants/m$^2$ respectively for the loading frequencies 1X, 2X and 3X, and the stem diameters were 8, 11 and 11 mm. 1X was significantly lower than 2X and 3X (Table S1 of statistical significance provided online in the Supplementary Information http://www.iwaponline.com/washdev/004/024.pdf). These values were lower than those reported by Kengne *et al.* (2008) for *E. pyramidalis*, of 400 plants/m$^2$ (with 10 mm stem diameter), however the loading rate was 300 kg TS/m$^2$*year. Other studies have also shown increased plant growth with increased loading frequency. For example, twice weekly loadings increased the size of cattails with FS (Koottatep *et al.* 2005). With wastewater sludge, Stefanakis & Tsihrintzis (2011) observed in Greece that an increased loading frequency was important for the survival of *Typha latifolia* and *Phragmites australis*. These same studies also observed that water stress led to reduced stem diameters, likely due to reduced

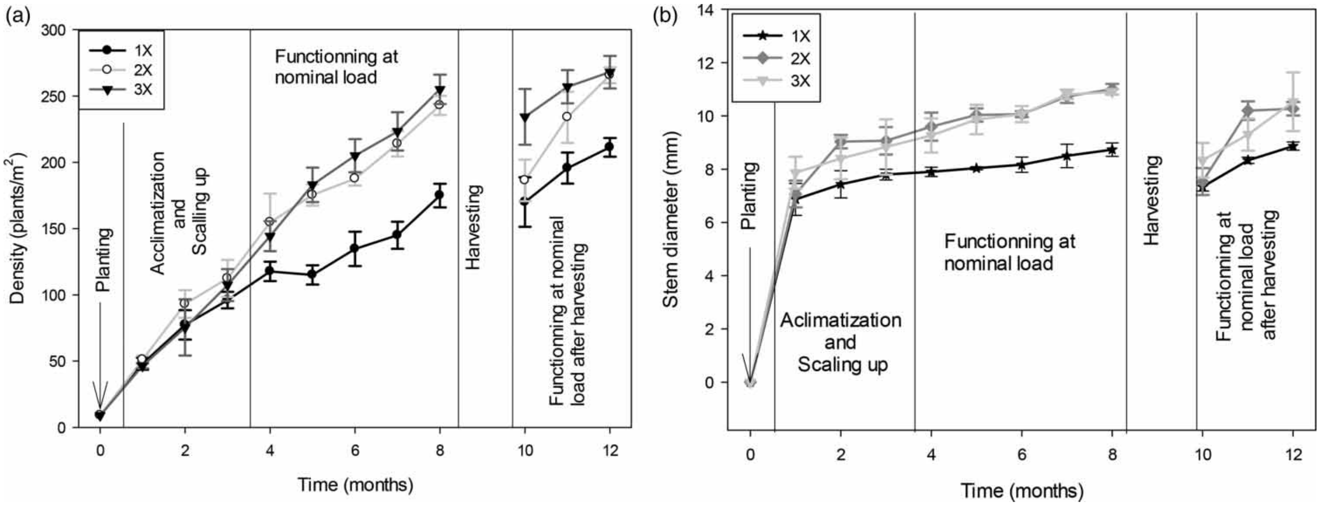

**Figure 1** | (a) Plant density and (b) stem diameter over a one year period with 1X, 2X and 3X weekly loading frequencies of FS at 200 kgTS/m$^2$*year.

water availability compared to natural growing conditions due to rapid percolation (Kengne *et al.* 2008; Stefanakis & Tsihrintzis 2011). Koottatep *et al.* (2005) also observed better growth of cattails when loading beds with FS twice a week over once a week.

As shown in Figure 1, plants were harvested at eight months. Harvesting is necessary to prevent plant mortality due to overcrowding with increased density, and to maintain the efficiency of the planted drying bed. Harvesting should be done with cattails when they have passed the culmination of their growth cycle (Koottatep *et al.* 2005), and with *E. pyramidalis* to allow them to replicate from rhizomes rather than from the aerial internodes (Kengne *et al.* 2008). Following harvesting, plant density also increased more rapidly, but not stem diameter, as also observed by Kengne *et al.* (2008). Plant growth can have a significant impact on drying bed performance, but also for the potential beneficial end-use as harvesting allows for selling plants for fodder or other beneficial uses. If beneficial end-use of plants is a treatment goal, then operation of the bed with loadings of 2X or 3X a week is more beneficial than 1X.

## Drainage of leachate

The volume of leachate collected was between 28 and 58% by volume of the sludge loaded. On average, over the entire study, 51% of the volume drained as leachate for 1X, 43% for 2X and 44% for 3X (which was 6, 4 and 3 days, respectively). In the 1X loading frequency a larger volume of leachate drained through the bed, and at a faster rate, which means there was a lower residual water content in the bed (Molle *et al.* 2006). This explains the lower plant growth in the 1X treatment, and also the 12–13% increased volume of liquid that left the system as evapotransporation in the 2X and 3X loading frequencies due to increased plant growth.

Qualitative observations were made regarding how many days there was free water on the bed surface during the 7 days following loadings. If free water was observed after 7 days this was recorded as 'clogging'. Clogging occurred more frequently during the first 6 weeks of the study, and then again during the operations immediately following plant harvesting. Although larger volumes of leachate were collected with the 1X treatment, there was also more clogging (9, 5 and 3% for 1X, 2X and 3X, respectively). The application of larger volumes of sludge can result in more frequent clogging, as the SS settle and form a cake on the surface of the bed which increases resistance to infiltration (Dominiak *et al.* 2011a, 2011b). This 'specific cake resistance' increases with volumetric load due to cake compression and increased hydrostatic pressure (Christensen & Keiding 2012). Dominiak *et al.* (2011b) also observed with wastewater sludge that smaller and more frequent loadings reduced clogging.

## Leachate characteristics

In this study, loading frequency had no effect on the removal of TS, TSS and COD, but did result in increased nitrification.

The percentage of solids that remained within the sludge layer versus the leachate was 64–96% of the influent for TS and 89–99% for TSS, but due to the high initial concentration of solids in the FS this meant that even with high percentage of removals the leachate still contained 883–5,228 mg/L TS and 49–727 mg/L TSS. Similar trends were observed for COD (Figure 2). Removals were 85–99%, with remaining concentration in the leachate of 92–1,853 mg/L. These results are similar to previous research that observed high removals of TSS in leachate (>90%) (Kengne *et al.* 2009b). The consistent percentage removals even with highly variable hydraulic loadings demonstrated that the planted drying beds were relatively resistant to 'shock' loadings, which shows they are robust for realistic operating conditions. However, the remaining TS, TSS and COD concentrations in the leachate are in the range of that expected with 'low' to 'high' strength wastewater influent (Metcalf & Eddy 2003) illustrating the need for further treatment of the leachate before it can be discharged to the environment. Possibilities include co-treatment with wastewater if the FS drying beds are located at a wastewater treatment facility, or treatment with a subsequent treatment wetland step (Kengne *et al.* 2014). Averages for the entire study were also skewed by relatively poor performance during the third and fourth loadings of the study. This potentially indicates the need for a longer acclimatization period, or careful monitoring during the initial loading period.

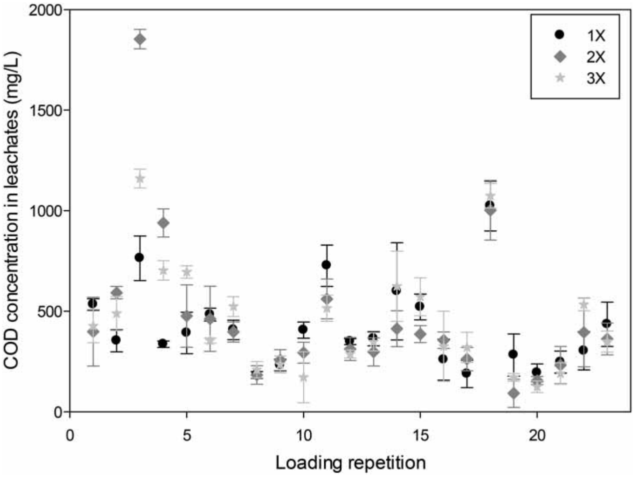

**Figure 2** | COD concentration of leachate over a one year period with 1X, 2X and 3X weekly loading frequencies of FS at 200 kgTS/m$^2$*year.

The removal mechanism for TS, TSS and COD was likely due to removal by the filter media more than biodegradation. TSS is, in general, removed by sedimentation and trapping in a filter (Wang *et al.* 2009). In this study, COD, TS and TSS removals all followed similar patterns, as is typically the case since COD is associated with TSS (Kuffour *et al.* 2009).

TKN concentrations were similar for all three treatments, however the 1X concentration was significantly higher than 2X and 3X, with leachate concentrations of 28–159, 20–76 and 5–82 mg/L for 1X, 2X and 3X, respectively, and an average of 66, 45 and 43 mg/L (Table S1 of statistical significance provided online in Supplementary Information http://www.iwaponline.com/washdev/004/024.pdf). $NH_3$ concentrations in the leachate were significantly different for 1X, 2X and 3X, with the highest concentration in the 1X loading frequency of 12–72, 6–59 mg/L for 2X and 3–30 mg/L for 3X, and an average of 38, 22 and 12, respectively. Whereas $NO_3^-$ concentrations were significantly higher in the 3X loading frequency with a range of 7–28, 18–43 and 28–51 mg/L for 1X, 2X and 3X, respectively, and an average of 18, 26 and 37 mg/L. TP concentrations were significantly higher in the 1X loading frequency with a range of 3–14, 2–11 and 2–8 mg/L for 1X, 2X and 3X, respectively, and an average of 7, 5 and 4 mg/L. It was observed that rates of nitrification as indicated by concentrations of $NH_3$ and $NO_3^-$, were greatest with the 3X loading frequency. This is likely the result of increased oxygen in the system with increased frequency of loading (Kayser & Kunst 2005), and also due to the longer retention time for nitrification to occur in the filter media. These results indicate that if increased nitrification and phosphorus removal are treatment goals, then beds should be operated with more frequent loadings.

## Characteristics of accumulated sludge

The accumulated sludge layer was between 10 and 12 cm. No differences in stabilization among 1X, 2X and 3X treatments were observed. The averages for all three treatments of the stabilization metrics are reported in Table 2. The C:N was 9, slightly less than the threshold of 12 for stabilized compost (Bernal *et al.* 1998) and is also similar to the value of 11 observed in field studies in Cameroon (Kengne *et al.* 2009a). The $NH_3$:$NO_3^-$ was 0.3, higher than the value of

**Table 2** | Physical-chemical characteristics of sludge that accumulated on the top of planted drying beds at the end of the study. The values are averages for all three treatments (nine drying beds)

| Parameters | Units | Sludge characteristics[1] | Kengne *et al.* 2009a, 2009b | Processed fish[2] | Poultry manure[2] | EU guidelines[3] |
|---|---|---|---|---|---|---|
| *Stability* | | | | | | |
| $NH_3$:$NO_3^-$ | | 0.3 (0.0) | | | | |
| C:N | | 9.2 (0.1) | 11 | 6.3 | 13.9 | |
| CEC | meq/100g | 41.4 (3.4) | | | | |
| *Nutrients* | | | | | | |
| Total N | % | 2.4 (0.3) | 2.00 (0.20) | 5.1 | 2.6 | |
| $NH_3$ | % | 11.6 (1.3) | | | | |
| $NO_3^-$ | % | 32.3 (3.6) | | | | |
| TP | % | 1.2 (0.1) | 2.30 (0.60) | 13.3 | 3.9 | |
| $PO_4^{3-}$ | % | 0.4 (0.3) | | | | |
| Total K | % | 0.4 (0.0) | 0.03 (0.01) | 1.0 | 1.7 | |
| *Metals* | | | | | | |
| Ni | ppm | 18 | 14 | | | 300–400 |
| Cu | ppm | 198 | 575 | | | 1,000–1,750 |
| Zn | ppm | 785 | 703 | | | 2,500–4,000 |
| Cr | ppm | 22 | 26 | | | 100 |
| Pb | ppm | 33 | 63 | | | 750–1,200 |

[1] Mean and standard deviation in parentheses.

[2] Organic amendments that are used in agriculture in Senegal (Gueye-Girardet 2010).

[3] Directive 86/278/EEC of the European Union for the use of sludge in agricultural (E.U.C. 1986).

<0.16 for stabilized compost set by Bernal *et al.* (2009), but lower than the value of <1 defined by Ko *et al.* (2008). However, the CEC was 41 meq/100 g, which is less than the limit of >60 meq/100 g defined by Harada & Inoko (1980). CEC is considered by some authors to be an important indicator of the degree of humification, as mineralization releases ions and increases CEC (Harada & Inoko 1980; Iglesias Jiménez & Perèz García 1992). However, the maturity of compost cannot be assessed by a single parameter and requires two or more metrics (Bernal *et al.* 2009). Planted drying beds could be considered as a passive form of composting because oxygen transfer from the plant rhizosphere in the accumulated sludge layer and surface reaeration of the sludge due to the movement of plant stems promote biological stabilization and mineralization of the sludge (Metcalf & Eddy 2003; Bastviken *et al.* 2005).

The value of nutrients in the accumulated sludge are presented in Table 2 in comparison with other organic nutrients used in agriculture in Senegal (Gueye-Girardet 2010) and a planted drying bed study with FS conducted in Cameroon (Kengne *et al.* 2009a). Concentrations of nitrogen in the sludge are similar to other organic soil amendments, but the phosphorus concentrations are lower than fish processing waste soil amendments. Concentrations of Cu, Cr, Pb, Ni and Zn are also presented in Table 2, along with the limits of Directive 86/278/EEC of the European Union for the use of sludge in agriculture (E.U.C. 1986). Their concentration was lower than those mandated by the EU. Metals concentrations in sludge are dependent on the origin of the FS and not the treatment. The low concentrations of metals are due to the FS treated at Cambérène being mainly of domestic origin, and based on nutrients and metals concentrations has good characteristics for use in agriculture.

The concentrations of *Ascaris* eggs in the accumulated sludge were 60–86 total eggs/g TS, and 10–17 viable eggs/g TS. The majority of helminth eggs are concentrated in the accumulated sludge layer due to filtration, which can block 71–96% (Keraita *et al.* 2008) to 100% of helminth eggs (Kengne *et al.* 2009b) of the incoming sludge. The concentrations in this study are greater than the WHO guidelines for use in agriculture (<1 viable egg/g) (WHO 2006), and also greater than those observed by Kengne *et al.* (2009a) of four viable eggs/g TS after six months of maturation. The inactivation of helminth eggs is due to environmental stresses such as desiccation, UV radiation, pH, $NH_3$ and temperature (Aitken *et al.* 2005; Koné *et al.* 2007; Pecson *et al.* 2007). In planted drying beds longer storage times can result in increased inactivation of helminth eggs, with a minimum of six months storage for planted drying beds required for the adequate reduction of helminth eggs in tropical countries (Kengne *et al.* 2009a). These results, together with the stabilization metrics, indicate that the sludge needs longer periods of storage and/or further treatment such as composting prior to use in agriculture.

## CONCLUSIONS

At this time, there is very limited information available on the operation of planted drying beds for FS treatment. Additional research on the impact of variable TS loadings with constant hydraulic loadings representative of FS treatment plants will be valuable for scaling up research results. Based on this first pilot-scale study conducted with *E. pyramidalis* in the semi-arid conditions of sub-Saharan Africa, these important conclusions can be drawn for the operation of drying beds:

- splitting the load into increased loading frequencies resulted in increased plant growth and larger volumes of liquid lost due to enhanced evapotranspiration;
- leachate from FS drying beds requires further treatment prior to discharge to the environment;
- planted drying beds need a minimum of three months of acclimatization, or transition to full-scale loading, prior to loading with FS;
- percentage removals of TS, TSS and COD were consistent even with highly variable hydraulic loadings;
- increased frequency of sludge loading resulted in increased nitrification but did not have an effect on rates of the accumulated sludge stabilization;
- FS requires storage periods longer than three months or additional treatment to achieve full stabilization and helminth eggs inactivation.

## ACKNOWLEDGEMENTS

This study was funded through the Swiss Development Corporation (SDC) and the Eawag Partnership Program. The authors would like to extend their gratitude to Dr. Doulaye Koné for his supervision and contribution to the experimental design. The authors are also grateful to Dr. Domonique Masse at the French Research Institute for Development for his analytical assistance.

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First received 19 February 2014; accepted in revised form 24 July 2014. Available online 25 August 2014