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Faecal sludge drying beds: increasing drying rates for fuel resource recovery in Sub-Saharan Africa

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ABSTRACT

In urban Sub-Saharan Africa, the collection and transport of faecal sludge (FS) typically ends up with FS directly dumped into the urban environment, as safe treatment and disposal options are too expensive or non-existent. Resource recovery from FS treatment, such as dried FS as an industrial fuel, could provide a financial incentive to increase access to FS management services. In Dakar, Senegal, enhanced drying to reduce the footprint of drying beds for fuel production was evaluated. Greenhouses did not increase drying rates over uncovered beds, however, daily mixing of FS on the surface of the beds resulted in a 6 day reduction to achieve 90% total solids (TS). FS was dried to 90% TS in 2 weeks for loading rates of 100 kg TS/m^2*year, and 3 weeks for 150 kg TS/m^2*year. The results indicate that with simple but innovative adaptations, footprints of treatment plants could be reduced and/or treatment capacities increased by 20%. FS can be adequately dried in Dakar to produce fuel, meaning 8.25 tons of dried FS could currently be produced daily, contributing 31,403 GJ/year fuel to industries. In addition, this financial incentive could reduce FS that is currently discharged untreated to the environment, and provide an additional 116,705 GJ/year.

Key words | developing countries, faecal sludge management, sanitation, solar drying, waste to energy

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NOMENCLATURE

wt%	per cent by weight
MJ/kg TS	mega joule per kilogram dry solids
m^2/capita	square metre per capita
kg TS/m^{2*}year	kilogram dry solids per square metre per year

ABBREVIATIONS

BOD	biochemical oxygen demand
COD	chemical oxygen demand
EC	electrical conductivity
FS	faecal sludge
FSTP	faecal sludge treatment plant
TS	total solids
TVS	total volatile solids

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INTRODUCTION

Worldwide, the sanitation needs of 2.7 billion (10^9) people are met by onsite sanitation technologies such as septic tanks and pit latrines (Strande 2014). Faecal sludge (FS) is the raw or partially digested, semisolid or slurry, resulting from collection, storage and treatment of blackwater and excreta from onsite technologies, with or without greywater (Strande 2014). Historically, onsite technologies were only considered as temporary solutions for urban areas, but the reality is they exist in great numbers, are more affordable than sewer-based solutions, and will be required to cope with rapid urbanization in low-income countries (Dodane *et al.* 2012). However, it is not only the provision of onsite technologies, but the collection, transport, treatment, and safe end-use or disposal of FS that needs to be in place to meet human health goals of separating excreta from human contact.

The biological and energetic potential of FS should be viewed as resources for urban development instead of only a disposal problem, and could provide financial incentives to enhance FS management services (Strande 2014). Resource recovery options in Sub-Saharan Africa include solid fuel for combustion, biogas from anaerobic digestion, protein for animal feed, a component in building materials, and soil conditioner (Diener *et al.* 2014). The value of FS treatment products varies depending on the local market, however, in Sub-Saharan Africa energy recovery appears to have the greatest financial potential (Diener *et al.* 2014). In contrast to wastewater sludge, information on the use of dried FS as a fuel is lacking (Werther 1999). FS has an average calorific value of 17.3 MJ/kg dry solids, which is comparable to other commonly used biofuels (Muspratt *et al.* 2014). However, reported concentrations of total solids (TS) in FS of 8.9–58 g/l indicate the need for cost-effective drying methods to achieve the 90% TS required by industries for fuel (Werther 1999; Cofie *et al.* 2006; Madlool *et al.* 2011; Dodane *et al.* 2012; Bassan *et al.* 2013).

Drying beds are one of the most commonly employed technologies for sludge dewatering (Tchobanoglous *et al.* 2003). They are appropriate technologies for low-income countries, as they have low-operational requirements, and low-capital and operating costs; however, a major drawback is the required footprint. For example, 0.08 m^2/capita land area was required to achieve 20% TS (Heinss *et al.* 1998; Cofie *et al.* 2006). The objective of this study was to investigate whether greenhouses or mixing FS on beds could increase drying rates and/or reduce the required footprint, and produce a 90% TS. Characteristics including energy potential and pathogen concentration were also evaluated to determine the viability of energy recovery.

MATERIALS AND METHODS

Study area

In Dakar, Senegal, the sanitation needs of 60% of the population, or approximately 1.5 million people, are met by onsite sanitation technologies, which are mostly septic tanks. Currently, 1,500 m^3 FS are delivered daily to three operating faecal sludge treatment plants (FSTP), while it is estimated four times that amount is dumped directly into the urban environment (Cabinet EDE, H_2O Engineering 2011). The process flow consists of screening, settling-thickening and drying beds (BMGF 2011). Dakar is semi-arid with distinct dry and rainy seasons from November to May and from July to October, respectively. The mean annual rainfall is 514 mm and average temperatures range from a low of between 18 and 25 °C to a high between 25 and 31 °C (World Meterological Organization 2014).

Research facility

This research was conducted over a period of 9 months at a pilot-scale facility at Cambérène Wastewater and FSTP in Dakar. The facility consists of two 17.5 m^3 settling-thickening tanks followed by 12 2 m × 2 m drying beds, as illustrated in Figure 1. The beds have a 10 cm coarse gravel (7–15 mm), 10 cm fine gravel (3–7 mm), and 5 cm sand layer (0.2–0.6 mm). Greenhouses were constructed on the beds, with conventional greenhouse film, that were 1.5 m tall with two openings on the roof for ventilation. During preliminary experiments, the greenhouses were operated first without active ventilation to evaluate drying by passive ventilation. Based on these experiments, ventilators were installed in the roof vents. One ventilator drew dry air into the greenhouse, while the other extracted moist air. Ventilators were operated for 12 hours a day to minimize energy costs (1 hour on – 1 hour off). Experiments were also conducted to evaluate the effect of mixing FS on beds once a day starting from the third day after loading. Treatments (i.e. greenhouses or mixing) were randomly assigned to drying beds and done in triplicate.

Loading pattern of drying beds

Loading rates were calculated as 100 kg TS/m^2*year and 150 kg TS/m^2*year based on Heinss *et al.* (1998) and Cofie *et al.* (2006). The rates were calculated based on a drying time of 21 and 28 days, respectively, however, the adjusted rates based on actual drying times during experiments were 92–117 kg TS/m^2*year and 150–175 kg TS/m^2*year, respectively. The hydraulic loading was 7.1–39.5 cm, which is in reason with ≤30 cm recommended by Heinss *et al.* (1998). FS was collected by vacuum trucks and

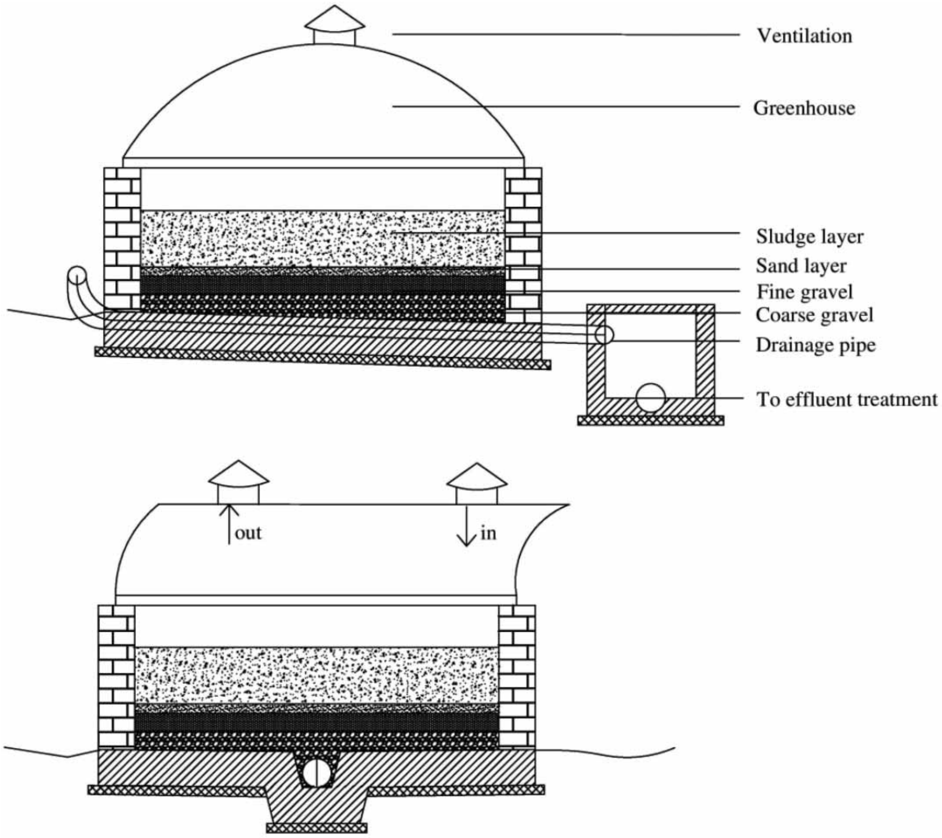

Figure 1 | Cross sections of the drying beds at the pilot-scale research facility at Cambérène.

discharged at the FSTP through a bar screen into a settling-thickening tank. Preliminary tests were done with un-thickened sludge, and the remaining tests were done following 1 week of thickening. Following thickening, the sludge was pumped into an 18 m^3 mixing tank for homogenization and sample collection before loading onto the drying beds. For each loading rate, drying beds operated with greenhouses were compared to uncovered drying beds, with two complete sets of experiments during the rainy season and five during the dry season. The effect of mixing on drying times was repeated three times for each loading rate. In total 10 complete sets of experiments in triplicate were monitored for each loading rate.

Sampling

FS samples were collected from the mixing tank and from the surface of drying beds. To obtain a representative sample, thickened and un-thickened FS was sampled following 20 minutes of mechanical mixing. For the drying bed samples, the beds were divided into four sections, and then grab samples were collected from the centre of the drying bed and each of the four sections. The collected samples were kept on ice and transported to the laboratory the same day, and one composite sample was prepared for analysis.

Analysis methods

FS was analysed for electrical conductivity (EC), pH, salinity, TS, total volatile solids (TVS), chemical oxygen demand (COD), biochemical oxygen demand (BOD) and Ascaris eggs. Additionally, dried sludge was analysed for calorific value and Ascaris eggs. Analysis of solids parameter and BOD was based on standard methods (American Public Health Association [APHA] *et al*. 2005). EC, pH, and salinity were determined with a Hach HQ40d multi-parameter meter according to the manufacturer's directions. TS were measured gravimetrically by drying in an oven at 105 °C, and TVS at 550 °C. Ash content was determined as the remaining wt% after TVS determination. BOD was determined by incubating samples at 20 °C for 5 days. COD was determined with Hach kits, a Hach DRB200 heating block and DR4000v spectrophotometer based on the manufacturer's directions. Calorific value was determined according to manufacturer's specifications on dry FS samples with a Parr Instrument calorimeter 1341EE. Viable Ascaris eggs were enumerated according to Moodley *et al.* (2008). Analyses were either started immediately upon arrival at the laboratory, and/or samples were stored at 4 °C until analysis. An Oregon Scientific weather station was used to collect meteorological data.

RESULTS AND DISCUSSION

Characteristics of FS

Results of the physical, chemical, and biochemical characteristics of FS used in the experiments are presented in Table 1. The low concentration of TS is due to the predominant use of septic tanks in Dakar. The values are comparable to those observed in areas served mainly by septic tanks, for example 4.5 g/l in Dakar (Vonwiller 2007) and 9.0 g/l in Ouagadougou (Bassan *et al.* 2013). Based on the TVS to TS ratio of 0.6, it is likely that FS is partially digested during storage in septic tanks, as has been observed in other studies in Dakar (0.55) (Sonko *et al.* in press). In contrast, FS sludge collected from public toilets in Ghana and Kampala had a higher fraction of TVS (0.7) (Koné & Strauss 2004; Fichtner Water & Transportation GmbH (2008)). Settling-thickening increased the TS concentration by on average 4.6 wt%, compared to 3–5 wt% observed with conventional thickening in wastewater treatment (Tchobanoglous *et al.* 2003). The thickened sludge contained on average 51,260 viable Ascaris eggs/l, or 1,138 Ascaris eggs/g TS, similar to values of 20,000–60,000 helminth eggs/l observed in high-strength FS (Strauss *et al.* 1997).

Greenhouses

The results of preliminary experiments with passive ventilation indicated that active ventilation is required for a net-drying benefit with greenhouses. Considerable condensed water vapour was observed on the inside of the walls, which confirmed the need for automated heat vents and/or ventilators to ensure the removal of moist air (Luboschik 1999).

As shown in Figure 2, during the rainy season, FS in the greenhouses with active ventilation reached 90% TS in 20 and 27 days with loading rates of 100 and 150 kg TS/m^2*year, respectively. In comparison, the control without greenhouse reached 57% TS and 59% TS for 100 and 150 kg TS/m^2*year, respectively, in the same amount of time. The average ambient temperature was 29 °C.

Experiments were also conducted during the dry season, as drying times are increased during rainy periods (Pescod 1971; Cofie *et al.* 2006). As illustrated in Figure 2, results among repetitions of the same experiment carried out at different times had good replication with standard deviations between 0 and 10%. All leachate drained from the beds within 2–4 days for loading rates of 100 kg TS/m^2*year or 6–8 days for loading rates of 150 kg TS/m^2*year.

Table 1 | Physical, chemical, and biochemical parameters of un-thickened and thickened FS that was loaded onto drying beds

	Parameter Unit	pH –	Salinity g/l	EC ms/cm	TS g/l	TS %	TVS g/l	COD g/l	BOD$_5$ g/l	Viable Ascaris n/g TS
Un-thickened FS	Mean	7.8	2.5	4.5	5.5	0.5	3.5	9.3	2.3	ND
	SD	0.1	0.8	1.7	2.2	0.2	1.6	6.6	7.5	ND
	n repetitions	6	6	6	6	6	6	6	6	ND
Thickened FS	Mean	7.7	1.8	3.5	50.3	5.1	29.9	77.0	13.4	1,138
	SD	0.3	0.7	1.2	15.1	1.4	9.5	25.8	31.1	475
	n repetitions	11	11	11	11	12	12	12	12	5

ND = not determined.

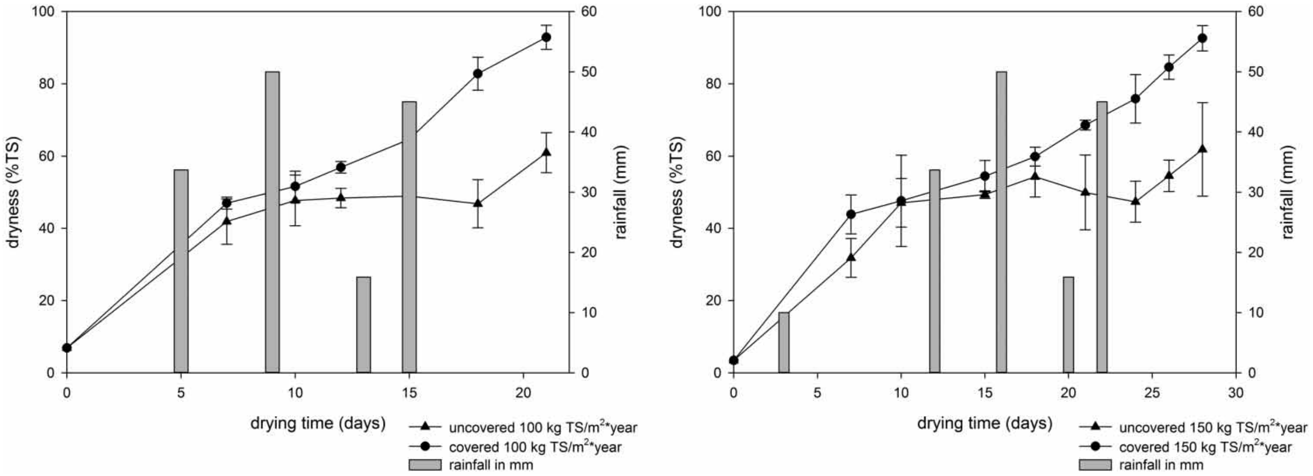

Figure 2 | Dryness of FS (% TS) over time during the raining season for drying beds operated with and without a ventilated greenhouses and loading rates of 100 kg TS/m^2*year (left) and 150 kg TS/m^2*year (right).

As shown in Figure 3, ventilated greenhouses did not significantly improve the drying rate during the dry season. The difference in the required time to achieve 90% TS between beds with and without greenhouses was less than 1 day. With an average ambient temperature of 33 °C, 19 and 24 days were required to achieve 90% TS for loading rates of 100 and 150 kg TS/m^2*year, respectively, for treatments both with and without greenhouses. This indicates that the previous results of enhanced drying during the rainy season were most likely due to functioning as a rain-cover, and not enhanced evaporation. However, greenhouses are commonly used for drying of dewatered wastewater sludge in various climates (Bennamoun 2012). It is likely that these results are due to the arid climate in Dakar, meaning greenhouses are not beneficial. Other possibilities include the comparison to FS versus mechanically dewatered wastewater sludge, and the design of the greenhouse.

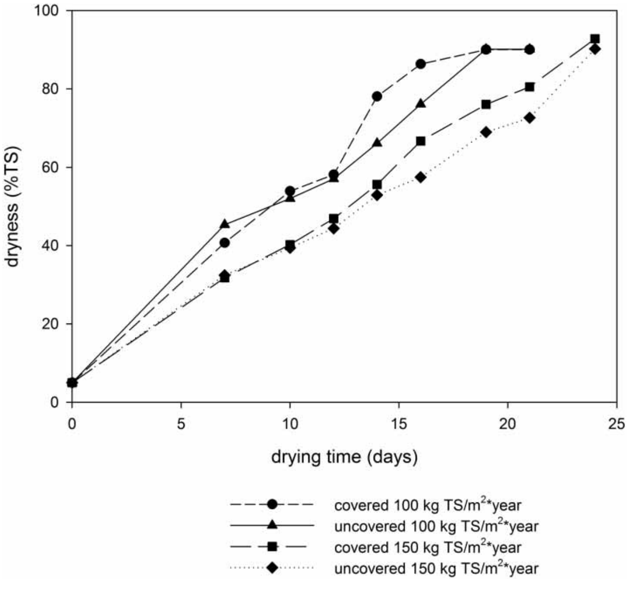

Figure 3 | Dryness of FS (% TS) over time for drying beds operated with and without a ventilated greenhouse and a loading rate of 100 and 150 kg TS/m^2*year.

Mixing of FS

Daily mixing of FS had a significant impact on rates of drying, with a 6 day reduction in drying time to achieve 90% TS. Drying was 31% faster for loading rates of 100 kg TS/m^2*year, and 23% faster for loading rates of 150 kg TS/m^2*year. The control treatments with no mixing took 19 ± 1 days to achieve 90% TS for loading rates of 100 kg TS/m^2*year and 26 ± 2 days for loading rates of 150 kg TS/m^2*year. The results of one repetition of the mixing experiments are presented in Figure 4. It took 14 days to achieve 90% TS for a loading rate of 100 kg TS/m^2*year, and 22 days for a loading rate of 150 kg TS/m^2*year. Over all repetitions with daily mixing, 13 ± 2 and 20 ± 4 days were required to achieve 90% TS. The observed variability between repetitions with the same loading rates was most likely due to the variability of FS, climatic factors such as ambient temperature, solar radiation, humidity and wind

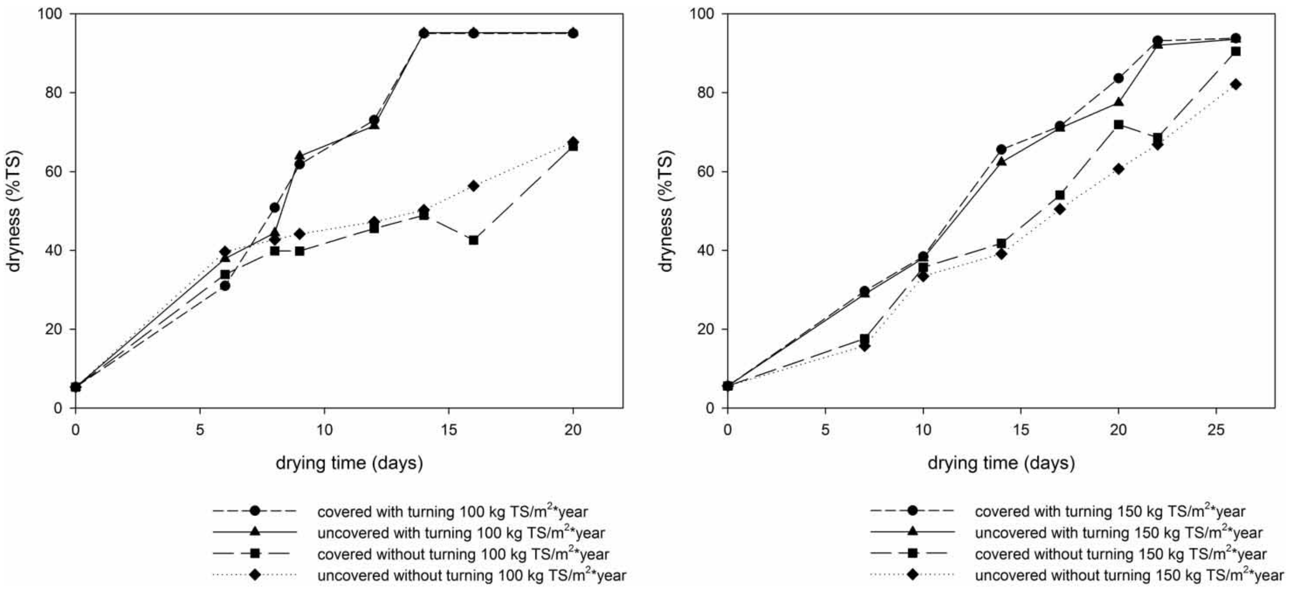

Figure 4 | Dryness of FS (% TS) over time for drying beds operated with and without greenhouses, and in addition, with and without daily mixing for loading rates of 100 kg TS/m^2*year (left) and 150 kg TS/m^2*year (right).

speed, and sludge application depth based on initial TS concentrations (Pescod 1971).

Relevance of study results

As summarized in Table 2, the drying times observed in this study were faster than many previous studies. Pescod (1971) reported drying times of 5–19 days for FS in Bangkok, to achieve 25% TS with an initial concentration of 1.7–6.4% TS. Strauss *et al.* (1997) and Cofie *et al.* (2006) reported similar results for pilot-scale drying beds in Accra and Kumasi. In Accra, 20% TS was achieved within 10 days with an initial concentration of 1.6–6.7% TS. In Kumasi, 7–8 days were required to achieve 20% TS with an initial concentration of 1.2–5.8% TS. No publications could be found for comparison that evaluated drying times to achieve 90% TS with FS.

Performance of drying beds depends on the desired final TS concentration, the initial TS concentration, characteristics of the sludge, and drainage and evaporation rates

Table 2 | Summary of relevant FS drying parameters of existing research results and the present study

Reference		**Present study**		**Pescod (1971)**		**Strauss *et al.* (1997)**	**Cofie *et al.* (2006)**	
Location		**Dakar, Senegal**		**Bangkok, Thailand**		**Accra, Ghana**	**Kumasi, Ghana**	
Season		**Dry**	**Wet**	**Dry**	**Wet**	**NR**	**Dry**	**Wet**
Target dryness	% TS	90		≥ 25		≥20	≥ 20	
COD/BOD		2.8–9.9		NR		NR	2.2–3.8	2.7–4.0
TVS	% TS	39–65		NR		NR	58-74	65–76
TS	%	2.9–7.7	3.4–6.9	1.75–5.5	1.7–6.49	1.6–6.7	1.2–5.8	
Hydraulic load	cm	7.1–39.5	21–28	20–50	20–50	NR	< 30	
Loading rate	kg TS/m^2*year	92–175	100–156	148–475	67.5–278	130–330	196–321	
Drying time	Days	11–30	20–27	5–19	11–52	10	7–8	12–59

NR = not reported.

(United States Environmental Protection Agency [USEPA] 1987). Differences between this study and the ones summarized in Table 2 include that the FS in this study was thickened for 1 week prior to application to drying beds, which increased the initial TS concentration. The drying beds in this study had a sand layer of 5 cm, compared to 10–15 cm (Cofie *et al.* 2006) and 35 cm (Pescod 1971), and increased sand layers reduce the drainage rate (Tchobanoglous *et al.* 2003). The sludge depths on drying beds in this study were relatively thin, as solid loading rates were calculated based on drying cycles of 21 and 28 days, and evaporation has a greater effect on total dryness with thin sludge layers (USEPA 1987). The studies in Table 2 had significantly higher solid loading rates, and Pescod (1971) higher hydraulic loading rates, both of which increase required drying times. An increase in hydraulic loading of 10 cm increases the required drying time by 50–100% (Pescod 1971). In addition, the TVS to TS ratio in this study indicated the sludge had undergone some digestion, and sludge that has undergone digestion has better solid–liquid separation (Heinss *et al.* 1998; Koné & Strauss 2004). The influence of hydraulic loading and solids loading on FS dewaterability, drying, leachate quality, and clogging is still not well understood and requires further research for reliable design and operation.

Dried FS characteristics for energy recovery

The dried FS had an average calorific value of 12.2 MJ/kg TS at the end of the drying period, and an average ash content of 41.7 wt%. During five repetitions of the drying experiments, the ash content of dried FS was 6 wt% ash greater than FS before being applied to drying beds. This increase indicates that some quantity of the sand filter layer is removed with the sludge. Additionally, the disposal of solid waste by households into septic tanks, and the sandy soils in Dakar, also contribute to the observed high-ash content. In contrast, other biomass fuels such as sawdust and wastewater sludge have ash contents of 1 and 23.5 wt%, respectively (Klass 1998), or up to 41.5 wt% for wastewater sludge (Werther 1999). High-ash contents are not desirable for fuel, as they do not contribute to the calorific value (fuel potential), can have an effect on the combustion performance, and ash needs to be disposed of, all of which can increase process costs (Klass 1998). To alleviate this, grit chambers could be employed at the influent of FSTPs to reduce the ash content and increase the market value of dried FS.

The dried FS had an average of 69 total Ascaris eggs/g TS, which are the most predominant helminth ova in Dakar (Yolande 2013). Viable eggs were reduced by both greenhouses and daily mixing of FS, although not significantly enough to justify their use for this purpose. This could be explained by elevated temperatures and increased exposure to solar radiation, key factors influencing parasite die-off (Koné *et al.* 2007). The dried FS contained quantities of viable helminth eggs greater than those recommended for agricultural use (World Health Organization [WHO] 2006). However, one of the benefits of using FS as a fuel is that exposure pathways are greatly reduced, mitigating associated risks to human health.

A total of 8.25 tons FS as dry solids (TS) are being delivered daily to FSTPs in Dakar (based on an average TS concentration of 5.5 g/l (Table 1)). Currently, they are landfilled or sold as an inexpensive soil conditioner. If used as a fuel, this amount of FS could contribute 31,403 GJ/year to industries, providing a financial incentive for sustainable sanitation services. In addition, incentives could increase the amount of FS that is delivered to treatment plants and reduce dumping in the environment, which could provide an additional 116,705 GJ/year (BMGF 2011).

CONCLUSIONS

Simple but innovative adaptions to drying beds can significantly increase the drying performance, and thus, reduce their required footprint while providing opportunities for resource recovery of treatment products. Greenhouses did not improve drying rates, other than by providing a rain shield, which would only be a benefit during the rainy season. This illustrates the importance of adapting innovations to the local climate and FS characteristics. Further research could adapt greenhouse designs and modes of operation for local climates and FS throughout Sub-Saharan Africa. Daily mixing of FS on drying beds resulted in 90% TS within 2 and 3 weeks for loading rates of 100 and 150 kg TS/m^2*year, respectively. This indicates that the footprint of future infrastructure projects could be reduced and/or treatment capacities be increased by 20%, which is significant in urban areas where available land for treatment facilities is limited. However, these benefits need to be balanced with the associated increased operational and capital costs. The required footprint could potentially be further decreased with additional research, for example, on the use of conditioners, the frequency of mixing, and a more detailed understanding of the influence of hydraulic and solid loading rates. The calorific value of FS is comparable to other commonly used biofuels, thus, technology innovations increase treatment potential while simultaneously providing the opportunity for using FS as a fuel, and a revenue stream to offset treatment costs and enhance sustainable sanitation services.

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