

## Research Paper

### Faecal sludge as a solid industrial fuel: a pilot-scale study

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#### ABSTRACT

Revenues from faecal sludge (FS) treatment end products could offset treatment costs and contribute to financially viable sanitation. In urban sub-Saharan Africa, energy-producing resource recovery has the potential to generate greater revenue than use as soil conditioner. In contrast with wastewater sludge, the technical feasibility of using dried FS as solid fuel in industries has not been investigated. This study evaluated it through characterization of dried FS from drying beds and by assessing the combustion performance in two pilot-scale kilns, in Kampala and Dakar. Results from the fuel characterization demonstrate that dried FS had comparable fuel characteristics as wastewater sludge considering calorific value and ash content. The calorific values and ash contents were 10.9–13.4 MJ/kg dry matter (DM) and 47.0–58.7%, respectively. Results from pilot-scale experiments suggest that dried FS can be effective in providing energy for industries. Temperatures in pilot-scale kilns fueled by FS were 800 °C, sufficient for curing of clay bricks, and 437 °C, sufficient for waste oil regeneration. In Kampala and Dakar, an estimated 20,000 tons of FS DM per year accumulate. Tapping the industrial fuel market and financial benefits could be realized through optimization of onsite sanitation and treatment technologies.

**Key words** | co-combustion, fecal sludge management, heavy metals, resource recovery, sanitation, waste-to-energy

#### INTRODUCTION

Worldwide, the sanitation needs of 2.7 billion people are met by onsite sanitation technologies (Cairns-Smith *et al.* 2014). This results in the accumulation of large quantities of faecal sludge (FS), defined as *the raw or partially digested, semisolid or slurry resulting from collection, storage or treatment of combinations of excreta and blackwater, with or without greywater*, in onsite sanitation technologies (Strande 2014). Lack of financial resources is one reason why FS management services frequently do not exist or cannot be sustained in low-income countries

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(Murray & Drechsel 2011; Bassan *et al.* 2014). Hence, large amounts of FS are discharged untreated into the environment, jeopardizing public and environmental health (Peal *et al.* 2014).

A market exists for FS treatment end products, including solid fuels, biogas, soil conditioner, protein, fertilizer and compost (Diener *et al.* 2014; Gold *et al.* 2014). However, most of these markets remain untapped, with only limited use of treated FS as soil conditioner (Diener *et al.* 2014). In sub-Saharan Africa, energy producing options

have a higher revenue potential than other treatment end products (Diener *et al.* 2014), and can be recovered within urban markets reducing transportation, and generated income could offset treatment costs. Large-scale industrial markets such as cement or coal-fired power plants are especially promising due to their large and consistent fuel demands.

In Europe, the USA, China and Japan, wastewater treatment sludge has already been used for many years as a solid industrial fuel in cement industries and coal-fired power plants (Werther & Ogada 1999; Spinosa 2011). For example, in Germany, power plants substitute 3–10% of coal consumption (by weight) with 10,000 to 100,000 tons of wastewater sludge dry matter (DM) per year (Richers *et al.* 2002). In Switzerland, one cement company uses around 15,000 tons of wastewater sludge DM per year, and in 2012, 27% of wastewater sludge produced in Switzerland was used as an industrial fuel in cement production (Tezcan 2013). The calorific value of FS is 12.2–19.1 MJ/kg DM, which is comparable with that of wastewater sludge and other biofuels (Muspratt *et al.* 2014; Seck *et al.* 2015). However, in contrast to wastewater sludge, dried FS fuel has not been assessed for use as an industrial fuel (Werther & Ogada 1999; Luts 2000; Niwagaba *et al.* 2006). Research is currently lacking in FS characteristics that influence combustion and adverse environmental impacts (Trezza & Scian 2005; Obernberger *et al.* 2006; WBCSD 2014). In contrast to wastewater sludge, FS is collected from individual households and hence has highly variable characteristics (Niwagaba *et al.* 2014). This suggests that experience with the combustion of wastewater sludge is not directly transferable to FS.

The objective of this study was to assess the suitability of dried FS from unplanted drying beds as a solid industrial fuel based on (i) fuel characteristics in comparison to existing industrial fuels such as wastewater sludge and (ii) kiln temperatures and end product characteristics in two different pilot-scale industrial applications.

## METHODS

This research was conducted over a period of 10 months in Dakar and Thiès, Senegal, and in Kampala, Uganda.

### Faecal sludge sampling

In Dakar, FS samples were collected from: vacuum trucks discharging into settling-thickening tanks (un-thickened FS); a mixing tank (thickened FS); the surface of drying beds; and dried FS following removal from beds. During vacuum truck discharge, four 1-L grab samples were collected. Grab samples were collected at the beginning, twice in the middle and once at the end of vacuum truck discharge. Drying beds were divided into sections, and grab samples were collected from the centre of each section. For the dried FS, grab samples were collected from the entire sludge volume that was removed from the beds and used in the pilot-scale kiln experiments. In Kampala, FS samples were collected from: vacuum trucks discharging onto drying beds; the surface of drying beds; and dried FS following removal from beds, in the same way as in Dakar.

One composite sample was prepared from grab samples and samples were kept on ice and transported to the laboratory the same day for analysis.

For comparison to faeces, one grab sample was collected from a source separation toilet in Nairobi, Kenya.

### Faecal sludge drying

In Dakar, FS was dried in four cycles on pilot-scale drying beds, based on Seck *et al.* (2015). In each cycle, septic tank FS from nine to ten vacuum trucks was discharged through a bar screen into a settling-thickening tank for settling-thickening between 2 and 6 days. Following this, the sludge was pumped into a mixing tank for homogenization and sample collection before loading onto the drying beds. In cycles one and two, the sludge was dried to 90% total solids (TS) (bulk density: 500 kg/m<sup>3</sup>) and removed as sludge cakes that were 30 to 50 mm thick. In cycles three and four, the sludge was dried to 60% TS and mechanically processed into FS briquettes (650 kg/m<sup>3</sup>) and pellets (720 kg/m<sup>3</sup>) before drying to 90% TS. Drying times were between 16 and 22 days. On average, the hydraulic loading rate was 33 cm. Based on the actual time it took to achieve 90% TS, the solid loading rates were 316, 205, 214 and 207 kg DM/m<sup>2</sup>\*year.

In Kampala, FS was dried in parallel on four full-scale drying beds. On each drying bed, FS from six to 21 vacuum trucks was discharged through a bar screen. In

Kampala, sanitation needs are met by both pit latrines and septic tanks (Fichtner Water & Transportation 2008). Therefore, one drying bed was loaded with FS collected from septic tanks, one with FS collected from lined pit latrines, and two with a mix of FS collected from septic tanks and lined pit latrines. FS drying was hindered by poor drainage due to clogged sand filter layers and rainfall within the study period. Therefore, solid loading rates based on the actual drying times are misleading. On average, the hydraulic loading rate was 52 cm. Drying beds were loaded with 62 m<sup>3</sup> septic tank FS, 96 m<sup>3</sup> lined pit latrine FS, and 103 and 77 m<sup>3</sup> mixed FS. Mixed FS consisted of approximately 50% septic tank and 50% pit latrine FS. Prior to pilot-scale kiln experiments, the 90% TS FS was milled into a fine powder ( $424 \pm 15 \text{ kg/m}^3$ ) with a manual hand-driven mill.

### Design and operation of pilot-scale kilns

Specifications of the pilot-scale kilns are presented in Figure 1. They were designed and operated to mimic brick curing at Ugandan Clays in Kampala and waste oil regeneration at Société Sénégalaise de Régénération des Huiles Minérales (SRH) in Dakar.

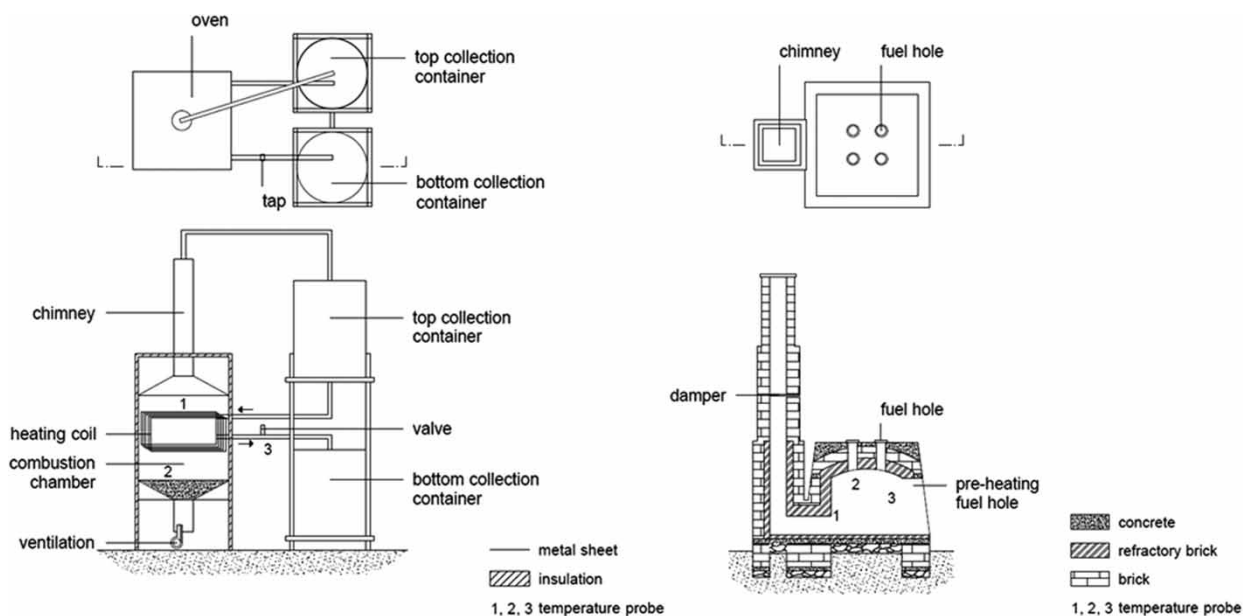
In Dakar, the kiln was loaded with 5 kg of dried FS for 1 hr of combustion. Combustion of FS cakes (triplicate),

pellets (triplicate) and briquettes (duplicate) were compared to charcoal (triplicate) ( $300 \text{ kg/m}^3$ ). Based on preliminary experiments, ventilation of the combustion chamber was set to 7–16 m/s. FS ignition was started with 150 mL of acetone. Flow of waste oil from the top collection container through the heating coil into the bottom collection container was controlled with a temperature-based valve in the combustion chamber.

In Kampala, the kiln was loaded with 340–460 unfired clay bricks obtained from Ugandan Clays. Based on their operation, the kiln was pre-heated with firewood for 2.3–5.3 hours to remove moisture in the bricks. After pre-heating, the kiln was fed with dried FS through holes located at the top for 2.3–2.5 hr. Combustion of 70–160 kg FS (quadruplicate) was compared to coffee husks (duplicate) ( $260 \text{ kg/m}^3$  based on Suarez (2003)), which are currently used by Ugandan Clays as a fuel. With coffee husks, the kiln was pre-heated for 4–4.5 hr and fed with 140–180 kg crushed coffee husks for 3–3.2 hr.

### Monitoring of kiln operation

Kiln temperatures, waste oil temperature and compressive strength of bricks were used as metrics to assess kiln performance. Kiln temperatures were measured with type K



**Figure 1** | Design of the pilot-scale kilns in Dakar in 1:50 (left) and Kampala in 1:100 (right) including the position of the temperature probes.

thermocouples and recorded with a data logger. In Dakar, temperatures in the combustion chamber (temperature probe 1 and 2) and the waste oil (temperature probe 3) were recorded every 30 sec, and in Kampala every 30 sec at three points (temperature probe 1, 2, 3).

## Analyses

DM was measured gravimetrically at 105 °C, and ash content by determination of total volatile solids in a furnace at 550 °C (APHA 2005). Biochemical oxygen demand (BOD) was determined by incubating samples at 20 °C for 5 days. Chemical oxygen demand (COD) was determined with Hach kits based on the manufacturer's directions. In Dakar, a Hach DRB200 heating block and DR4000v spectrophotometer and in Kampala a Hach COD Reactor 45,600 heating block and a Helios Aquamate NRTL/C spectrophotometer were used. Calorific value was determined according to manufacturers' directions with a Parr Instrument calorimeter 1341EE in Dakar and a Gallenkamp Auto-Bomb in Kampala. Helminth eggs were enumerated according to Bailenger (1979) in Dakar and Moodley *et al.* (2008) in Kampala.

Ultimate analysis was conducted by X-ray fluorescence (XRF) with a Spectro Xepos according to the manufacturer's directions. For ultimate analysis, FS samples were pulverized with a Retch mixer mill and pressed into 32 mm pellets. Carbon, nitrogen and sulfur were analysed in duplicate on pulverized samples with a HEKAtech Eurovector and a Leco TruSpec CHNS Marco Analyzer.

In Kampala, compressive strength of bricks was determined with an Avery Denison Universal Compressive Testing Machine according to Standard Methods (BSI 1983). Brick colour was determined qualitatively by comparison to bricks produced by Ugandan Clays.

## RESULTS AND DISCUSSION

### Faecal sludge characteristics

As shown in Table 1, FS from vacuum trucks in Kampala and Dakar contained over 95% water. FS contained 0.8–3.4% DM in Kampala and 1.2% DM in Dakar. These results are similar to those previously reported, 0.5–0.9% DM for

**Table 1** | Physical-chemical characteristics of FS loaded onto drying beds

Parameter	Dry mass %		COD g O <sub>2</sub> /L		BOD <sub>5</sub> g O <sub>2</sub> /L	
	Mean	SD	Mean	SD	Mean	SD
FS Kampala						
Septic tank FS	0.8	–	8.9	–	8.4	–
Lined pit latrine FS	2.3	–	11.5	–	6.6	–
Mixed FS 1	2.3	–	8.1	–	5.5	–
Mixed FS 2	3.4	–	21.0	–	12.0	–
FS Dakar						
Un-thickened FS	1.2	0.6	12.4	7.6	3.3	1.8
Thickened FS	4.9	3.1	36.0	28.0	9.5	9.7

SD: standard deviation.

FS in Dakar, and 2.2–4% DM for septic tank FS and lined pit latrine FS in Kampala (Fichtner Water & Transportation 2008; Niwagaba *et al.* 2014; Sonko *et al.* 2014; Seck *et al.* 2015; Gold *et al.* 2016). Industries commonly require fuels with less than 10% water, therefore, effective dewatering and drying technologies are key for the production of dried fuels from FS (Diaw, personal communication; Holcim (Schweiz) AG 2013; Seck *et al.* 2015).

In Dakar and Kampala, the dried FS had helminth egg concentrations of 197 ± 247 eggs/g DM and 75 ± 96 eggs/g DM, respectively. These values are comparable to those observed by Seck *et al.* (2015) of 69 Ascaris eggs/g DM. However, in contrast to use of dried sludge as soil conditioner in agriculture, one benefit of dried FS as an industrial fuel is that pathogen transmission pathways can be greatly reduced.

### Faecal sludge fuel characteristics

Table 2 presents typical characteristics of selected solid fuels and guideline characteristics for use of solid fuels. The average calorific values and ash contents of 10.9–13.4 MJ/kg DM and 47.0–58.7% for FS in this study were comparable to typical values of 7.0–14.4 MJ/kg DM and 39.5–57.0% DM for wastewater sludge in Europe (Luts 2000; Helena Lopes *et al.* 2003; Otero *et al.* 2007; Judex *et al.* 2012). The ash content of FS was much higher than that of faeces and excreta, with reported ash contents of 8 and 21% DM, respectively (Schouw *et al.* 2002; DWA 2008). High concentrations of ash are not desirable as it does not contribute to

**Table 2** | Characteristics (all in dry mass) of dried FS in comparison to wastewater sludge, excreta, coal, guideline values for use of solid fuels in industrial applications and industrial limits

Parameter	Unit	Faecal sludge				Wastewater sludge <sup>a,b,c,d</sup>	Excreta <sup>e</sup> , faeces <sup>f,g</sup>	Coal <sup>a,b</sup>	Guiding values <sup>h,i</sup>	Industrial limits <sup>j,k,l,m,n</sup>
		Kampala		FS Dakar						
		Mean	SD	Mean	SD					
Calorific value	MJ/kg	10.9	3.5	13.4	2.0	7.0–14.4	–	31–34.9	–	>8–14
Moisture	%	8.1	2.9	6.7	0.7	6.6–26	–	1.6–10	–	<10
Ash	%	58.7	11.5	47.0	4.0	39.5–57	7.9–21.1	7.5–15	–	<60–15
Carbon	%	27.8	3.1	28.8	3.4	16.9–31.6	–	70–79.1	–	–
Hydrogen	%	4.2	0.5	4.2	0.4	3.3–7.6	–	4–5.0	–	–
Nitrogen	%	3.2	0.4	3.0	0.6	0.4–4.2	3.9–11.8	1.2–1.8	<2.5–0.6	–
Sulfur	%	0.7	0.1	1.7	0.0	0.7–1.6	0.5–1.6	0.7–2.1	<0.2–0.1	<2.5–0.5
Chlorine	%	0.04	0.01	0.14	0.03	0.07–0.4	–	0.06	<0.3–0.03	<0.5–0.2
Phosphorus	%	1.4	0.4	1.0	0.1	3.1	1.3–2.3	0.51	–	<1.0
Arsenic	ppm	0.6	0.4	2.8	0.5	<0.3–14	–	<0.3–4	–	–
Cadmium	ppm	<2.0	0.0	<1.8	0.4	4–10.1	0.3–0.4	<1–0.17	<5	–
Chromium	ppm	485	298	401	212	190–530	0.7	12.2–33	–	–
Copper	ppm	114	12	216	47	5.3–400	22–36	1.8–32	–	<3,000–1,000
Mercury	ppm	<0.9	0.5	<0.8	0.4	2.1–5.4	0.3	0.08–0.2	–	<10
Nickel	ppm	24	4	30	1	40–45	2.5–4.8	12–19	–	–
Lead	ppm	28	8	59	14	220–365	0.7–1.2	2.0–19	–	–
Zinc	ppm	646	56	918	257	1,132–4,900	135–355	22.8–50	<800	–

SD, standard deviation.

<sup>a</sup>Helena Lopes *et al.* (2003).<sup>b</sup>Luts (2000).<sup>c</sup>Otero *et al.* (2007).<sup>d</sup>Judex *et al.* (2012).<sup>e</sup>Schouw *et al.* (2002).<sup>f</sup>Vinnerås *et al.* (2006).<sup>g</sup>DWA (2008).<sup>h</sup>Obernberger *et al.* (2006).<sup>i</sup>van Loom & Jaap (2008).<sup>j</sup>Diaw (personal communication; Directeur Qualité-Sécurité-Environnement, Sococim Industrie, Rufisque, Senegal).<sup>k</sup>Holcim (Schweiz) AG (2013).<sup>l</sup>Barikurungi (personal communication; Industrial Ecology Coordinator, Hima Cement Ltd, Kampala, Uganda).<sup>m</sup>Madlool *et al.* (2011).<sup>n</sup>WBCSD (2014).

the fuel value (Tyagi & Lo 2013). In comparison to coal and recommended guideline values, dried FS has elevated concentrations of nitrogen, sulfur and chlorine, which indicates the potential for dioxin, furan, NO<sub>x</sub>, N<sub>2</sub>O, SO<sub>2</sub>, HCl, HF and C<sub>x</sub>H<sub>y</sub> formation during combustion (Werther & Ogada 1999; Roy *et al.* 2011). This indicates the need for high operating temperatures, above which, dioxins and furans are completely destroyed (Werther & Ogada 1999), and the need for large-scale applications which can effectively control emissions.

Dried FS in this study had comparable concentrations of elements affecting ash production and ash fusion temperatures as those reported for wastewater sludge (see Supplementary material, Table S1, available with the online version of this paper). This explains the comparable ash fusion temperatures of FS and wastewater sludge (1,142–1,361 °C and 1,183–1,374 °C, respectively) (unpublished data, Pivot Works; Weidong *et al.* 2010), which indicates that FS fuel would not increase fouling or slacking over wastewater sludge.

As shown in Table 2, dried FS analysed in this study had lower heavy metal concentrations than those reported for wastewater sludge, and was comparable with those reported for FS of 751–782 ppm zinc, 113–139 ppm copper and 66–77 ppm lead by Bassan *et al.* (2013) and 2.3 ppm arsenic, 0.7 ppm cadmium, 61 ppm copper, 2.4 ppm lead and 34 ppm zinc by Appiah Effah *et al.* (2015). As shown in Table 2, heavy metal concentrations in FS in Dakar and Kampala were higher compared to those in faeces and excreta (Schouw *et al.* 2002; Vinnerås *et al.* 2006).

Fuel requirements of cement companies in Switzerland, Uganda and Senegal are also included in Table 2. Whether FS meets the limits for ash, sulfur and phosphorus depends on the location. In contrast, heavy metal concentrations were below guideline values. In general, cement industries only accept fuels with total heavy metal concentrations of As + Ni + Co + Se + Te + Cr + Pb + Sb + Sn + V <10,000 to 2,500 ppm, and Cd + Hg + TI <100 ppm (Diaw, personal communication; Madlool *et al.* 2011; WBCSD 2014). These values were, on average, 594 ppm and 1 ppm in Kampala and 549 ppm and 2 ppm in Dakar.

This characterization indicates that dried FS as a fuel is viable and comparable to wastewater sludge, e.g., in coal-fired power plants or cement industries (Werther & Ogada 1999; Luts 2000; Diener *et al.* 2014; WBCSD 2014).

### Pilot-scale kiln experiments

In Kampala, the pilot-scale kiln was operated with FS fuel to mimic industrial brick curing at 800 °C for 1 hr (Gita,

personal communication; Gita Kilns Enterprises/Ugandan Clays, Kampala, Uganda); the resulting temperature profiles are shown in Figure 2. Kiln temperatures were highly variable within the kiln and between repetitions. In general, temperatures and variability were highest in the middle of the kiln within the combustion zone, and lowest at the bottom of the kiln next to the chimney. Average temperatures over all four repetitions were 524 °C with maximum temperatures of over 800 °C in all repetitions. Temperatures were comparable with those obtained with coffee husks of 421 °C and 552 °C, with maximum temperatures of 850 °C. As a metric of quality, the compressive strength of bricks cured with FS was  $8.3 \pm 2.4$  MPa, and with coffee husks 5.9 and 8.4 MPa, which was comparable to commercial products from Ugandan Clays of 6.2 and 7.9 MPa.

In Dakar, the pilot-scale kiln was operated with FS fuel to mimic an industrial waste oil regeneration process, which includes distillation at 360 °C to remove water vapour and volatile compounds. The resulting temperature profiles are shown in Figure 3. Repetitions with the same fuel type were replicable. Acetone was used to start ignition, and resulted in a temperature spike within the first 5 min. Therefore, these results were excluded from analysis. The highest temperatures of 437 °C were obtained with FS cakes compared to 315 °C for FS pellets, 280 °C for FS briquettes and 262 °C for charcoal. FS briquettes and pellets were comparable to charcoal with reasonably stable temperatures around 250 °C. However, to meet the 360 °C required by this specific industrial application would require additional fuel loading and/or optimization of the kiln design.

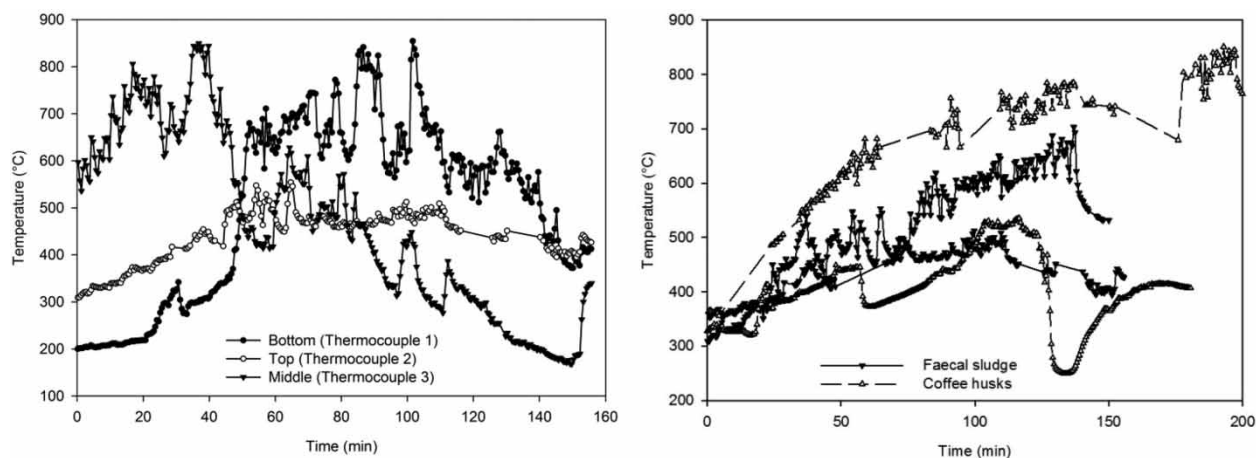
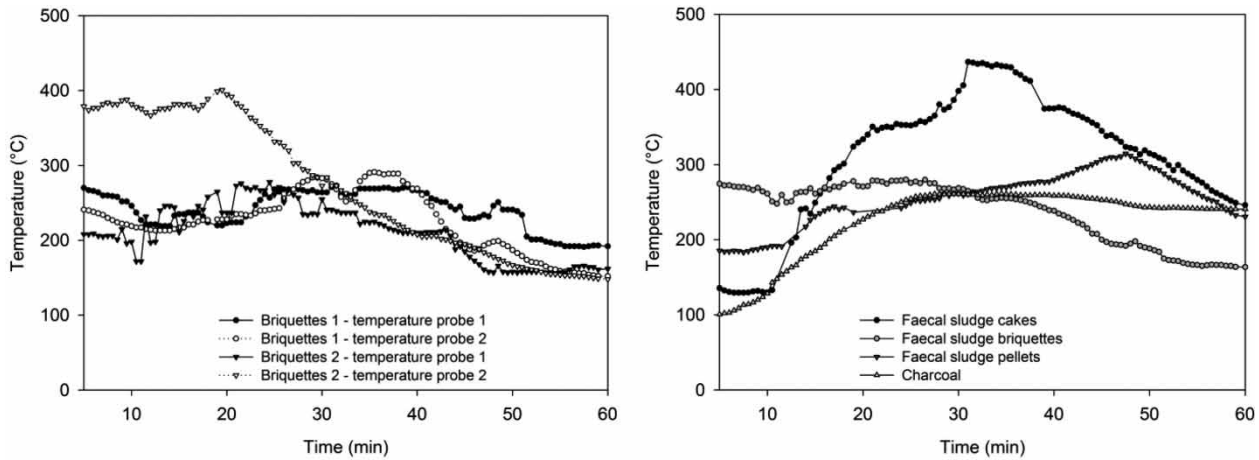


Figure 2 | Pilot-scale experiments in Kampala: temperature during one repetition with FS (left) and during repetitions with FS and coffee husks (right) (thermocouple 2).



**Figure 3** | Pilot-scale experiments in Dakar: temperature during two repetitions with FS briquettes (left) and during all repetitions with FS cakes, briquettes, pellets and charcoal (right).

Qualitative observation of odour from FS combustion was negligible in both Kampala and Dakar.

### Implications for faecal sludge management

Currently, the industrial demand for fuel in Dakar and Kampala greatly exceeds the amount of FS that reaches treatment plants, which is 2,600 tons FS DM per year in Dakar and 2,700 ton FS DM per year in Kampala. These values are based on [Seck et al. \(2015\)](#) for Dakar and the average DM concentration in [Table 1](#) and a treatment capacity of 400 m<sup>3</sup>/d at the Lubigi Wastewater and Faecal Sludge Treatment Plant in Kampala (6-day operation per week). Fuel demands in cement companies operating in Dakar and Kampala are four to 40 times this treated FS quantity (based on fuel consumption of cement companies in Germany and Switzerland discussed in the Introduction). Potentially, this huge industrial demand could be a driver for increasing FS collection, transportation and treatment capacities. For example, for Dakar and Kampala, it can be estimated that 20,000 tons FS DM are produced per year but do not reach treatment ([Vinnerås et al. 2006](#); [Diener et al. 2014](#)). Further improvements to treatment performance that would increase the potential for use of FS as a fuel include avoiding sand or soil entering onsite sanitation technologies or removing them with grit chambers, and preventing sand from drying beds entering FS by using other technologies.

### CONCLUSIONS

This research demonstrated that dried FS can be used as an industrial fuel in industries thereby providing revenues to offset treatment costs and provide an incentive to sustain FS treatment. Key findings include the following:

- Knowledge from combustion of wastewater sludge appears to be transferable to FS.
- Dried FS can be as effective in providing energy for industries as coffee husks and charcoal.
- FS fuel characteristics require further refinement (e.g., ash content), and quantities of treated FS need to be increased.
- FS characteristics are variable, therefore, prior to implementation, FS characteristics should be analysed on a case-by-case basis.

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