

Fuel potential of faecal sludge: calorific value results from Uganda, Ghana and Senegal

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ABSTRACT

This research tested the viability of using faecal sludge (FS) as solid fuel – an end use that could unlock an environmentally and financially beneficial replacement for disposal-oriented FS management, while replacing fossil energy. FS samples were collected from pit latrines, septic tanks, drying beds and stabilization ponds in three cities, Kumasi, Dakar and Kampala. For each sample, the average calorific value, solids and water content, and their variation with source and age were determined. The average calorific value of untreated FS across the three cities was 17.3 MJ/kg total solids (TS), which compares well with other biomass fuels. The age of FS did not affect its calorific value, nor did the reduction in chemical oxygen demand (COD) that occurred while it was in drying beds. The TS content of FS depended on its source but ranged from 1 to 6% for sludge from septic tanks and pit latrines, respectively. Harnessing net energy from FS requires partial drying. The results indicate that sufficient drying occurs within two weeks in open-air drying beds, or in a matter of days with simple drying bed innovations.

Key words | calorific value, drying beds, reuse, sanitation, sludge drying, sub-Saharan Africa

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INTRODUCTION

Provision of adequate, safe and sustainable sanitation coverage is an ever-increasing challenge facing urban areas in sub-Saharan Africa. As urban migration increases, available latrines are receiving more and more users. However, while latrine coverage may remain insufficient, the safe collection and treatment of faecal sludge (FS) from systems that do exist is arguably the weakest link in the sanitation value chain. An estimated 2.4 billion users of on-site sanitation systems generate FS that goes untreated, resulting in pervasive environmental contamination (Koné *et al.* 2010). This has led to growing interest in approaches for safe emptying, transport and end use or disposal of FS (Montangero & Strauss 2004). This research evaluates a new FS management solution: converting FS to solid fuel for use in industrial kilns and boilers.

FS management schemes that are designed for resource recovery may yield the financial drivers necessary to sustain reliable and safe collection and treatment. The use of processed FS as fuel in industrial boilers and kilns has yet to be explored. However, there exists a corollary: the use of sewage sludge (a byproduct of conventional wastewater treatment plants) as fuel in industry is an increasing trend, with examples from the US, across Europe, Japan and China. The trend is driven largely by pressure to find permissible disposal options, where limits on landfilling and land application have been enforced (Fytili & Zabaniotou 2008). Not only is sewage sludge being used as fuel, but when used by cement or brick manufacturers, the remaining ash can be used as a raw material that is incorporated into

final products (Okuno & Yamada 2000). In the cement industry, the ash is incorporated into clinker, a pre-cursor to Portland cement, offsetting the need for raw materials like clay, and transforming sludge into a zero-waste feedstock.

The sewage sludge used for fuel is primarily derived from activated sludge systems and may have undergone anaerobic digestion. In either case, stabilization has occurred, which significantly reduces the calorific value of the sludge (Tchobanoglous *et al.* 2003; Fytili & Zabaniotou 2008). For example, after primary settling the calorific value of sewage sludge averages 25 MJ/kg of dry solids but this value is halved following anaerobic digestion (Tchobanoglous *et al.* 2003; Fytili & Zabaniotou 2008). Therefore, the hypothesis driving this research was that if stabilized sewage sludge can be made a viable fuel, than fresh faecal sludge stands to be an even more attractive feedstock.

Pre-drying the sludge is a requirement for using it as fuel. Even if technically viable, the commercial or large-scale viability will be dependent upon identifying cost-effective ways to dry FS. This study serves as a starting point for exploring the use of FS as fuel and the potential for increasing drying rates while minimizing costs. If achieved, industrial fuel is an end use that could unlock an environmentally and financially beneficial replacement for costly, disposal-oriented FS management solutions.

MATERIALS AND METHODS

Site descriptions

Kumasi, Ghana

With a population of approximately 1.5 million people, Kumasi is the second largest city in Ghana. The average annual rainfall in the city is 1,402 mm, and the average temperature is 25.6 °C, with a range of ± 3 °C (World Meteorological Organization).

About 38% of the population use unsewered public toilets, 30% use household toilets connected to septic tanks, and 8% use ventilated improved pit (VIP) latrines (Erni 2007). Eight per cent of the population is connected to simplified sewage systems that carry wastewater to

community-scale waste stabilization ponds but the majority of the 24% not captured above rely on unimproved services (Vodounhessi 2006). Presently, FS that is collected in Kumasi is delivered to the Dompoase Faecal Sludge Treatment Plant (FSTP), which comprises a series of eight stabilization ponds. The system was commissioned in 2005 but loading rates now far exceed the intended design, which has compromised the treatment performance.

Dakar, Senegal

Dakar is the capital city of Senegal and has a population of 1 million people. Much dryer than Kumasi, the city's average annual rainfall is 513 mm and the average temperature is 24.3 °C, with a range of ± 6.5 °C (World Meteorological Organization).

Approximately 90% of the population is serviced by on-site sanitation infrastructure, which leads to a daily FS generation of 1,500 m³ (Mbégué *et al.* 2010). This waste was discharged at one of three FSTPs in the city, Cambérène, Niayes, or Rufisque, all managed by the National Sanitation Utility of Senegal (ONAS). The plants consist of settling tanks, followed by unplanted drying beds for dewatering, and parallel wastewater treatment plants where the leachate is treated. Cambérène and Niayes have activated sludge wastewater treatment, and Rufisque uses lagoons. The drying beds at Cambérène are no longer operational, and the FSTPs at Niayes and Rufisque frequently have operational problems as a result of problems with the pumps that transfer sludge from the settling tanks to the drying beds.

Kampala, Uganda

Kampala, the capital of Uganda, has a population of 1.7 million people (UBOS 2012), receives an average annual rainfall of 1,225 mm, and has an average temperature of 21.5 °C, with a range of ± 2 °C (World Meteorological Organization). Seven per cent of the population is served by sewer, 86% with on-site sanitation systems, and 7% is without official access (UBOS 2006). Collection and transport companies collect FS from on-site sanitation systems and discharge into an open pit that is located at the Bugolobi Wastewater Treatment Plant (BWWTP). While FS goes

untreated, the functional wastewater treatment plant receives and treats wastewater from the sewerage areas of Kampala. The facility is managed by National Water and Sewage Corporation (NWSC).

Sampling process

Sampling plans were tailored to the three cities and designed to capture the range of archetypical sanitation systems in each region.

In Kumasi, untreated samples were taken from public and private pit latrines, and septic tanks. These samples were retrieved directly from septic tank emptiers and composite samples were made from three 1-L samples collected at the start, midpoint and end of the truck emptying. Samples were also taken from four different locations in four anaerobic ponds at the Dompase treatment plant. The process was repeated for five consecutive weeks. In addition, samples were also collected from an offline anaerobic pond that had last been fed six months prior to sampling (Table 1). A composite sample was made by combining 1-L samples from six different locations, and samples were taken weekly for six weeks. All samples were collected in 1-L plastic bottles and immediately placed on ice. The samples were transported to the Department of Chemistry at the Kwame Nkrumah University of Science and Technology (KNUST) for analysis.

In Dakar, samples were collected from septic tanks and a fully lined pit latrine. These samples were retrieved directly from cesspit emptiers and again composite samples were made as described above. Samples were also collected from seven open-air drying beds at the Niayes FSTP for

three consecutive weeks (Table 1). The beds were initially filled to a height of 20 cm with wet FS from the settling tanks. Samples were collected and delivered to the laboratory for analysis at the Université Cheikh Anta Diop de Dakar.

In Kampala, samples were taken from unlined pit latrines, partially lined private and public latrines, fully lined private and public latrines, and septic tanks. These samples were retrieved directly from exhauster trucks and composite samples were made as described above. Samples were also collected from open-air drying beds filled with sewage sludge from the BWWTP in Kampala for three consecutive weeks (Table 1).

Sludge drying

Solar drying

In Ghana, researchers conducted additional FS drying experiments aimed at increasing drying rates through simple modifications to FS drying beds. The drying bed designs used by *Cofie et al. (2006)* were adapted and applied to the construction of experimental-scale beds. Namely, a dewatering cloth was added between the sludge and sand layers to prevent sand from contaminating the sludge. The constructed drying beds had a series of layers made with sand, dewatering cloth and expanded wire mesh, which facilitated the dewatering and filtering processes. The drying bed was divided into six different sections, each for testing different variables associated with faecal sludge.

The influx of rainwater can significantly decrease the sludge-drying rate; therefore, the constructed design included a roof made with transparent, durable plastic. The roof was angled at around 15 degrees to optimize sunlight penetration and removal of evaporated moisture off the roof's surface, but minimizing chances of the roof being blown off.

The relationship between faecal sludge depth in the drying beds and drying rates was observed for two weeks in June. Wet FS was poured into the partitioned beds at three different depths: 6, 8 and 10 cm. One of the sections also contained faecal sludge that had been dosed with polymer (a flocculating agent) before being poured into the drying bed at a depth of 6 cm. Once faecal sludge was

Table 1 | Breakdown of sample sources and sizes from the three research sites

Faecal sludge source	Kumasi	Dakar	Kampala
Fully lined pit latrine	20	1	23
Unlined pit latrine			14
Partially lined pit latrines			22
Septic tank	10	19	15
Drying beds – Raw FS		28	28
Drying beds – WWTP sludge			28
Anaerobic ponds	88 ^a		

^aIncludes 80 from functional pond and 8 from non-functional pond.

poured into the partitioned drying bed, samples were taken daily to measure changes in total solids content. The samples were dried in a laboratory oven at KNUST. Total solids content of each sample was recorded before and after oven drying.

Rapid prototyping to identify ways to increase drying speed

While passive solar drying in beds is the most common approach for sludge dewatering in developing regions, the large land requirements are a major drawback. Thus, researchers in Ghana used rapid prototyping techniques to identify interventions and methods that may reduce the land needed for solar drying. Rapid prototyping refers to a style of innovation that favors quick, order of magnitude results, over slow-to-gather but very precise data. It is often used to identify solutions that warrant in-depth research and to eliminate those that are not worth pursuing.

Out of the team's rapid prototyping exercise, flocculation emerged as an interesting possibility. FS was thoroughly mixed with BASF Zetag 7861 flocculating polymer and the free water was allowed to drain overnight. Approximately 50 L of the polymerized sludge was placed in a closed bag of porous dewatering cloth and then pressed between two pieces of plywood weighted by a 90-kg stone. Another 10 L was left to dry on a slanted cement surface to learn whether an angled drying bed can improve water runoff and drainage rates. Both pressed and unpressed samples were left to dry in the sun in areas with different degrees of exposure to the wind. The depths of the FS samples in the drying beds were kept at 1–2 cm to minimize the drying time and gain quick insights.

Analysis

Two replicate analyses were conducted for each sample. Calorific value, water content and total solids (TS) were determined according to *Standard Methods* (1995). To measure calorific value, bomb calorimeters were used and the heat capacity was calibrated using benzoic acid as a standard (Dorner & Fairchild 2006). In Kumasi, an IKA Model C 5000 digital bomb calorimeter was used, in Dakar the Perking Elmer AE 380H was used, and in Kampala, a

Gallenkamp Auto-Bomb Calorimeter (Cat. No. CAB001. AB1.C) was used. In Kampala, chemical oxygen demand (COD) was measured according to the closed reflux colorimetric method (*Standard Methods* 1995) to assess its correlation with calorific value. Percentage solids were measured using the gravimetric method, whereby fresh samples were dried to standard weight at 105 °C. The final weight of solids divided by the initial weight of fresh sample was used to calculate % TS.

RESULTS AND DISCUSSION

Calorific value

Variation on the basis of FS source and treatment

The average calorific value of raw FS from Kumasi, Dakar and Kampala was 19.1 MJ/kg TS, 16.6 MJ/kg TS and 16.2 MJ/kg TS, respectively.

As shown in *Figure 1*, these values compare very favorably to other biomass fuels in common use in sub-Saharan Africa. And of note, calorific value was not particularly sensitive to the source (i.e. pit versus septic) or city, suggesting that the use of FS as fuel could be easily transferred across cities and countries (*Figure 2*).

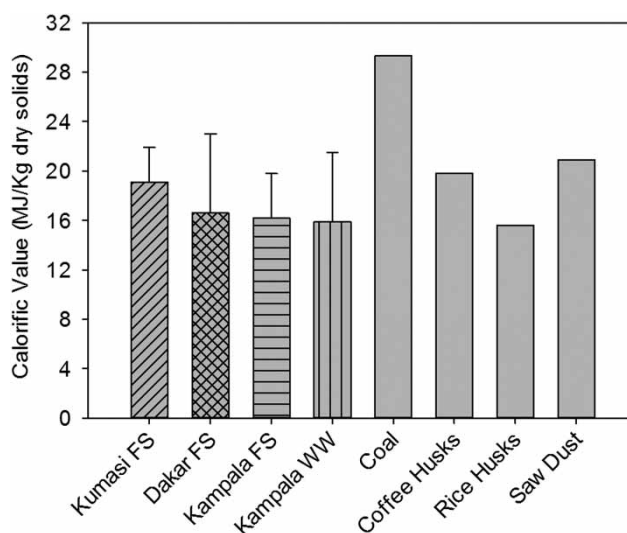


Figure 1 | Average calorific value of raw faecal sludge from Kumasi ($n = 11$), Dakar ($n = 26$), and Kampala ($n = 29$), and WWTP sludge from Kampala ($n = 4$) compared with traditional biomass fuels (Alakangas et al. 2007).

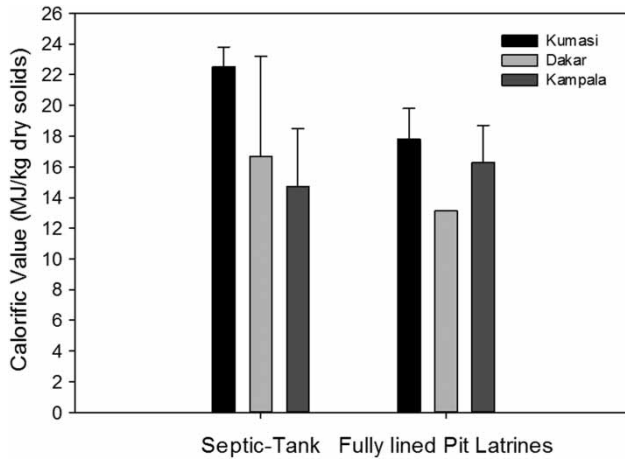


Figure 2 | Average calorific value of faecal sludge samples from septic tanks and fully lined pit latrines in Kumasi (Septic $n = 10$; PL $n = 20$), Dakar (Septic $n = 19$, PL $n = 1$), and Kampala (Septic $n = 15$, PL $n = 23$).

In Kumasi, FS samples were collected from anaerobic stabilization ponds to compare its calorific value with that of raw FS. Samples from active (in use) ponds had a calorific value of 14.6 MJ/kg, while samples taken from anaerobic ponds that had been offline for six months had an even lower value of 11.3 MJ/kg. These values represented a 25–40% drop from the calorific value of raw FS, which was predictable given results of previous studies on the effect of treatment on sewage sludge. The loss in calorific value over time in the ponds is attributed to the biological breakdown and release of carbon in the form of methane and carbon dioxide during anaerobic digestion (Ostrem *et al.* 2004). Given this phenomenon, a large-scale system designed for harnessing embodied energy as solid fuel should avoid digestion.

Variation on the basis of COD and FS age

The COD measurements taken in Kampala were systematically higher in fresh FS samples than in samples from drying beds, where it quickly dropped off (Figure 3). Fresh FS samples averaged 0.06 g COD/g TS from unlined pit latrines and septic tanks, and 0.09 g COD/g TS from lined pit latrines. After just one week in a drying bed the g COD/g TS was non-detectable. In absolute terms, average COD in fresh samples of FS was 1,406 mg COD/L and the drying bed samples, after two weeks, had a COD value of

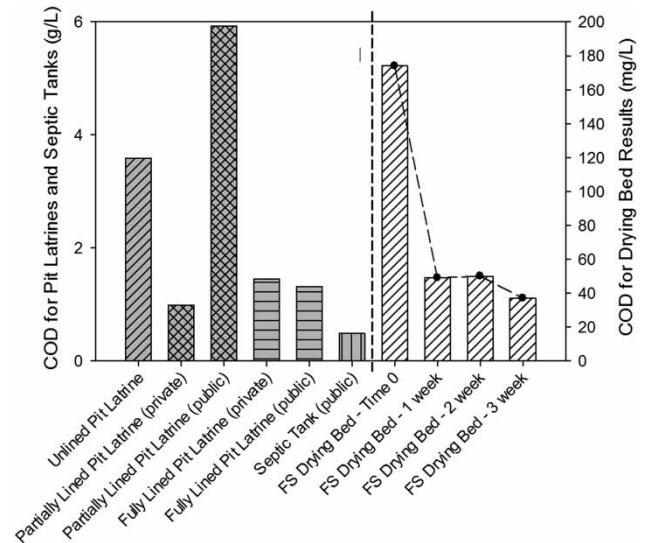


Figure 3 | Relationship between faecal sludge age and calorific value, indicating no correlation.

50 mg/L. Despite the decrease in COD over time, however, the calorific value remained fairly constant.

There was no correlation found between the age of FS from different sources and its calorific value (Figure 3). This combination of findings suggests that the calorific value comes from recalcitrant organic molecules that degrade very slowly, and thus are potentially not oxidized during the breakdown of COD. This is similar to coal, where the chemical bonds are not very susceptible to microbial attack (Kögel-Knabner 2000).

Harnessing energy from faecal sludge solids

Total solids content in raw faecal sludge

The technical and financial viability of turning FS to solid fuel is dependent on both the energy value embodied in the solids and the total solids (TS) content of a given volume of FS. Total solids were found to vary by source. The TS of FS from unlined pit latrines was 6% of wet weight – higher than that of fully lined pit latrines and septic tanks, which averaged 2.7 and 1% of wet weight, respectively. The higher TS in unlined pits is attributed to liquid leaching to the soil. Conversely, septic tanks – designed more like holding tanks in many dense urban areas – had the lowest solids content because of the

limited leaching and the excess grey water they receive. These data correspond with other values presented in the literature for sub-Saharan Africa. For example, Koné and Strauss found that public toilet sludge in Accra had a concentration of 52,500 mg/L (5.3% TS), and septage in Accra and Burkina Faso had a concentration of 12,000 (1.2% TS) and 19,000 (1.9% TS), respectively (Koné & Strauss 2004).

Sludge drying

With TS averaging just 6%, an efficient and effective means of drying the FS is critical. Drying bed experiments in Kampala yielded a solids content of about 30% after two weeks in the beds. In Senegal, sludge averaged 37% solids after one week, 49% solids after two weeks, and 58% solids after three weeks.

In Ghana, FS at all three depths (6, 8, 10 cm) achieved nearly 60% total solids within 15 days (Figure 4) – faster than Kampala and Dakar and some other published studies (Cofie et al. 2006). For example, drying bed tests in Ghana by Cofie et al. achieved just 45% total solids after 34 days of drying at an initial depth of <30 cm. In another Ghanaian study using a mix of public septage and sludge from primary settling ponds, faecal sludge reached 40% total solids after

eight days at a depth of <20 cm (Montangero & Strauss 2004). The more commensurate results between the latter study and our own suggests that shallower initial depths improve drying rates.

Rapid prototyping to increase drying speed

Adding polymer and enabling the free water to drain was quite effective at reducing moisture content. This increased the solids content from 5 to 16%, removing 72% of the total water in the sludge. Commercial greenhouse sludge drying beds are capable of providing evaporating rates between 1 and 3.3 kg water/m²/day (Bux & Bauman 2003). By removing 72% of the water through polymerization first, the land requirement is likewise reduced by 72%.

Furthermore, the crude pressing setup removed an additional 46% of the remaining water, increasing the solids content from 16 to 26%. These rapid prototyping results indicate that flocculating with polymer and then pressing out the water would reduce land requirements for drying beds by 85% (Table 2). However, more rigorous experimentation is needed to confirm this result and a cost analysis must be carried out to assess the trade-off between faster drying rates but higher costs of purchasing the polymer.

The combination of polymerization, pressing and drying in thin 1–2 cm layers dried the sludge substantially faster than the first set of drying bed experiments in Ghana. In the previous experiment, it took 15 days for FS to reach approximately 60% solids by weight, whereas 60% solids were achieved in 2.5 days with the rapid prototyping interventions.

One other condition that was briefly tested was drying polymerized sludge on slanted concrete, which allowed water to drain off rather than filter down into the bed. The slanted bed was nearly as dry as the pressed sludge at the end of day 4, suggesting that a slanted concrete surface

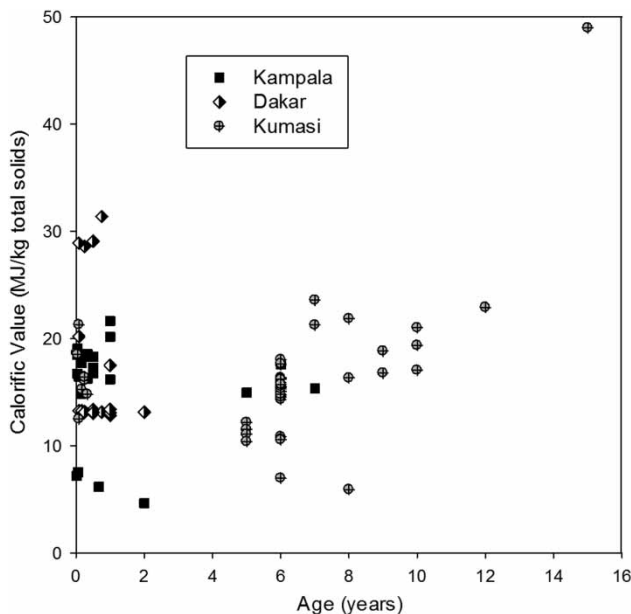


Figure 4 | Sludge depth, total solids (TS) and rainfall over the 15-day trial. Drying beds were covered by a transparent roof, initial sludge depth 6–10 cm, drying to 60% TS over 15-day drying period (Rainfall data from Solar Resource Center, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana).

Table 2 | Potential for polymerization and pressing to reduce land requirements for drying beds

Intervention	Total solids (%)		Land reduction over baseline (%)
	Baseline	After	
Polymerization	5	16	72
Pressing	16	26	46
Total: polymer + pressing	5	26	85

may be more appropriate than a flat sand bed for drying polymerized sludge. Although the results from the rapid prototyping round are not exhaustively researched, they do highlight promising areas for future investigation.

Use of dried sludge as fuel

The combined calorific values and sludge drying results bode well for the technical and financial viability of using FS as solid industrial fuel. The average calorific value is highly competitive with other biomass fuels, and simple innovations in open-air FS drying beds may unlock significant improvements in drying rates, while keeping costs to a minimum.

From a financial perspective, this sanitation solution is viable if the cost of drying the FS to (at least) the point where net energy may be harnessed is less than the price that may be commanded for the resulting fuel. The analysis in Table 3 shows the value of 500 m³ of FS as fuel, when dried to 27, 60 and 85% dry solids. (The analysis is based on assumptions shown in Table 4.) As shown, 27% solids is the minimum dry solids content from which net energy can be harnessed from the FS. The rapid prototyping results

illustrated that 27% solids can be nearly achieved with coagulation and pressing alone (Table 2). Achieving 60% solids is possible in a matter of days when combined with thin layer solar drying.

CONCLUSION

Converting faecal sludge to a renewable biofuel may be a means of tackling sanitation challenges in sub-Saharan Africa. With its calorific value fairly consistent across cities, sources of FS and age, the results of this study suggest that FS-to-solid-fuel could be a widely transferable solution for FS management.

Designing systems to optimize energy recovery as solid fuel will require a new way of approaching sanitation, as digestion (anaerobic or aerobic) can nearly halve the amount of energy that is harnessed in the solids, and should thus be avoided. Fast and effective drying techniques should also be further researched knowing that the land area needed for traditional open-air drying beds may be prohibitive in many urban areas.

Table 3 | Summary of fuel value of 500 m³ raw FS when dried to 27, 60 and 85% solids. Assumptions described in Table 4

	Water heating energy (KJ/wet tonne)	Vaporization energy (KJ/wet tonne)	Steam heating energy (KJ/wet tonne)	Total energy used (MJ/wet tonne)	Energy content of DS (MJ/wet tonne)	Deficit/Gain (MJ/d)	Value fuel cost/savings (US\$/d)
S1	228,855	1,649,800	1,592,699	4,339	4,617	6,945	28
S2	125,400	904,000	872,712	2,378	10,260	197,059	807
S3	47,025	339,000	327,267	892	14,535	341,085	1,397

Table 4 | Assumptions used to assess fuel value of FS shown in Table 3, S1, S2 and S3 represent three scenarios

Global assumptions	Scenario assumptions		S1	S2	S3
Latent heat vaporization (KJ/kg)	2,260	Sludge solids state (%)	27	60	85
Specific heat water (KJ/kg)	4.18	DS/ton (kg/tonne)	270	600	850
Specific heat steam (KJ/kg)	1.86	Water/tonne (kg/tonne)	730	400	150
Starting temperature (°C)	25	Daily fuel quantity (wet tonnes)	93	42	29
Kiln/boiler temperature (K)	1,273	Daily sludge quantity (dry tonnes)	25	25	25
Sludge calorific value (MJ/kg DS)	17.3				
Fuel cost (coal Senegal) ^a (US\$/GJ)	4.10				
Kiln/boiler efficiency (%)	80				

^aBased on cost of coal in Senegal (US\$106.50/tonne) and assuming 26 GJ/tonne coal.

This study identified several possible drying bed enhancements. A transparent roof is a simple design intervention to speed drying and thus decrease the land area needed for drying beds. Other promising interventions include flocculating the sludge with polymer and mechanical pressing, which have potential to reduce land requirements by as much as 86%. Furthermore, designing to optimize drainage is key in humid climates, as this is the driving mechanism for water removal. Ultimately, the end value of the fuel must be weighed against the cost of drying to determine the optimal processing conditions, but additional energy for drying FS can be harnessed with minimal recurring costs.

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