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A value proposition: Resource recovery from faecal sludge—Can it be the driver for improved sanitation?

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ABSTRACT

There is currently a lack of access to affordable sanitation in urban areas of Sub-Saharan Africa. This study evaluated the potential for resource recovery from innovative faecal sludge treatment processes to generate a profit that could help sustain the sanitation service chain. A total of 242 interviews were conducted in Accra, Ghana; Dakar, Senegal; and Kampala, Uganda to compare markets in different cultural and regional contexts. Products identified to have potential market value include dry sludge as a fuel for combustion, biogas from anaerobic digestion, protein derived from sludge processing as animal feed, sludge as a component in building materials, and sludge as a soil conditioner. The market demand and potential revenue varied from city to city based on factors such as sludge characteristics, existing markets, local and regional industrial sectors, subsidies, and locally available materials. Use as a soil conditioner, which has been the most common end use of treated sludge, was not as profitable as other end uses. These findings should help policy and decision makers of sanitation service provision to design financially viable management systems based on resource recovery options.

1. Introduction

In urban areas of Sub-Saharan Africa, 80% of existing sanitation access is met by onsite technologies, and the sludge that accumulates in these systems is referred to as "faecal sludge" (Koné, 2010). However, despite improvements in worldwide access to sanitation over the last decade, 70% of the population in Sub-Saharan Africa still lacks access to improved sanitation (UNICEF and WHO, 2012). One reason for this is the high economic burden that sanitation places on local governments and households. Although the private sector may fill a gap in service provision, such service is either barely financially viable for entrepreneurs or not affordable for the urban poor (Boot and Scott, 2009). Solving the sanitation problem will require innovative approaches in infrastructure, technology, and cost recovery. The lack of profitable or financially viable options for managing the entire sanitation service chain constitutes a major barrier hindering development. Finding innovative ways to create viable business opportunities in sanitation is considered a promising pathway for improvements in this sector (SDC 2004).

Viable business models could emerge from designing faecal sludge management systems around resource recovery, which would in turn help ensure sustainable provision of adequate sanitation (Murray and Ray, 2010). In urban areas where the sanitation problem is the worst, it has been demonstrated that faecal sludge management technologies have overall annualized capital and operating costs that are five times less expensive than conventional sewer based solutions (Dodane et al., 2012). However, households served by on-site sanitation technologies pay significantly more of their annual incomes for this service than households served by sewer based systems (Dodane et al., 2012). In Accra, Ghana, for example, the cost to poor households for emptying their latrine is ten times more than the percentage of household income that is

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considered to be equitable for sanitation services (Boot and Scott, 2009).

Faecal sludge management systems require many interactions among stakeholders (e.g. household, collection and transport company, treatment plant, enduse or disposal), in comparison to one utility managing a sewer-based system. The financial burden of sanitation on households and governments can be shifted by creating new value propositions from human waste. One way to generate additional financial flow is at the back-end of the service chain, by tapping into a customer segment interested in resource recovery from waste derived products (Murray and Ray, 2010). This new value proposition of selling end products following treatment would complement the existing value proposition, which is typically only an emptying service to the household customer group. With a multi-stakeholder approach to sanitation, it is important to develop commercially viable business models that depart from subsidy-driven approaches, with self-sustaining or, even profit-oriented business approaches, in which costs are recovered fully (Gebauer and Reynoso, 2013; London and Hart, 2010). An additional revenue stream by sale of products generated from treated waste could alter the financial flow of the service chain, and result in an offset of disposal costs. This could potentially reduce the amount paid at the household level, thereby increasing a household's ability to pay for service, which in turn improves the overall access to sanitation and impacts on hygiene, health and wellbeing.

Traditionally, the most common use of treatment end products has been in agriculture. An objective of this study was to evaluate whether more lucrative options exist, with the intention of contributing to the decision making process for sustainable faecal sludge management. However, it is difficult to calculate cost recovery from faecal sludge products because there have been so few treatment technology implementations, and as a result values are not known. This study attempted to identify innovative end products of faecal sludge management, their potential market demand, and their financial value in three Sub-Saharan African countries.

2. Materials and methods

2.1. Background

In order to make a cross-comparison of different cultural and regional contexts, the study was carried out in three cities in Sub-Saharan Africa: Dakar, Senegal; Accra, Ghana; and Kampala, Uganda (Fig. 1).

Dakar, the capital of Senegal, is located on a peninsula at the very western point of Africa. There are 2.5 million inhabitants in the greater metropolitan region of Dakar, 30% of whom are served by a centralized sewer system and wastewater treatment. Fifteen percent of the wastewater is treated using activated sludge technology, and the rest is discharged untreated to the ocean. The majority of residents (1.8 million) are served by a faecal sludge management system, including cistern/pour flush toilets connected to septic tanks on a household level (Dodane et al., 2012). The effluent of septic tanks is discharged into open drains or infiltrates into the subsurface.

Approximately 1500 m^3 of faecal sludge is collected daily by private vacuum truck companies and delivered to the Cambérène, Niayes, or Rufisque faecal sludge treatment plants where it is treated in settling/thickening tanks followed by unplanted drying beds. It is estimated that 6000 m^3 faecal sludge is produced daily, meaning the remaining 4500 m^3 of faecal sludge is disposed of directly into the environment (Bill and Melinda Gates Foundation, 2011). The total solids content of faecal sludge in Dakar is reported to be 3.5–4.5 g/l (Dème et al., 2009). Using an average value of 4 g/l

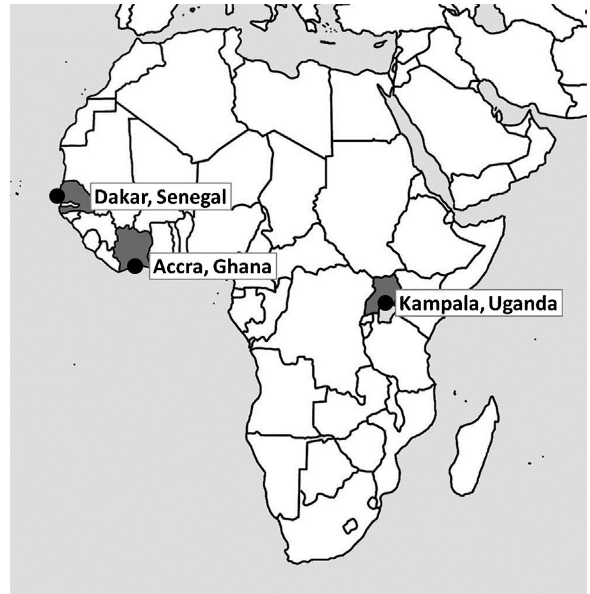

Fig. 1. Three cities in Sub-Saharan Africa where data was collected: Dakar, Senegal; Accra, Ghana; and Kampala, Uganda.

of total solids means that 6 tonnes of total solids are delivered each day to faecal sludge treatment plants, while an estimated 18 tonnes daily are dumped indiscriminately.

Accra, the capital of Ghana, is currently facing rapid population growth. In the year 2000 there were 3 million inhabitants, but by 2010 the population was estimated to be 4 million (Ghana Statistical Service, 2011). Of the metropolitan area, 15% is served by a sewer system, but with no functioning wastewater treatment plant. The majority of the population is served by onsite sanitation facilities including septic tanks, public toilets, VIP pit latrines, and bucket latrines. Sludge from onsite systems is collected and transported by private companies. Historically, there were three faecal sludge treatment plants in Accra, but none of them are currently functioning. The only current official faecal sludge dumping site is Lavender Hill at Korle-Gonno beach, which receives approximately 750 m^3/day. There is no estimate for the actual total amount of faecal sludge produced in Accra. At Lavender Hill, untreated faecal sludge is discharged directly to the ocean. The average total solids of faecal sludge in Ghana is reported to be 20–50 g/l (Cofie et al., 2009; Kuffour et al., 2009). Estimates using an average value of 35 g/l total solids results in 26 tonnes of total solids discharged daily at Lavender Hill.

Kampala, the capital of Uganda, has a population of approximately 1.7 million people, based on census data from 2002 and an average growth rate of 3.7% (Uganda Bureau of Statistics, 2006). In Kampala, 5–7% of the population is served by a centralized sewer system, and the wastewater is treated by primary clarification tanks with subsequent trickling filters. Unsewered areas of the city use onsite sanitation systems, including various types of public and private pit latrines (80%), or septic tanks (20%) (NWSC, 2004). The faecal sludge is collected and transported by various private companies and the government, operating in the city with a total of 37 trucks (Schroeder, 2011). Faecal sludge in Kampala is discharged at Bugolobi Sewage Treatment Works (BSTW). The faecal sludge is collected in a large pond intended for settling. When sludge is removed from that pond it is landfilled. The Bugolobi treatment plant receives 400 m^3/day of faecal sludge. There is no estimate for the total amount of faecal sludge produced in Kampala. The average total solids in faecal sludge of Kampala is around 50 g/l for pit latrines, and 3 g/l for septic tanks (Muspratt et al., 2014). Using these values and the distribution of different on-site systems amounts to an estimated 16 tonnes of total solids that are discharged daily at BSTW.

2.2. Data collection

The main methods used for data collection in the three cities were: (i) document analysis, comprising a systematic search for information, evidence, or insight from documents directly or indirectly related to the issue of faecal sludge management; (ii) stakeholder identification and selected individual semi-structured interviews (face-to-face); (iii) focus groups and workshops; and (iv) direct observations and measurement or estimation of quantitative data.

The first step consisted of identifying key and primary stakeholders in faecal sludge management, including the potential users of products derived from faecal sludge. Focus group discussions with researchers and practitioners from the sanitation sector were used as a starting point for identifying an initial group of stakeholders, and possible end-uses and end-users of faecal sludge derived products. Using the first steps of stakeholder analysis as described by (Schmeer, 2000) and the (Overseas Development Administration, 1995), stakeholder identification also followed an iterative process. During interviews, stakeholders were asked who they thought was not on the stakeholder list but should be (Bryson, 2004). New names were continuously added to the list until no new stakeholders were mentioned. After identifying stakeholder groups or organizations, and identifying key informants, these were then interviewed using open-ended or semi-structured protocols, along with direct observations. If deemed interesting for obtaining quantitative data, a further visit then followed up with mass flow measurements or estimations. The topics of interviews included:

- Overview of interviewee's business activities;
- Identification of products in use today that could be directly replaced by faecal sludge (e.g. solid fuel, fertiliser), or derived from faecal sludge (e.g. animal feed, biogas);
- Perceptions concerning the use of products derived from faecal sludge;
- Knowledge of other possible end-uses, and potential stakeholders.

The types of stakeholders, and number of interviews conducted with each type of stakeholder in each city, are presented in the Supplemental Information. The data were collected at the beginning of 2012 over a four-month period, by one interviewer in each city.

Due to fact that in most cases there is no use of faecal sludge products, the questionnaires were structured in order to assess information on products used today, which potentially could be replaced by faecal sludge. For example, questions for the farmers were directed towards different fertilisers in use, cost of the fertilisers, and their willingness to use faecal sludge as an alternative soil conditioner. To calculate the projected gross values of treated sludge end products, the replacement cost approach (RCA) was employed. For example, identifying to calculate the value of faecal sludge as a fuel in combustion, the calorific value was used as a metric of the expected energy output, and was compared to the calorific value of fuels that are currently in usage (Murray and Ray, 2010).

3. Results and discussion

3.1. Identified end-uses

Following the literature and document analysis, and the expert focus groups and workshops, five potential faecal sludge derived product groups were identified: dry sludge as fuel for combustion; biogas from anaerobic digestion of sludge; protein derived from sludge processing to be used as animal feed; dried sludge for use as a component in building materials; and treated sludge as a soil conditioner or organic fertilizer. Of these five products, the only one observed in practice is very limited agricultural use of raw and treated sludge as a soil conditioner and fertilizer in Dakar and Accra. Other sludge-derived products are not yet produced nor used in any of the three cities.

3.2. Dry sludge as fuel for combustion

Use of faecal sludge as a dry combustion fuel in industry has not yet been implemented, but seems very promising based on the use of wastewater treatment sludge (biosolids) as an alternative fuel in the cement industry in Europe and the US (Boesch and Hellweg, 2010; WBCSD, 2005). Laboratory and pilot scale research conducted in Dakar and Kampala has demonstrated the technical viability (Gold et al., 2014), and the average calorific value of faecal sludge is 17 MJ/kg solids (Muspratt et al., 2014) which is comparable to the 8.0–23 MJ/kg observed with biosolids (Mödinger and Mayr, 2006; Skjeggerud et al., 2009; Spinosa and Vesilind, 2001). For a net energy benefit, sludge must be adequately dried to a minimum of 28% dry solids (Muspratt et al., 2014).

The main potential market for sludge as fuel in all three cities was identified as the industrial sector; industries have both the fuel demand and ready willingness to use the product. The interviews revealed that depending on the city, country and type of industry, a variety of fuel sources could be supplemented or replaced with faecal sludge. In Dakar, industries were either using electricity as their sole source of energy (15 of 34 interviewed), or liquid fuels such as diesel, heating oil, or kerosene (19 or 34). The use of solid fuels was not observed in Dakar. Also in Accra, industries were most dominantly using electricity (5 of 6), and to a limited degree also liquid fuels (1 of 6) but not solid fuels. Solid fuels require more air than liquid fuels to burn efficiently, so existing boilers and kilns for liquid fuels would have to be modified (Morvay and Gvozdenac, 2008). The 19 interviewed companies using liquid fuel in Dakar were using 10,090 m^3/year, or 363,179 GJ/year (based on LHV of 42 GJ/tonne, and density of 857 kg/m^3 (Pandey et al., 2012), representing a significant demand. Based on the faecal sludge that is currently collected in Dakar, and a calorific value of 17 GJ/tonne (Muspratt et al., 2014), combustion of faecal sludge could meet 35% of the identified demand. All interviewees were interested in the potential of faecal sludge as a fuel, but first wanted to see a demonstration to verify the feasibility. Other important concerns that were expressed for using faecal sludge as a fuel included the final form for ease in transportation, distribution, and feeding into boilers and kilns.

In contrast, in Kampala due to the pervasive use of multiple types of solid fuels, focus was set on surveying only industries already using an energy source other than electricity. Of the 16 industries interviewed in Kampala all are using either one or more types of solid or liquid fuels including coffee husks, sawdust, firewood and charcoal, used engine oil, and diesel. Current fuel values and price ranges are presented in Table 1. All of these products would potentially compete with sludge products, however, 45% of the interviewed companies were immediately willing to use faecal sludge if it met their requirements, 30% were dependent on verification of compatibility with current infrastructure, and 25% were undecided.

The reason industries gave for using multiple fuels was that the availability of one fuel type could not fulfil demand for high heat requirements. Sawdust and coffee husks are used in clay and cooking oil industries as a powdery, dry fuel that is blown into the kilns. Sludge would need to be processed in a similar form to compete in the existing market. Interviewees, however, also

Table 1
Combined annual fuel usage, market prices, and market value of 16 interviewed industrial companies in Kampala, Uganda (including cement plants, brick manufacturing, blacksmiths, and industrial boilers).

Fuel type	Annual fuel use (GJ/year)	Unit price	Calorific value (MJ/kg)	Price (USD/GJ)	Market value (USD/year)
Coffee husks[a]	1290	0.2–1.5 USD/m^3	16	0.05–0.4	65–520
Firewood[b]	700	0.11 USD/kg	16	6.9	4800
Sawdust[c]	210	1.2 USD/m^3	20	0.3	63
Charcoal[d]	80	12.0 USD/m^3	28	1.9	125
Used engine oil[e]	150	400 USD/1000 l	33	13.3	2000
Diesel[f]	35	1400 USD/1000 l	42	40.5	1420

[a] de Ramos e Paula et al. (2011) and Suarez and Beaton (2003).
[b] Afrane and Ntiamoah (2012) and Mödinger and Mayr (2006).
[c] Lehtikangas (2001).
[d] Baker (1985).
[e] Skjeggerud et al. (2009).
[f] Pandey et al. (2012).

highlighted the increasing prices of these fuels over the past few years. For instance, the price for used oil, which is obtained from gas stations, has increased by 30% in one year (300–400 USD for 1000 l) given the high demand by industry. Other fuels such as sawdust, coffee husks, or rice husks used to be considered a waste and disposal problem and were given away free of charge, but this has changed with the high demand for fuel.

The greatest demand for faecal sludge as a combustion fuel was identified in Kampala. It was not as strong in Dakar and Accra, as the use of liquid fuels was more pervasive than solid fuels in the latter two cities. If 16 tonnes of faecal sludge are disposed of daily at Bugolobi (Table 2), with an average calorific value of 17 GJ/tonne, this represents a fuel potential of 84,864 GJ/year (6 days a week operation). If this cost could be translated to a dollar amount based on calorific fuel potential, it would represent a gross value of anywhere from USD 4243–1,128,691 per year using the low-end value for coffee husks, and a higher value for used engine oil. Similar cost comparisons are not available for Dakar and Accra since these alternative fuels are not being used, but the calorific value of faecal sludge that is currently delivered to legal discharge sites there is 31,824 and 137,904 GJ/year respectively. All calculations and assumptions are presented in the Supplemental Information.

3.3. Production of animal protein

Using faecal sludge as a medium for rearing insect larvae for protein in animal feed is a potential treatment and resource recovery option. There are no full scale implementations, however at the laboratory scale the use of faecal sludge as a feed source for black soldier fly (BSF) larvae, *Hermetia illucens*, has been successfully demonstrated by Nguyen (2010). Similarly, in South Africa the company Agriprotein is operating a treatment plant processing waste with insect larvae for the production of chicken and fish feed (van Huis et al., 2013). In addition, insect larvae are widely cultivated for feed in aquaculture, chicken farms, and frog farms using other forms of municipal organic waste (Calvert et al., 1969; Hem et al., 2008; Ocio and Vinaras, 1979; Ogunji et al., 2007; St-Hilaire et al., 2007). Given that the global price for fish meal has tripled from 2005 to 2013, and is expected to remain high due to declining wild fish stocks and the on-going increase of aquaculture, the revenue potential from larvae is very attractive (Naylor et al., 2009).

In Kampala, farmers are already mixing their own feed because of limited trust in the feed industry and the quality of products. Farmers buy small dried fish as protein source at USD 0.75/kg. In Dakar, farmers buy fishmeal for USD 0.80/kg and in Accra 45–65 USD/50 kg bag depending on the grade and brand. The dried fish is on average 60% protein, and the fishmeal 70% (Sauvant et al., 2004).

One tonne of faecal sludge at 40% dry solids can produce 20 kg of dry black soldier fly larval meal (Nguyen, 2010), at 35% protein (Diener et al., 2009; St-Hilaire et al., 2007). In Dakar, 6 tonnes of faecal sludge per day are discharged at the faecal sludge treatment plants (Table 2). This translates to 300 kg of black soldier fly meal or 105 kg of protein that could be produced per day. Setting a price for black soldier fly meal based on a comparable cost per kilogram of protein of fishmeal results in a gross value of USD 37,440/year. In addition, when considering the amounts of faecal sludge that are generated but currently not collected, the amount would be four times higher (USD 149,760). In Accra the same calculation yields USD 222,768/year, and in Kampala USD 109,200/year. In addition the remaining processed solids after BSF-treatment can also be used as a soil amendment. Dry solids are reduced 60% by the larvae, which would mean 2.4, 10.4, and 6.4 tonnes of soil conditioner per year remaining in Dakar, Accra and Kampala respectively. This would generate an additional gross value of USD 2995, 12,979–32,448, and 19,968/year solids in Dakar, Accra and Kampala respectively (based on calculations presented below under Soil Conditioner).

3.4. Biogas

As of yet, there are no full-scale operational anaerobic digesters for the centralized treatment of faecal sludge in developing countries. The only wide scale implementation is small scale, rural digesters, for example, the 200 biogas plants using human excreta

Table 2
Amount of faecal sludge that is currently discharged at legal disposal sites or treatment plants in each city, and projected gross values of faecal sludge endproducts.

	Dakar	Accra	Kampala	
Faecal sludge currently legally discharged	6[a]	26	16	tonnes/day[b]
Fuel–combustion	NA	NA	4,243–1,128,691	USD
Protein[c]	40,435	235,747–255,216	129,168	USD
Fuel–biogas[c]	NA	248,004–257,964	158,743	USD
Soil conditioner	12,480	53,664–134,160	81,120	USD

NA = not available.
[a] It is estimated that the total amount generated is 24 tonnes/day (Bill and Melinda Gates Foundation, 2011).
[b] Total dry solids.
[c] Including selling remaining residue as soil conditioner.

and animal dung as feedstock in Ghana (Bensah et al., 2010). However, research is being conducted to adapt this technology from wastewater treatment where it is commonly employed (e.g. The Partnership for Urban Resource Recovery project, www.sandec.ch), and a full scale reactor is currently in project preparation phase in Dakar, Senegal with funding from the Bill and Melinda Gates Foundation. Interviewees expressed some mistrust of this technology based on the lack of existing implementations. However, industrial interviewees were all open to the idea of using biogas if it was available and reliably being produced.

Accra was identified as having the highest current market potential for biogas based on current usage. Even at the household level, 30% of energy is currently supplied with propane gas (Arthur et al., 2011). In addition, the majority of faecal sludge in Accra comes from public latrines with short sludge retention times and hence, has undergone less stabilization, and should have a greater potential for gas production. Over a temperature range of 15, 20, 25, and 30 °C, 14, 37, 39, and 87 mL of gas/g faecal sludge (i.e. not stabilized, short retention time in onsite storage) is produced (Song et al., 2012). The gas production observed by (Song et al., 2012) only represents a 30% reduction of volatile solids, whereas the theoretical production is 50–60%. This potentially indicates that gas production would be higher if operating conditions were optimized. In Accra, 750 m^3 of faecal sludge with a solids content of 35 g/l are discharged daily at Lavender Hill. The 26 tonnes dry matter, at an operating temperature of 30 °C, would yield 705,744 m^3 of biogas/year, which has a gross value of USD 241,364/year. The same calculation for Kampala yields USD 148,532/year. The calculation was not done for Dakar, as the faecal sludge comes from septic tanks with longer sludge retention times, and hence, the faecal sludge would not have as much readily degradable organic matter available for biogas production. In addition to gas yield, the digestate from the biodigester can be used as a soil amendment (Bensah et al., 2010; Nwafor and Okorie, 2005). Following digestion of 26 tonne/day of faecal sludge, producing 705,744 m3 biogas per year, about 1660 tonnes total solids faecal sludge/year would remain, this could generate an additional gross value of USD 6640–16,600/year in Accra, and USD 10,211/year in Kampala (based on calculations presented below under Soil Conditioner).

3.5. Building materials

No examples of use of faecal sludge in building materials was found in the literature, however, research conducted with wastewater sludge found that addition of 20% by weight of dry sludge in clay bricks did not have a significant impact on functional characteristics (Liew et al., 2004). In addition, the combustion of sludge within bricks can introduce small cavities that improve the freeze–thaw expansion and bonding adherence to mortar (Alleman et al., 1990). Brick manufacturing is pervasive in Kampala, so the use of faecal sludge in building materials was pursued during interviews with brick manufacturers. However, there was a relatively negative perception among brick manufacturers with regard to this enduse. The main reasons given during interviews were concerns about consistent characteristics of faecal sludge, and the abundance of conventional raw materials negates the need for an alternative. This indicates that faecal sludge incorporation into building materials can be considered but would probably only be of interest in areas where raw materials are limited.

3.6. Soil conditioner

The most common form of enduse and resource recovery from sludge is land application. It is commonly carried out in an informal fashion without regards to treatment objectives such as pathogen reduction, but has the potential to be anything from use in agriculture to bagged compost products sold for use at the household level (Strande et al., 2014). In Dakar and Accra there was very limited use of faecal sludge as a soil conditioner, and it was non-existent in Kampala. In Ghana co-compost from faecal sludge has previously showed limited demand by farmers and nitrogen enrichment is suggested to increase value and demand (Nikiema et al., 2013). The farmers who were interviewed in Dakar used on average 246 m^3 of faecal sludge/year. The average price they pay for faecal sludge from drying beds is USD 4/tonne, in contrast to animal manure, which sells for twice as much due to its higher acceptance. In Dakar, customers such as small-scale farmers and horticulturists mix the faecal sludge with animal manure and *Casuarina equisetifolia* L. leaves (Filao leaves) to achieve a consistency that is easier to work with, as the form in which faecal sludge is currently sold is not considered optimal. Customers reported they would prefer to buy faecal sludge as a fine powder, and all 23 interviewees stated that adequate dryness is the key quality criterion. Nutrients and hygienic aspects were ranked as less important. In Dakar, if all of the faecal sludge that is currently being collected were sold as a soil amendment and assuming 60% dry solids (based on operating experience) it would generate a gross value of USD 12,480/year.

In Kampala, although famers were not using faecal sludge, 8% of farmers were using wastewater sludge as a soil amendment. Compost from animal manure (28%) and composted household waste (23%) are applied by many farmers as soil conditioners, and are obtained at the very low price of 0–8 USD/tonne. Among farmers interviewed in Kampala, 58% stated they would use faecal sludge if available, 12% were undecided, and 26% said they were unwilling. Nineteen percent of farmers are already using synthetic fertilizers, and 19% have also used separately collected urine as a fertilizer. In Kampala sewage sludge from drying beds sells for USD 10/tonne. If all of the faecal sludge that is discharged at Bugolobi was sold for this price, it would generate a gross value of USD 81,120/year.

In Accra, 30% of the farmers interviewed used organic soil amendments. Poultry manure is the preferred soil amendment (used by 12%) because it is high in nitrogen, followed by cow dung (9.8%), and cow dung mixed with poultry manure (3.6%). When answering the questionnaire, none of the farmers were willing to use faecal sludge, but then upon further questioning, 15% said they had actually already used faecal sludge on crops at some point. Reasons given by farmers for not using faecal sludge were its market scarcity (46%), that it was not a traditional practice (27%), concerns over odour emissions (6%), and the associated health risks (1%). Risks and perceptions of factors in the future can be mitigated by more studies demonstrating the risks associated with methods of land application (Mariwah and Drangert, 2011). For example, in Tamale, Ghana the risk of using raw faecal sludge in agriculture was found to be quite low due to the timing of application and the hot, arid climate (Cofie and Jackson, 2013). This could also be the case in the hot arid climate of Dakar, but in contrast, Kampala has a more tropical climate with greater rainfall. Presently, most of the farmers interviewed in Accra collect organic wastes for free, except for poultry manure and cow dung, which are sold in 25-kg bags for USD 0.75 or USD 30/tonne. As faecal sludge is not currently being sold in Accra, the range of prices observed in Dakar and Kampala were used as proxies. If all of the faecal sludge that is discharged at Lavender Hill were sold as soil conditioner, it would generate gross value in the range of USD 53,664 and USD 134,160/year.

3.7. Implications

Estimated potential revenues per tonne in each of the cities that could be realized from selling products derived by treatment of faecal sludge from on-site sanitation systems are presented in Fig. 2. Most treatment technologies required to produce these treatment products have not yet been implemented at scale, however they

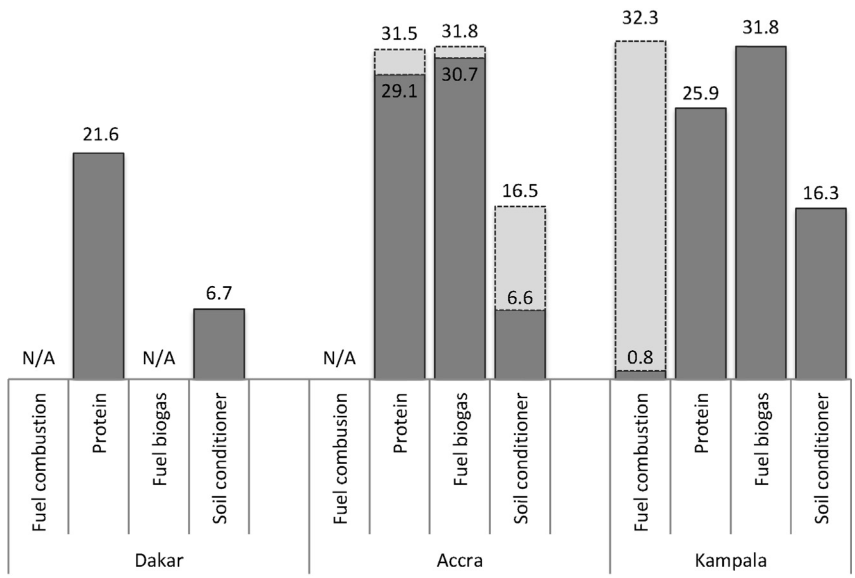

Fig. 2. Potential market value (in USD) of different products derived from faecal sludge processing technologies per tonne faecal sludge (dry weight) in three African cities. Values are variable based on available data (upper range in lighter shade of grey), calculations are presented in the Supplemental Information. For Kampala, only dry fuel types were taken into consideration (e.g. coffee husks, sawdust, charcoal).

have been tested with faecal sludge at the laboratory or pilot-scale level, or have been successfully implemented with wastewater sludge, and therefore show great potential. It is impossible at this time to evaluate net profits, as capital and operating costs will vary greatly depending on type of treatment technology, where it is installed, and the distribution and collection networks There is very limited operational experience of faecal sludge treatment plants to base estimates on. However, research indicates that for example a 15 m^3 per day treatment plant with drying beds would be 4.5 times less expensive to build than highly mechanized systems (e.g. sequencing batch reactors) (Robbins and Santos, 2014). In general, based on current knowledge, treatment options such as BSF and drying beds (i.e. for protein and combustion) have low capital and operating costs, whereas highly mechanized treatments such as anaerobic digestion (i.e. biogas) have high capital and operating costs (Strande et al., 2014). Capital and operating costs need to be taken into consideration to ensure maximum profit from sale of end products. As innovations and implementations increase, actual capital and operating costs can be determined, and hopefully these innovations will also increase the potential for revenue generation.

During the market demand study, industries in all three cities also requested pilot-scale implementations to assess factors such as feasibility, quality, transportation, distribution, marketing and performance prior to taking up innovative technologies. Without this type of proof the financial risk is too high for industry to uptake innovative technologies. To address this, pilot scale kilns were constructed in Dakar and Kampala to demonstrate the technical feasibility of dry sludge as fuel for combustion (Gold et al., 2014). There is a great need for investment in additional pilot and then at scale research for technologies such as biogas and protein which have had minimal to no full-scale implementations, to create a basis for understanding upscaling factors, and context specific factors that will affect cost and operation. However, technologies such as drying beds have been implemented at full scale, for example in Dakar and Kampala.

The market potential for faecal sludge varied strongly from city to city, depending on factors such as characteristics, existing markets, regional industrial sectors, subsidies, and locally available materials. In addition, the revenue that could be generated also varied significantly. This illustrates the importance of considering market demand together with potential revenue (and capital and operating costs) when evaluating solutions. For example, the use of sludge as a soil amendment has traditionally been the most commonly implemented end use, but the analyses shows that the market demand is higher for other end products which also potentially have a greater revenue.

Currently, faecal sludge products are not well utilized. They are mostly landfilled, discharged to the environment, or given away or sold for very little. The values in Table 2 are based on the existing situation, but the faecal sludge market is under leveraged. If valuable faecal sludge-derived products were to be generated, the volumes of raw sludge that are properly collected and managed in cities would most likely greatly increase as a result of the financial market incentive. For example, in Dakar this would increase the values in Table 2 by a factor of four (Bill and Melinda Gates Foundation, 2011). This is in contrast to the current reality of finding the easiest and cheapest place to dump sludge. Reducing or eliminating indiscriminate dumping of human waste would give way to healthy and sanitary environments.

Another benefit of identifying markets for faecal sludge treatment products, is to ensure that technologies are designed appropriately for the intended enduse. By not over- or under-designing treatment plants, it ensures that they are most cost efficient. The market demand for end products can also help to ensure that the treatment plants are operated properly, as operators are trying to fulfil customer satisfaction.

4. Conclusions

The gap in sanitation services could be fulfilled with profitable business based approaches to faecal sludge management. Resource recovery from faecal sludge treatment products could provide a key financial incentive. This is in contrast to the current status quo where sanitation services in low-income countries are not profitable, and hence, typically not fulfilled. This represents a shift in thinking to considering treatment products as a source of revenue generation from resource recovery, versus a disposal problem. The current state of knowledge for implementing resource recovery enduses of faecal sludge and research needs include:

- Evidence suggests that resource recovery from faecal sludge could provide a financial incentive for sanitation service provision

- Possibilities for resource recovery include combustion as fuel, protein production, biogas production, use in building materials, and use as a soil conditioner
- Prior to implementation at a city-wide scale, investments in research at the full-scale are necessary to prove the robustness of technologies, and to determine capital and operations costs
- Use as a soil conditioner, historically the most common form of resource recovery, potentially does not generate as much revenue as energy producing options
- There is not one universal sanitation solution, it is imperative to consider the local market when selecting and designing treatment and enduse, as markets vary significantly among locations
- These results combined with further technical studies, will help policy and decision makers in evaluating potential options for managing the sanitation service chain

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.resconrec.2014.04.005.

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