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ORIGINAL PAPER

Dewaterability of faecal sludge and its implications on faecal sludge management in urban slums

Faecal sludge pre-treatment by dewatering

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Abstract The current practices of faecal sludge management in urban slums pose risks to public health and environmental pollution. Given that faecal sludge contains high water content, dewatering it presents an important step of managing it effectively. This paper therefore explores the applicability of dewatering as the first step in decentralized treatment of faecal sludge (FS) generated from pit latrines, the commonest sanitation technology used in urban slums. A total of 22 and 10 FS samples were collected from lined and unlined pit latrines, respectively. The high moisture content of 92.4 and 83.4 % of FS from lined and unlined pit latrines, respectively, depicted a need for dewatering. Dewaterability extent and rate were measured in terms of per cent cake solids and capillary suction time, respectively. The average dewaterability extent of FS from unlined pit latrines (31.8 %) was significantly higher than that of lined latrines (18.6 %) ($p = 0.000$) while the dewaterability rate (1122 and 1485 s of FS from lined and unlined pits, respectively) was not significantly different ($p = 0.104$), although very low compared to sewage sludge. To obtain high dewaterability extent of FS from lined pit latrines, volatile solids should be reduced and sand content increased. To maintain high dewaterability extent of FS from unlined pit latrines, the particle sizes should be $\leq$1 mm. The results from this study suggest that FS from pit latrines in Kampala can be conveniently dewatered without thickening, thereby reducing costs of FS management.

Keywords Decentralized · Environmental pollution · Faecal sludge · Particle size distribution · Pit latrine

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Introduction

Over 80 % of the urban population in sub-Saharan Africa (SSA) rely on on-site sanitation technologies such as septic tanks and pit latrines for human excreta disposal (Strande 2014). Pit latrines are the most common technologies in urban areas of SSA used by over 80 % of the population in countries such as Uganda, Tanzania, Rwanda, Democratic Republic of Congo, Central African Republic and Mali (Nakagiri et al. 2016). The sustainability of using pit latrines necessitates faecal sludge management (FSM), which entails collection, transportation, treatment and end-use or disposal of their contents that are partially digested semi-solid wastes known as faecal sludge (FS) (Strande 2014). However, FSM in many urban areas of SSA remains a challenge. In these areas, <50 % of the generated FS quantities is collected, of which 25 % is received at centralized plants for appropriate treatment (Koné and Strauss 2004; Blackett et al. 2014). The rest is either unemptied or disposed of indiscriminately onto surrounding land, water

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courses or unsafely used in agriculture/aquaculture (Klingel et al. 2002; Murungi and van Dijk 2014). The uncollected FS is mainly found in urban slums, the densely populated areas in cities, often located on marginal land and inhabited by the poor. Some of the challenges of collecting FS from these areas are high emptying costs due to long haul distances and/or high density of housing units, which limit access by emptying equipment such as vacuum trucks (Murungi and van Dijk 2014). Consequently, the affected slum dwellers resort to unhygienic practices of emptying FS into the living environment or disposing it into nearby open drains, often, leading to surface water bodies (Kulabako et al. 2010). Improper FSM poses a high risk to human health and environmental pollution as human excreta is a source of many pathogens and pollutants (organic matter and nutrients).

Limited accessibility in slums may necessitate modified/specialized emptying equipment, primary collection vehicles, transfer stations and secondary collection vehicles, which make the entire FS service chain complicated and expensive. As a result, there is a need to reduce the costs by treating FS at or near the point of generation referred to as decentralized treatment (Semiyaga et al. 2015). The first stage in developing decentralized FSM systems in slums is dewatering—a process of separating solid and liquid streams through evaporation, sedimentation and filtration. This option is based on the fact that more than 90 % of the FS collected from pit latrines and septic tanks is water (Murray Muspratt et al. 2014), a fraction of which can be recovered, treated and safely disposed of or utilized in the slum areas to minimize pollution. Through dewatering, the water content of sludge is reduced, decreasing the final solids volume for better handling, storage, transportation to places of need, disposed of or converted into useful products within slum areas, which reduces management costs (Novak and O'Brien 1975). Transformation of FS into useful products is very relevant for the urban poor, because their income-generating opportunities are limited and therefore they could establish businesses around the processing and trade in FS-derived products, also resulting into control of environmental pollution risks.

The dewatering of sewage and FS is already widely practised in low- and middle-income countries at the treatment plants by using sand beds. The dewatering mechanism here consists of water filtering through sand layers and evaporation from the surface exposed to air. However, the applicability of sand beds in urban slums is limited by lack of space. For example, about 50 m^2 of land is required for a sand bed that performs three dewatering cycles per month with an average load of 15 m^3 of FS per cycle and a depth of 30 cm (Dodane and Ronteltap 2014). Other technologies commonly used in dewatering sewage sludge such as a belt press, filter press and a centrifuge (Pan et al. 2003) have not been widely investigated in the treatment of FS, and their applicability in urban slums is thus not known.

The selection of dewatering technologies depends on the type and characteristics of FS, space availability and capital costs among other factors (Metcalf and Eddy 2003). For decentralized dewatering of FS in urban slums, it is pertinent to understand the dewaterability characteristics of FS from sanitation facilitates such as pit latrines commonly used in such areas. Characteristics of FS may vary with location, type, design and construction of pit latrines (Still and Foxon 2012). Some of the pit latrines in urban slums are occasionally lined because of the high water table conditions (Nakagiri et al. 2015). In this context, lined pit latrines consist of cement-mortar-sealed containment pits that prevent liquid loss, while unlined pit latrines act as leach pits by permitting infiltration of liquid content (leachate) into the surrounding soils. However, in high water table areas, the flow could be retaliated; for instance, groundwater could also enter from surrounding soils into the pit. Furthermore, in areas that are prone to flooding, the flood water could also find its way into the pit. Unlined latrines in areas with weak soils could cause soils to cave in, during use or emptying operations and the soil could mix with the FS. These factors influence the FS characteristics in the different pit types and their locations as well as conditions in those areas and therefore in turn affect dewaterability characteristics such as particle size (Karr and Keinath 1978; Houghton et al. 2002). The dewaterability characteristics of sewage sludge have been extensively published, but that of FS from lined and unlined pit latrines is lacking in the literature and yet the results are not transferable.

This paper was aimed at determining the characteristics of FS from lined and unlined pit latrines found in urban slums and assessing their possible influence on dewaterability in order to provide data necessary to identify strategies of managing it on-site in urban slums of low- and middle-income countries. The study sought to link relevant FS characteristics to two dewaterability measures; that is dewaterability rate (rate at which water filters out of the sludge) expressed in terms of capillary suction time (CST) and dewaterability extent (per cent dry solids in the sludge cake) (Peng et al. 2011). The influence of the design/construction of the pit latrine in terms of lined or unlined was also evaluated.

Materials and methods

Study area and FS sampling

The FS samples used in this study were collected during the period of September 2015 to December 2015 from

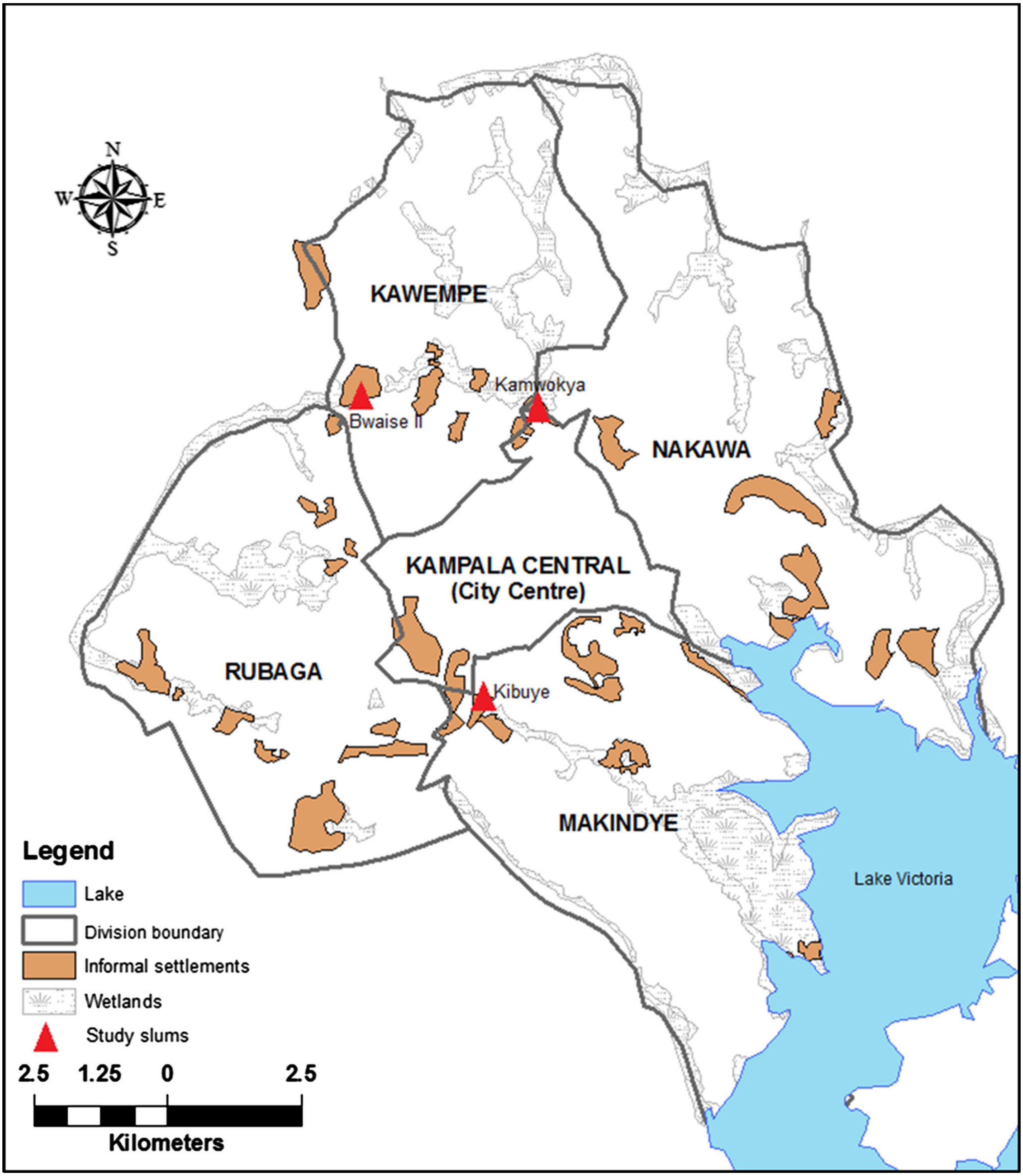

Fig. 1 A map of Kampala City (Uganda) showing location of study slums (Bwaise II, Kibuye and Kamwokya)

three different slum clusters found within Kampala city (Uganda), namely Bwaise II, Kibuye and Kamwokya (Fig. 1). These slums were selected as typical of low and high water table areas having both lined and unlined pit latrines (Nakagiri et al. 2015). In these areas, there is lack of access by FS-motorized truck emptiers to empty the latrines due to the unplanned nature of the areas, resulting into congestion of buildings and narrow roads access. A total of 22 lined and 10 unlined pit latrines were purposively selected. The selection criteria included willingness

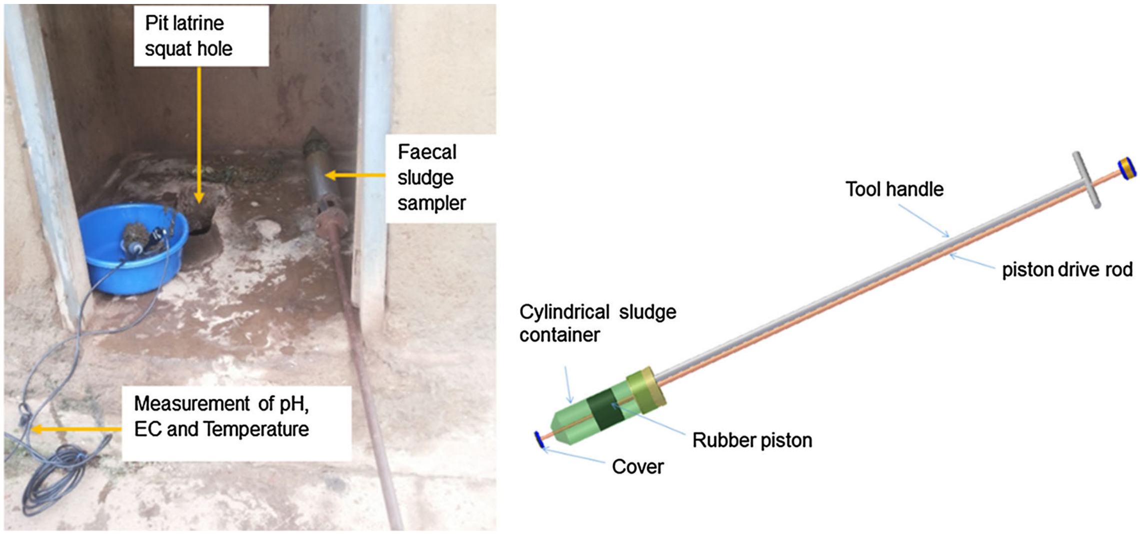

Fig. 2 A fabricated multi-stage faecal sludge sampler used in obtaining faecal sludge samples from a pit latrine through a squat hole (left) and schematic diagram of a faecal sludge sampler (right)

of the latrine owners to participate in the study; availability of more than one stance per pit latrine, so that residents could still access the latrine during periods of sampling; and the latrine facility had to be nearly full to provide sufficiently large quantity of FS content and depth for sampling. Due to the variation in the construction details of pit latrines, a clear distinction had to be made between lined and unlined pits. In addition, some unlined pit latrines with dry FS material were not included in the study, since these were assumed to be already dewatered. This is reinforced by the fact that in practice, such pits are emptied with semi-mechanized technologies like the *gulper*, where the operators fluidize the pit contents with water to an average moisture content of about 82 %.

A fabricated multi-stage sampler, developed by Water For People, Uganda (an NGO which deals in water and sanitation to help people in developing countries improve their quality of life) (Fig. 2), was used to obtain FS samples. When the container of the sampler was inserted at the required depth, the operator pushed the piston rod to open the cover. The rod was then pulled to suck in the FS sample, while closing the sampler at the same time. The sample was then pulled out and put in a separate container. Three grab samples (~1L each) were obtained through the squat hole of the pit latrine: one at the surface, one in the middle and one close to the bottom of each pit latrine. These samples were thoroughly mixed by use of a soup ladle to make a composite sample. At this point, the parameters of temperature, pH, electrical conductivity (EC) and oxidation reduction potential (ORP) of the extracted FS were taken using a potable meter (Hach HQ30d flexi model). Thereafter, two duplicate samples, 500 mL each were put in the plastic containers (polypropylene, microwave oven safe), placed in a cool box (4 °C) and transported to the Public Health and Environmental Engineering Laboratory at Makerere University for analysis. FS samples were stored at 4 °C for not more than 24 h before analysis. Prior to analysis, samples were removed from the fridge and left to attain room temperature.

Sample preparation

Preparation of FS samples before analysis involved passing them through a 5-mm sieve in order to remove the extraneous materials (Burton 2007). FS to be used for analysis of COD, total solids (TS), total volatile solids (TVS) and sand content was homogenized by use of an electric blender (NIMA, model no. BL 888A, 1.5L, 350 watts, Japan), operated for one minute at its maximum speed. These parameters are not affected by FS physical structure and homogenization limit disparities in analysis since FS is highly variable (Reddy 2013). However, a non-homogenized FS sample was used in the determination of capillary suction time (CST) and particle size distribution, since these parameters are affected by particle structure.

Characterization of faecal sludge

TS, TVS and COD were determined according to standard methods as applied to examination of water and wastewater (APHA/AWWA/WEF 2012). TS concentration was determined gravimetrically by taking the weight of oven-dried sample at 105 °C till a constant weight (for 24 h) as a fraction of wet sample volume. TVS was determined by taking the weight difference between oven-dried solids and the 2-h muffle furnace-ignited sample at 550 °C and expressed as a percentage of TS. Ash content was the residue after ignition in the furnace at 550 °C for 2 h. COD was determined using the closed reflux colorimetric method (APHA/AWWA/WEF 2012). Sand content was determined by use of the acid method, where solid residue (ash) was washed with 0.1 M HCl solution into ash-less filter papers. The filter paper and content were then ignited in a furnace at 550 °C and sand content was taken as the residue, which was then expressed as a percentage of TS. Crude protein as an indicator for extracellular polymeric substances (EPS) was determined by multiplying a factor of 6.25 to the difference between total and ammonium nitrogen (NH_4–N) (Han and Anderson 1975; Kabouris et al. 2009). Concentrations of total and ammonium nitrogen in FS from lined and unlined pit latrines were determined with standard vial tests of Dr. Lange: LCK 302 (47–130 mg/l NH_4–N) for ammonium nitrogen and LCK 238 (5–40 mg/l TN) for total nitrogen, respectively. All samples were analysed in duplicate to attest reproducibility of the experimental results.

Determination of particle size distribution

Particle size distribution analysis was determined by sieving FS samples in a water jet (Møller et al. 2002). FS samples (50–100 ml) were placed into the top sieve of a stack of sieves with decreasing mesh sizes of 1 mm, 75 and 32 µm. Therefore, FS was washed through the largest sieve size (1 mm) first and then through the other decreasing mesh sizes. After filtration, the amount of dried solids retained on each sieve was determined by washing each sieve content onto a filter paper and drying it in an oven at 105 °C for 24 h (till a constant weight). The concentration of solids on each sieve size fraction was determined by taking the difference between TS measurements before and after a particular fraction was removed.

Dewaterability rate and extent

The dewaterability rate and dewaterability extent were determined using capillary suction time (CST) and centrifuged per cent cake solids, respectively. CST values were measured in triplicate with a CST instrument (Type 304 M, Triton, England, UK) equipped with an 18-mm-diameter reservoir funnel and chromatography paper, as described in the standard method (APHA/AWWA/WEF 2012). The CST for distilled water (which was used to correct determined CST for FS from pit latrines) was stable at 8.4 s. The cake solids were determined using a centrifuge (MISTRAL1000 type, UK). FS sample (50 mL) was centrifuged at 3000 rpm for 20 min, which corresponds to 1,500 g (Jin et al. 2004). The supernatant was decanted off, and per cent solids content (wet basis) in centrifuged cake was determined from the wet and oven-dried (105 °C) cake weights analysed following the standard method (APHA/AWWA/WEF 2012).

Data analysis

Statistical analysis was carried out using SPSS version 21.0 for Windows. Descriptive statistics (means and standard deviations) were used to describe characteristics and particle size distribution (PSD) of FS from lined and unlined pit latrine. Pearson's correlation coefficient (R^2) was used to evaluate the relationship between dewaterability and the primary contributing factors. The strength of correlation was described as "very weak", "weak", "moderate", "strong" and "very strong" using the guiding coefficient of correlation value ranges provided by Evans (1996). Correlations were considered statically significant at 95 % confidence interval. The difference in dewaterability performance of FS from lined or unlined pit latrines was assessed using analysis of variance (ANOVA) at a 5 % significant level. Before analysis, all data were tested for normality using the Shapiro–Wilk test and homogeneity of variance by use of Levene's test in SPSS. The variations within each slum and each FS category (lined or unlined) were assessed before the variability between categories. Quality control was done by maintaining the difference between the mean values of the duplicate within 5 %.

Results and discussion

Characteristics of faecal sludge

Generally, values of measured physico-chemical characteristics were significantly higher in FS from unlined pit latrines apart from conductivity, moisture content, total volatile solids, crude protein content and oxygen reduction potential (ORP). However, values of temperature and pH in FS from lined pit latrines were not significantly different from those of unlined pit latrines (Table 1).

The low TVS proportions in FS from unlined pit latrines (50.0 ± 16.2 %TS) could be a reflection of reduced organic matter through microbial degradation into carbon dioxide and ammonia, resulting in higher ash content (Cofie et al. 2009). Since organic matter degrades with time, a high COD/TVS ratio of FS from unlined pit latrines (2.0 ± 0.3) than that of lined (1.5 ± 0.4) indicates longer retention time (higher age) of FS from unlined pit latrines (Gebauer and Eikebrokk 2006). This could also be explained by the observed lower oxidation reduction potential values in unlined (−100.64 mV) than lined (−64.12 mV) pit latrine FS, denoting the former being under more anaerobic conditions. Similarly, the lower

Table 1 Characteristics of FS from lined and unlined pit latrine from three slums

Parameter	Unit	FS from lined pit latrine ($n = 22$) Mean ± SD	FS from unlined pit latrine ($n = 10$) Mean ± SD	p value
Temperature	°C	23.0 ± 1.3	22.9 ± 1.0	0.947
pH		7.5 ± 0.4	7.7 ± 0.3	0.343
Total solids (TS)	g/L	51.4 ± 29.2	177.0 ± 78.1	0.000*
Conductivity	mS cm^{-1}	18.1 ± 7.6	12.5 ± 5.6	0.046*
COD	mg/L	65,521 ± 43,960	132,326 ± 43,786	0.000*
Moisture content	% (wet basis)	92.4 ± 1.8	83.4 ± 5.0	0.000*
Total volatile solids (TVS)	%TS	63.5 ± 11.5	50.0 ± 16.2	0.000*
COD/TVS		1.5 ± 0.4	2.0 ± 0.3	0.001*
Crude protein	mg g^{-1}TS	213.0 ± 46.5	109.0 ± 39.6	0.000*
Ash content	%TS	34.5 ± 20.4	50.2 ± 26.5	0.001*
Sand content	%TS	31.9 ± 13.4	50.4 ± 14.0	0.001*
Oxygen reduction potential (ORP)	mV	−61.12 ± 11.2	−100.6 ± 86.1	0.042*

SD standard deviation

* Significant difference between characteristics of FS from lined and unlined pit latrines at $p = 0.05$ using ANOVA

Table 2 Variation in characteristics of FS from lined and unlined pit latrines in the three slums (Bwaise II, Kibuye and Kamwokya)

FS category	Parameter	Unit	Bwaise II Mean ± SD	Kibuye Mean ± SD	Kamwokya Mean ± SD	p value
Lined pit latrine FS	Temperature	°C	22.8 ± 1.6	23.1 ± 1.1	23.7 ± 0.8	0.674
	pH		7.2 ± 0.4a	7.6 ± 0.2b	7.7 ± 0.2b	0.011*
	Conductivity	mS cm^{-1}	17.3 ± 9.0	22.7 ± 3.0	14.7 ± 7.8	0.114
	COD	mg/L	107,137 ± 32,542a	75,120 ± 28,778a	20,794 ± 8,456b	0.000*
	TS	g/L	75.1 ± 19.8a	61.9 ± 22.3a	21.4 ± 10.1b	0.000*
	TVS	%TS	70.4 ± 12.8a	68.5 ± 3.9a	53.0 ± 6.9b	0.002*
	Moisture content	% (wet basis)	92.1 ± 2.0	92.8 ± 1.6	N/A	0.513
	Sand content	%TS	27.3 ± 9.4	29.7 ± 16.1	38.7 ± 12.8	0.250
Unlined pit latrine FS	Temperature	°C	22.4 ± 0.2	22.5 ± 1.1	23.7 ± 0.9	0.135
	pH		7.4 ± 0.3	7.8 ± 0.3	7.7 ± 0.1	0.237
	Conductivity	mS cm^{-1}	9.9 ± 4.8	15.4 ± 8.1	12.3 ± 4.2	0.535
	COD	mg/L	140,607 ± 42,881	156,553 ± 46,953	107,960 ± 40,122	0.363
	TS	g/L	166.1 ± 51.7	237.7 ± 117.2	139.6 ± 41.3	0.274
	TVS	%TS	65.5 ± 12.5	50.1 ± 2.3	38.4 ± 16.0	0.069
	Moisture content	% (wet basis)	84.5 ± 1.1	82.3 ± 8.3	N/A	0.740
	Sand content	%TS	37.8 ± 11.5	57.8 ± 12.5	54.3 ± 12.6	0.170

SD standard deviation, *N/A* not analysed

* Significant difference in characteristics of FS from lined and unlined pit latrines among slums at $p = 0.05$ using ANOVA

Means with different letters are significantly different from each other

moisture in unlined pit latrine FS (83.4 ± 5.0) compared to that of lined pit latrine FS (92.4 ± 1.8) could be due to infiltration of liquid through pit sides as opposed to all retained sludge in lined pits. This in return decreases pit content volume, making unlined pit latrines of equivalent capacity to lined pits taking longer to fill and hence the subsequently high TS, ash and sand content in unlined pits.

The summary of mean characteristics of FS from unlined pit latrines grouped by slums was not significantly different among the three slums. This means that technologies for managing FS from unlined pits could easily be transferred in different slum areas. However, for lined pit latrines, some parameters (specifically pH, COD, TS and TVS) varied significantly among slums (Table 2). A Tukey

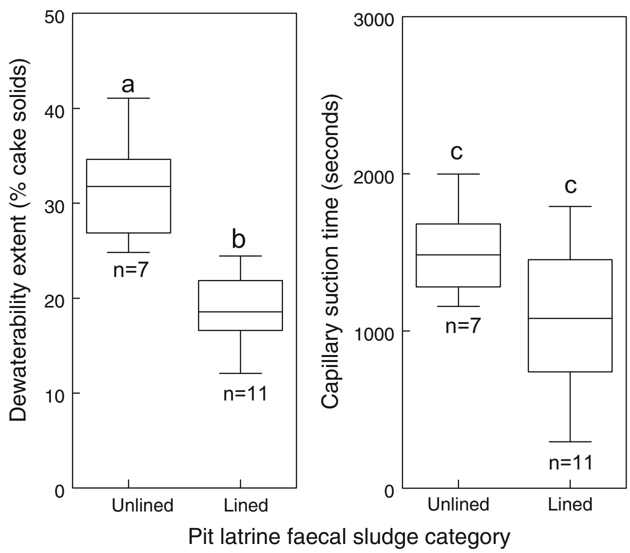

Fig. 3 Dewaterability extent (*left*) and dewaterability rate as CST (*right*) of FS from lined and unlined pit latrines. Graphs with different letters are significantly different from each other at $p = 0.05$. *Box* represents 50 % of the data points, and *line* in *boxes* represents the mean. *n* is the sample size

post hoc multiple comparison analysis revealed that COD, TS and TVS of FS from lined pit latrines in Kamwokya was significantly lower than that from Bwaise II and Kibuye. In general, other characteristics of FS from lined pit latrines in Bwaise II were not significantly different from that of Kibuye (Table 2).

Dewaterability of faecal sludge from pit latrines

The mean cake solids were significantly higher ($p = 0.000$) in FS from unlined pit latrines (31.8 %) than lined pit latrines (18.6 %) in the three slums (Fig. 3). Higher cake solids correspond to better dewaterability extent of FS. However, the capillary suction time (CST) in the two FS categories (1122 and 1485 s in FS from lined and unlined pits, respectively) was not significantly different ($p = 0.104$) (Fig. 3). The higher the CST, the lower the dewaterability rate. This result implied that the rate at which water filtered out of the FS from lined and unlined pit latrines was not significantly different, but less per cent solids resulted in FS from lined pit latrines after dewatering.

Dewaterability extent of FS from unlined pit latrines for a particular location was significantly higher than that of FS from lined pit latrines. However, multiple comparison of means using Tukey HSD revealed no significant differences in dewaterability rate and dewaterability extent of a particular FS category among slums (Table 3). This suggested that FS dewatered at the same rate irrespective of the FS category and slum location while the degree to which it dewatered was dependent on FS category and not slum location.

The causes of disparities in dewaterability extent between FS from lined and unlined pit latrines were further investigated by relating it to FS characteristics using linear regression analysis. TS, TVS and sand content were identified as significantly related to differences in dewaterability extent of FS from lined and unlined pit latrines (Table 4). A relationship between dewaterability extent and TVS of FS from lined pit latrines revealed a significant moderate negative linear correlation ($R^2 = -0.459$, $p = 0.016$). This showed that dewaterability extent of FS from lined pit latrines decreased with increasing TVS. This was not true for FS from unlined pit latrines, as there was a very weak linear correlation ($R^2 = 0.010$, $p = 0.069$) (Table 4).

There was a strong significant positive linear correlation ($R^2 = 0.719$, $p = 0.001$) between dewaterability extent of FS from lined pit latrines and their sand content. On the contrary, linear correlation for FS from unlined pit latrines was weak ($R^2 = 0.269$, $p = 0.188$) (Table 4). This implied that increase in sand content in FS from lined pit latrines could likely increase the dewaterability extent but this would not be the case for FS from unlined pit latrines. Finally, initial total solids content in FS from lined pit latrines had a strong significant positive linear correlation ($R^2 = 0.768$, $p = 0.004$) to its dewaterability extent. High initial TS concentration is a reflection that partial

Table 3 Multiple comparison of mean ± standard deviation for FS dewaterability rate and extent grouped by slum

FS category	Location	Dewaterability extent (%)	Dewaterability rate as CST (s)
Lined pit latrine FS	Bwaise II	16.6 ± 4.1 ($n = 3$)a	N/A
	Kibuye	19.3 ± 3.0 ($n = 2$)a	1365 ($n = 1$)a
	Kamwokya	19.2 ± 4.0 ($n = 7$)a	1091 ± 509 ($n = 8$)a
Unlined pit latrine FS	Bwaise II	31.0 ± 0.7 ($n = 2$)b	1578 ± 595 ($n = 2$)a
	Kibuye	37.9 ± 4.4 ($n = 2$)b	1551 ($n = 1$)a
	Kamwokya	26.9 ± 4.8 ($n = 4$)b	1485 ± 295 ($n = 4$)a

Means with different letters are significantly different at $p = 0.05$. Means with different letters are significantly different from each other. *n* is sample size

Table 4 Summary of Pearson's correlation coefficients (R^2) and p value between FS characteristics and dewaterability extent of lined and unlined pit latrine FS

FS type		TS	EC	COD	TVS	Sand content	pH
FS from lined pit latrine ($n = 11$)	R^2	0.001	0.030	0.024	−0.459	0.719	0.189
	p	0.907	0.590	0.631	0.016*	0.001*	0.158
FS from unlined pit latrine ($n = 7$)	R^2	0.768	0.172	0.156	0.010	0.269	0.074
	p	0.004*	0.307	0.333	0.815	0.188	0.515

* Significant correlation coefficients at $p = 0.05$

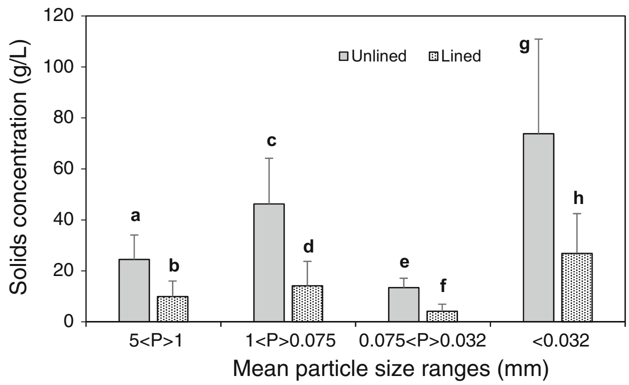

Fig. 4 Comparison of solids concentration in lined pit latrine FS ($n = 21$) and unlined pit latrine FS ($n = 9$) for a given particle size range. For example, 5<P>1 denotes solids passing 5-mm sieve and retained by 1-mm sieve and <0.032 denotes solids passing 0.032-mm sieve. Graphs with *different letters* are significantly different from each other at $p = 0.05$

dewaterability has occurred in unlined pits due to infiltration of liquid into the neighbouring soils.

Particle size distribution of faecal sludge from pit latrines

Generally, the concentration of solids in FS from unlined pit latrines for all grouped particle size ranges was significantly higher than FS from lined pit latrines (Fig. 4). FS from unlined pit latrines therefore does not only have higher initial solids concentration, but also higher concentrations for different particle size ranges. However, the highest concentration of solids for both pit latrine FS categories was in the region below 32 μm (Fig. 4).

Particle sizes bigger than 5 mm were not considered in this study as these were initially screened out before analysis. This is because particles sizes >5 mm have been regarded by Burton (2007) as fibrous in livestock manure. Examples of these materials were identified/isolated from pit latrine FS in this study and included: a variety of anal cleansing materials, solid wastes, maggots, stones and cockroaches. Such extraneous materials can be removed by having a preliminary screening process, where FS is passed through a 5-mm screen.

Solids with particle size >0.032 mm in FS from unlined pit latrines were not significantly different for any particular particle size group among the slums (Table 5). Solids of a size <0.032 mm in FS from unlined pit latrine were significantly different among slums. A Tukey post hoc multiple comparison revealed that the TS at particle size <0.032 mm were significantly lower for FS from unlined pit latrines in Kibuye (74.5 ± 23.3 g/L, $p = 0.039$) and Kamwokya (39.8 ± 4.5 g/L, $p = 0.04$) compared to that in FS from unlined pit latrines in Bwaise II (123.7 ± 7.7 g/L). There were no significant differences in TS of FS from Kibuye and Kamwokya ($p = 0.086$). This could be due to differences in soil properties (such as permeability) where the unlined pit latrines were constructed. TS of FS from lined pit latrines in all particle size ranges were significantly different among the slums. The Tukey post hoc multiple comparison revealed that TS for all particle size ranges of FS from lined pit latrines in Bwaise II and Kibuye were significantly higher than those of FS from lined pit latrines in Kamwokya. There were no significant differences in TS at various ranges of FS from lined pit latrines of Bwaise II and Kibuye (Table 5). This was due to lower initial total solids of FS from lined pit latrines in Kamwokya.

Normalization of FS from lined and unlined pit latrines by dividing a fraction of solids concentration retained on each sieve with their respective initial TS concentration gave solids proportions of particle sizes for a particular FS category. The cumulative percentage of solids in FS from lined pit latrines passing a given mesh size was higher than that from unlined latrines for particle diameters of <1 mm (Fig. 5a). A greater proportion of particles passed through the minimum sieve size (0.032 mm) for FS from lined pit latrines. This is indicative of the characteristic that FS from lined pit latrines has a higher proportion of fine particles than that from unlined pit latrines.

Variation in particle proportions and faecal sludge dewaterability extent

An attempt was made to relate variations in proportions of particles for particular size ranges to dewaterability extent.

Table 5 Mean TS concentration ± standard deviation for particle sizes of lined and unlined pit latrine FS in the three slums (Bwaise II, Kibuye and Kamwokya)

FS category	Mean particle size range (mm)	Bwaise II TS (g/L)	Kibuye TS (g/L)	Kamwokya TS (g/L)	*p* value
Unlined pit latrine FS	5 <P>1	27.2 ± 5.1	17.7 ± 9.9	28.6 ± 11.8	0.367
	1 <P>0.075	41.8 ± 16.5	58.9 ± 30.2	42.3 ± 13.3	0.589
	0.075 <P>0.032	14.6 ± 0.9	14.3 ± 5.9	11.7 ± 2.3	0.667
	<0.032	123.7 ± 7.7a	74.5 ± 23.3b	39.8 ± 4.5b	0.005*
Lined pit latrine FS	5 <P>1	14.6 ± 6.2a	8.6 ± 2.6a	6.8 ± 5.8b	0.029*
	1 <P>0.075	19.0 ± 8.4a	18.4 ± 9.8a	6.8 ± 5.5b	0.012*
	0.075 <P>0.032	5.2 ± 2.7a	6.4 ± 1.8a	1.5 ± 0.7b	0.000*
	<0.032	36.3 ± 15.5a	35.4 ± 6.6a	10.13 ± 6.6b	0.000*

TS total solids

* Statistically significant using ANOVA at $p = 0.05$

Means with different letters are significantly different at $p = 0.05$ for a particular particle size range

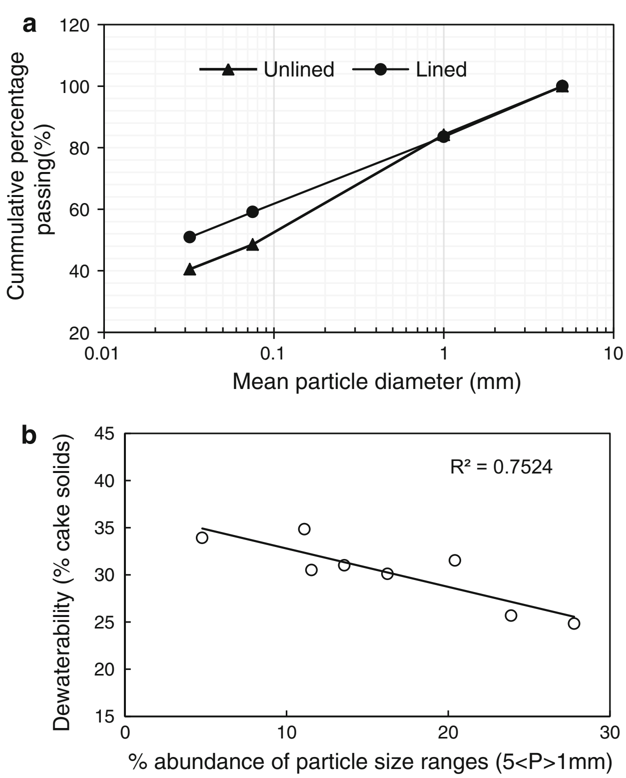

Fig. 5 **a** Normalized particle size distribution of FS from lined and unlined pit latrines; **b** Pearson's correlation between dewaterability extent and change in proportion of particles for size range (5 <P>1 mm) of FS from unlined pit latrine

Generally for FS from all pit latrine categories, there were no significant relationships of change in particle proportions to dewaterability extent apart from size ranges of 5–1 mm for FS from unlined pit latrines (Supplementary material). Particle proportions in a range of 1–5 mm depicted a significantly strong negative correlation ($R^2 = -0.7524$, $p = 0.005$) with dewaterability extent of FS from unlined pit latrines (Fig. 5b). This implies that increasing proportions of particles for different size ranges could not affect dewaterability of FS from unlined pit latrines except for size range of 1–5 mm where increase in proportions of particles significantly lowered dewaterability extent. Therefore, pre-treatment by using a screen of 1 mm diameter for FS from unlined pit latrines would help to maintain high dewaterability extent.

Characterization of faecal sludge from pit latrines versus dewaterability

The parameters of temperature and pH did not vary significantly between FS from lined and unlined pit latrines. The pH values of 7.5 ± 0.3 and 7.7 ± 0.3 for FS from lined and unlined pit latrines in this study compare with an average pH of 7.5 for FS from public toilets reported by Kengne et al. (2009). Such pH values (7.5–7.7) are of advantage if FS dewatering is to be enhanced using coagulants. Coagulants destabilize the colloidal charges and cause particles to agglomerate into larger and denser flocs which easily settle. Coagulants have been reported to hasten the dewatering process in centrifuges (Chu and Lee 2001) and drying beds (Murray Muspratt et al. 2014), which results in less energy required for separation. The reduced energy can be of advantage in design of manually operated centrifuges (instead of electrically driven ones) that can potentially be used in slum areas of sub-Saharan Africa with no connection to the electricity grid. Additionally, less coagulant dosages can be used to achieve maximum separation efficiencies when optimum pH ranges are maintained. Practically, FS dewaterability in urban slums can easily be achieved when use of chemicals in adjusting FS pH is minimized to reduce costs. This can be done through use of coagulants that work optimally at observed pH values for FS from lined and unlined pit latrines. For example, coagulants such as poly-aluminium chloride (PAC), alum, ferric chloride [$FeCl_3 \cdot 6H_2O$] and ferrous sulphate [$Fe_2(SO_4) \cdot 3H_2O$] have been reported to work optimally at pH ranges of 7.0–7.5 (Amuda et al. 2006; Ghafari et al. 2010). This implies that a wide range of coagulants could be applied across different locations in FS dewatering enhancement to achieve optimal solid–liquid separation with little or no adjustment of the pH.

The levels of COD and TVS show that there is considerable amount of organic matter in FS from lined and unlined pit latrines. COD had average values of 65,521 and 132,326 mg/L for FS from lined and unlined pit latrines, respectively. COD values for FS from unlined pit latrines falls within a range of 90,000–225,000 mg COD/L reported in South Africa (Still and Foxon 2012), while that of FS from lined pit latrines is close to 49,000 mg/L, which was reported for sludge from public toilets in Accra (Ghana) (Heinss et al. 1999). The difference could be attributed to TS, whereby TS of 20 % which were reported for FS from unlined pit latrines in South Africa are close to 17.6 % in this study, while the TS of 52.2 g/L for FS from public toilets in Accra (Ghana) are comparable to that of FS from lined pit latrines (51.38 ± 29.23 g/L) in this study. The COD values of FS from pit latrines in Kampala slums are more than 650-folds of the discharge standard (100 mg/L) set by the National Environmental Management Authority (NEMA) in Uganda. Indiscriminate disposal of such FS has potential negative impacts on receiving land and aquatic environment.

The FS from unlined pit latrines depicted a higher dewaterability extent due to recovery of more cake solids, but its dewaterability rate was not significantly different from that of FS from lined pit latrines. However, the average range of CST for lined and unlined pit latrine FS obtained in this study (1000–1500 s) was far higher than those for commonly reported wastewater activated sludge (120–250 s) (Chen et al. 1996; Lee and Liu 2000). This could be due to the presence of large fine particles and long retention time (age) of FS in pit latrines, as the dewaterability rate is reported to vary with storage time (Wakeman 2007a). Differences in dewaterability extent between FS from lined and unlined pit latrines were largely related to TS, TVS and sand content. Increased sand content and reduced TVS proportion were related to decreased dewaterability extent of FS from lined pit latrines. Sand content could have improved dewaterability extent of FS from lined pit latrines due to the sedimentation effect because of its high specific gravity of 2.65 (Chindaprasirt et al. 2004). Sand could have originated from pit latrine floor washings into the pit; moreover, greywater (which also contains sand) is commonly used in cleaning the latrine floor (Tumwebaze 2014). Additionally, for unlined pit latrines, sand could be due to soils from pit sides falling into the pit contents. The higher crude protein values of FS from lined pit latrines is a reflection of high levels of organic compounds (extracellular polymeric substances, EPS) present (Mikkelsen and Keiding 2002). EPS have a high affinity for water (hydrophilic) and are responsible for mechanical stability of the biofilm (Niu et al. 2013). As a result of this, more water proportion is retained in cake solids (Liu and Fang 2002; Neyens and Baeyens 2003), resulting in low dewaterability extent.

Particle size distribution versus faecal sludge dewaterability extent

Variation in particle size of sludge solids has been reported to influence its dewaterability (Karr and Keinath 1978; Chen et al. 1997). About 62 and 52 % solids in FS from lined and unlined pit latrines, respectively, cumulatively passed the mesh size 0.1 mm. Solids of diameter larger than or equal to 0.1 mm are regarded as settleable and can be removed through sedimentation (Karr and Keinath 1978). This signifies that 38 % and 48 % of solids in FS from lined and unlined pit latrines, respectively, are expected to be of diameter 0.1–5 mm and hence regarded as settleable. Pre-treatment by sedimentation could help improve dewaterability by eliminating a large portion of solids. Additionally, appropriate removal technology based on the sedimentation principle, by either gravity or enhanced gravity, as observed in centrifuges (Burton 2007) could be applied.

The highest concentration of solids for FS from lined and unlined pit latrines was of size below 32 µm. This size range contains mainly colloidal (supra and true) and dissolved solids, and hence, their behaviour is dominated by Brownian motion (Karr and Keinath 1978; Burton 2007). The digestion of larger particles over a long retention time is reported to produce fines of such size in sludge (Wakeman 2007a). This could be the case for fines in lined and unlined pit latrines in this study since they are reported to take more than six months to fill (Kulabako et al. 2010). However, FS from lined pit latrines had a higher proportion of fine solids. This could be due to initial stages of anaerobic digestion, reflected by oxidation reduction potential. Fines are created during early stages of anaerobic digestion due to the presence of biopolymer colloids released in solution (Murthy et al. 2000), leading to deterioration in dewaterability. The fines are further degraded as digestion proceeds and dewaterability again improves

(Rudolfs and Heukelekian 1934), as in the case of FS from unlined pit latrines. Higher treatment efficiencies can be achieved through removal of colloidal solids by use of filter membranes (Levine et al. 1991). However, due to large amounts of suspended particles in FS from pit latrines, membranes are susceptible to frequent clogging and hence require regular cleaning, consequently leading to higher maintenance costs.

Irrespective of particle size ranges in FS from lined pit latrines among the sampled slums, dewaterability extent was not significantly affected. This signifies that use of coagulants could increase the volume of solids settled due to settlement of suspended colloids, but not the cake solids. Coagulants have, however, been reported to instead increase the dewaterability rate (Lee and Liu 2000; Gold et al. 2016). FS from unlined pit latrines was only negatively strongly related to dewaterability extent in a range of particle sized between 1 and 5 mm.

Implications on faecal sludge management

Dewaterability characteristics of FS from pit latrines have influence on the entire FS management chain covering emptying, transportation, treatment and end-use. The characteristics in turn are dependent on the facility used by the community or individuals therein. The results from dewaterability extent showed that solids of FS from lined and unlined pit latrines almost double the original respective values after dewatering. Thus, FS once separated into liquid and solid streams can be further effectively and efficiently managed according to the available alternatives. For example, for some slums such as those in Nairobi (Kenya) that straddle sewer lines (WSP 2009), the liquid stream from the dewatering can be discharged to the sewers and treated together with sewage. The solid stream can then be either transformed into useful products within the slums or transported to treatment plants. This will be at a cheaper cost since the solid stream after dewatering is about 18.6 and 31.8 %TS from lined and unlined pit latrines, respectively. Moreover, it could be directly loaded to drying beds, thereby saving time and space used for the FS thickening stage at the treatment plants. This would also cut down the transportation costs since only the solid fraction is transported. For slum areas with no sewer lines in the vicinity, the liquid stream could be further treated and used in groundwater recharge or disposed of.

The total solids from characterization of FS from lined and unlined pit latrines in this study (51.4 ± 29.2 and 177 ± 78.1 g/L, respectively) are close to that obtained in faecal sludge treatment plants after thickening stage (separating liquid–solid by heavier particles settling as a result of gravitational forces). Raw FS from septic tanks (septage) at a treatment plant is thickened from average range of 12–35 gTS/L to 60–70 gTS/L for 7 days in Dakar (Senegal) (Dodane and Bassan 2014), while up to 150 gTS/L for 8 weeks in Accra (Ghana) has been reported (Heinss et al. 1998). Usage of thickening tanks necessitates extra cost in terms of land, materials and labour to construct as well as operate. FS from lined and unlined pit latrines in this study, therefore, does not require a thickening stage prior to dewatering. This would be ideal for decentralized FS management where space and costs are a major challenge.

Even at high initial TS values for FS from lined and unlined pit latrines, more water is available for further dewatering. This is often achieved in full-scale FS treatment plants by using sand beds (Cofie et al. 2006). These require large space, hence a limitation for decentralized treatment. Compact technologies like filter press, belt press and centrifuge could be appropriate for use in such settings. Use of filter press could be possible after flocculation to reduce high proportions of fine particles (colloids and supra-colloids) observed in the current study since they have a tendency of blinding filter pores resulting in long cake formation times (Wakeman 2007b). Similarly, belt presses work well with flocculated sludge to avoid blinding of the filter belt and enhance gravity drainage (Wakeman 2007b). However, coagulants may not be applicable to FS from unlined pit latrines because the high fluid consistency (viscosity) observed in this FS of the current study could restrict uniform mixing of the coagulants. Additionally, the observed low dewaterability rates of FS from lined pit latrines can be enhanced by use of coagulants, as they have been used to increase the dewaterability rates of FS (Gold et al. 2016).

There are reported recent studies of recovering energy from dried FS for industrial use, and the envisaged challenge is availability of enough FS volumes (raw material) when such projects are up-scaled (Gold et al. 2014). Given that 72 % of urban population in SSA is residing in slum areas (UN-HABITAT 2006), there is potential of generating significant large quantities of FS. However, the limited access to mechanized emptying is one of the major limitations. Innovative emptying technologies like the *Gulper* and vacutags are already used in some areas. Dewaterability as a first stage in FS treatment has proved necessary to increase FS solids after emptying. The volumes primarily collected after emptying would be less and hence less costly to manage. This would also reduce the tendencies of high risks of public health and environmental pollution as a result of indiscriminate dumping after emptying.

Centrifuges have been reported to handle higher solids content and are not much affected by presence of fine particles (Wakeman 2007b). Additionally, Broadbent (2001) developed a chart for an initial selection of centrifuge types depending on particle size and total solids content in the feeding sludge. Using this chart with consideration of FS from lined and unlined pit latrines in this study, due to particle sizes of <5 mm and solids content in the range of 7.6–16.6 %, the appropriate dewatering centrifuge types could be either a decanter or basket centrifuge.

Conclusion

- The very high organic levels in FS from pit latrines in Kampala slums pose risks of environmental pollution and make faecal sludge management an essential provision in urban slum sanitation.
- Faecal sludge from pit latrines has unique characteristics such as sand content, total solids and volatile solids, which influence its dewaterability. The design/construction of pit latrines, specifically lining or not, has an influence on characteristics of FS emptied from such pits and the subsequent dewaterability extent.
- The dewaterability rate of FS from lined and unlined pit latrines was not significantly different, although very low compared to sewage sludge. The dewaterability rate of FS from lined pits can be increased by exploiting its characteristics such as stable pH and the volume of fine particles by adding coagulants.
- The high organic matter levels of FS from lined pit latrines, which are inferred from the high TVS of the FS, were strongly related to its low dewaterability extent. This is a reflection of sludge structure, which holds water. Therefore, there is a need for research to improve the dewaterability extent by modifying the FS structure using physical conditioners, e.g. saw dust, char, coffee or rice husks.
- The dewaterability characteristics of sewage sludge have been extensively published, but that of FS is lacking in the literature and yet the results are not transferable. The characteristics of FS from lined and unlined pit latrines in Kampala slums resemble those of mixed FS sludge (from pits and septic tanks collected elsewhere) after sludge thickening. Therefore, the FS from lined and unlined pit latrines can be dewatered without need of sludge thickening, thereby reducing costs of treatment.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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