

MAKERERE



UNIVERSITY

**DEWATERING AS A CRITICAL STEP IN URBAN SLUM-BASED
FAECAL SLUDGE MANAGEMENT**

BY

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DOCTOR OF PHILOSOPHY OF MAKERERE UNIVERSITY**

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DECLARATION

This study is original and has not been submitted for any other degree award to any other University before.

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DEDICATION

This research work is dedicated to my Mum, wife, children, brothers, sisters and my PhD supervisors.

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LIST OF ABBREVIATIONS

APHA	American Public Health Association
AWWA	American Water Works Association
BOD	Biochemical Oxygen Demand
BSFL	Black soldier fly larvae
C/N	Carbon: Nitrogen ratio
CIDI	Community Integrated Development Initiatives
COD	Chemical Oxygen Demand
DALYs	Disability-adjusted life years
EPS	Extracellular polymeric substances
FaME	Faecal Management Enterprises
FS	Faecal sludge
FSM	Faecal sludge management
KCCA	Kampala Capital City Authority
KWT	Kanyama Water Trust
MAPET	Manual pit emptying technology
MLHUD	Ministry of Lands, Housing and Urban Development
MSW	Municipal Solid waste
NEMA	National Environment Management Authority
NGO	Non-governmental organisation
NWSC	National Water and Sewerage Corporation
PPE	Personal protective equipment
SSA	Sub-Saharan Africa
TS	Total solids
TVS	Total volatile solids
UBOS	Uganda Bureau of Statistics
UNICEF	United Nations International Children's Education Fund
USD	United States Dollars
UYDEL	Uganda Youth Development Link
WEF	Water Environment Federation
WFP	Water For People
WHO	World Health Organisation
WSP	Water and Sanitation Program

ABSTRACT

Faecal sludge (FS), a product from on-site sanitation facilities, poses one of the management challenges in densely populated urban slums of Sub-Saharan Africa (SSA). The collection and transportation of FS from slums to treatment facilities is costly due to high emptying costs; high density of housing units, which limits access to sanitation facilities by vacuum trucks; associated traffic jams and long travel distances to treatment plants. The technologies for decentralised management of FS at a household or community level in slums can eliminate such barriers. This coupled, with potential end-use of the product(s) from FS acceptable at particular slum level, can eventually increase the amounts of FS treated and thus, limit risks to public health and environmental pollution. Since FS contains over 90 % water, dewatering it presents an important step for resource recovery, thus incentivising its management to fully or partially bear its own cost. This study investigated the potential of centrifugation technology in dewatering of FS generated from pit latrines used in slums. Dewaterability extent and dewaterability rate were measured in terms of percent cake solids and capillary suction time, respectively. The average dewatering extent of FS from unlined pit latrines (31.8%) was significantly higher than that of FS from lined latrines (18.6%) ($p = 0.000$) while the dewaterability rate (1122 and 1485 seconds of FS from lined and unlined pits, respectively) was not significantly different ($p = 0.104$). The low dewatering extent of FS from lined pits was improved by addition of sawdust and charcoal dust conditioners. The dewatering extent improved by 22.9% and 35.7%, for FS conditioned with sawdust and charcoal dust, respectively, at optimum dosage of 75 % TS. The dewatering of FS conditioned with sawdust and charcoal dust was mainly governed by absorption and permeation (porosity). Centrifuge operating conditions necessary for dewatering FS conditioned with sawdust/charcoal dust were optimised. Rotational speed was a significant parameter for charcoal dust conditioned FS ($p = 0.0019$) and sawdust conditioned FS ($p = 0.0001$). In addition, the quadratic effect of time was significant for only sawdust conditioned FS ($p = 0.0494$). An optimal centrifugation time of 20 minutes at a speed of 920, 0 and 160 rpm for unconditioned, sawdust and charcoal dust conditioned FS, respectively, yielded the same per cent cake solids when the centrifugation container volume of 50 mL was filled to 70-80% with FS. Results showed that centrifugation technology can be further explored through proto-type design of a hand/cycle-powered centrifuge, thereby enabling decentralised treatment to reduce costs of FS management and support resource recovery at/near the source. Furthermore, emptying equipment that do not require changing FS moisture content should be used, since such emptied FS from pit latrines in slums would not require a thickening stage.

CHAPTER ONE

1 Introduction

1.1 Background and Justification

The sanitation needs of over 2.7 billion people worldwide are met by on-site sanitation facilities such as pit latrines, septic tanks and pour flush latrines. Over 80% of urban population in countries of sub-Saharan Africa (SSA) rely on on-site sanitation facilities (Strande *et al.*, 2014). These are likely to continue dominating in the near future due to their low capital and maintenance costs, as many people in low-income countries of SSA lack financial strength (Morella *et al.*, 2008). Their continued use is accompanied by frequent filling up due to high user loads. An example is the user load of 70 people per pit latrine stance in Kampala slums (Katukiza *et al.*, 2010). However, the sustainability of these sanitation facilities depends on how the faecal sludge (FS) that accumulates in them is properly managed. Faecal sludge management (FSM) service chain entails emptying of full sanitation facilities, transportation of FS to treatment facilities, treatment and end-use or safe disposal of treated FS. The commonly used equipment for emptying on-site sanitation facilities are mechanised cesspool emptier trucks, which thereafter, transport the emptied FS to centralised treatment facilities. However, less than 50% of the generated FS in SSA is collected. Additionally, only 25% of that collected is received at centralised plants for appropriate treatment (Blackett *et al.*, 2014). The rest is either unemptied/uncollected or disposed of indiscriminately into surrounding land, water courses or unsafely used in agriculture/ aquaculture (Klingel *et al.*, 2002).

The unemptied/uncollected FS is mainly found in urban slums (the densely populated areas in cities, often located on marginal land and inhabited by the poor), where about 72% of the urban SSA population reside (UN-HABITAT, 2006; Ezeh *et al.*, 2016). 70 % of the pit latrines in Kampala slums are reported to be full and unemptied (Nakagiri *et al.*, 2015). Some of the challenges in collecting FS from sanitation facilities in these slum areas are high emptying costs due to long haul distances to treatment plants and/or high density of housing units (Figure 1.1 A), which limit access to mechanised cesspool trucks. Consequently, the affected slum dwellers resort to unhygienic practices of emptying FS into the surrounding environment or disposing it into nearby open drains (Figure 1.1 B), thus, posing risks to public health and the environment (Murungi & van Dijk, 2014; Strande, 2014). Emptying and transportation of FS for treatment outside of the slums constitutes a

huge financial burden on the part of the slum communities, who have to bear the costs. Over 65 % of the slum dwellers residing in Kibuye 1 slum (Kampala) confessed not to empty their full pit latrines due to high costs charged by mechanised vacuum trucks (CIDI, 2012).



Figure 1.1 Overview of a typical slum in Kampala (Uganda) showing high density of housing units (A), a typical pit latrine in a Kampala slum, strategically located near a drainage channel for subsequent illegal emptying (B).

However, such challenges can be circumvented if a greater or entire part of FSM services chain is practiced at a decentralised scale (household or community level) within urban slums (Chapter 2). Therefore, instead of the current FSM service, a decentralised service chain could minimise transportation requirements FS through reduction of haulage distances to centralised treatment plants. This, coupled with safe treatment and resource recovery from FS through transformation into products that are beneficial and acceptable by the slum dwellers could enable the decentralised FSM service chain to fully or partially bear its own cost and hence minimise overall disposal requirements (Lilford *et al.*, 2016). Additionally, such products would have an added benefit of creating business opportunities in processing FS into utilisable products, and hence income generation and employment opportunities to urban slum dwellers.

1.2 Problem Statement

Pit latrines are the dominant sanitation facilities used for excreta disposal in urban slums of low-income countries. This is due to their low construction cost resulting from use of available raw materials, low amount of water requirement during operation and lack of affordability for water borne systems (Thye *et al.*, 2011; Tumwebaze *et al.*, 2013). Pit latrines can be unlined to allow leachate infiltration into surrounding soils or lined with a mortar seal to prevent leachate loss, in

places of high water table (Nakagiri *et al.*, 2015). The limited access to pit latrines, when full for emptying, by mechanised cesspool trucks, due to high housing density, has been partly resolved through innovation and usage of semi-mechanised technology options such as *Vacutug*, Manual Pit Emptying Technology (MAPET) and the *gulper* (Thye *et al.*, 2011). The challenge, however, remains with the lack of applicable technology options for subsequent treatment and resource recovery from the emptied FS, at a decentralised level.

Since FS from pit latrines contains over 90% water (Murray Muspratt *et al.*, 2014), dewatering it to achieve liquid-solid separation presents one of the most important process of effective FSM. A minor decrease in the amount of water in FS is reported to cause significant reduction in its volume. For example, increase of sludge dry solids by 10 % causes the decrease in initial sludge volume by over 85 % (Kołęcka *et al.*, 2017). Therefore, when carried out on-site, dewatering reduces transportation costs and makes it easier to handle the dewatered sludge (Tchobanoglous & Burton, 1991). In addition, dewatering of FS is a prerequisite to its conversion to a number of potentially valuable products such as energy briquettes, (vermin-) compost, and construction materials. The technologies commonly used for dewatering faecal sludge at a centralised scale such as thickening tanks and sand beds have limited applicability potential in densely populated urban slums due to large space requirements and high capital cost (Pan *et al.*, 2003). Research into compact applicable technologies for decentralised dewatering of FS from commonly used sanitation facilities in urban slums will potentially reduce cost of FSM, increase the amount of FS emptied for treatment, support local use of FS derived products, and thus, minimise risks for public health and the environment.

1.3 Overall objective

The overall objective of the study was to develop a better understanding of dewatering as a critical step in decentralised management of faecal sludge from urban slums for subsequent development of compact dewatering technology.

The specific objectives of the study were to;

- (i) review practices, technologies and end-uses of faecal sludge in urban slums,
- (ii) determine dewatering characteristics of faecal sludge from pit latrines,
- (iii) investigate how to improve faecal sludge dewaterability,
- (iv) Optimise operation conditions for faecal sludge dewatering technology.

1.4 Overview of the thesis structure

This thesis is based on four published papers (i to iv), which present the investigations guided by the specific objectives outlined (section 1.3). In structure, Paper (i) is a detailed literature review paper. Each of the other papers (ii to iv) comprise an abstract, introduction, methodology, results, discussion and conclusions. The citations of the papers are as follows;

- (i) Semiyaga, S., Okure, M. A. E., Niwagaba, C. B., Katukiza, A. Y. & Kansiime, F. (2015). Decentralized options for faecal sludge management in urban slum areas of Sub-Saharan Africa: A review of technologies, practices and end-uses. *Resources, Conservation and Recycling* 104, 109–119. doi:10.1016/j.resconrec.2015.09.001
- (ii) Semiyaga, S., Okure, M. A. E., Niwagaba, C. B., Nyenje, P. M. & Kansiime, F. (2017). Dewaterability of faecal sludge and its implications on faecal sludge management in urban slums. *International Journal of Environmental Science and Technology* 14(1), 151-164. doi:10.1007/s13762-016-1134-9
- (iii) Semiyaga, S., Okure, M. A. E., Niwagaba, C. B., Nyenje, P. M. & Kansiime, F. (2017) Enhancing faecal sludge dewaterability and end-use by conditioning with sawdust and charcoal dust. *Environmental Technology*. doi:10.1080/09593330.2017.1300191
- (iv) Semiyaga, S., Okure, M. A. E., Niwagaba, C. B., Nyenje, P. M. & Kansiime, F. (2017). Optimizing centrifugation operating conditions for dewatering physically conditioned faecal sludge in urban slums. *Environmental Technology and Innovation* 8, 28-39, Doi: 10.1016/j.eti.2017.03.005.

Overall, the thesis consists of seven chapters. Chapter 1 gives an introduction to the study. It brings this study into context and presents the overall picture of FS management. Furthermore, it gives a justification as to why the study of FS dewatering is important in managing the increasing quantities of FS generated in urban slums of developing countries, and further underpins the situation in Kampala.

Chapter 2 is based on literature review of current and potential practices, technologies and end-uses or disposal of FS at a decentralised level (household or community) in an urban slum setting (Paper i). The review paper (Chapter 2) discusses the possibilities of reducing FSM costs through decentralised management. It further, elaborates how “ability to pay” for sanitation services could be improved through resource recovery from FS that can replace commonly used products within slums.

FS in Kampala contains over 90 % water, yet dewatering is a prerequisite for recovery of a number of products/resources from FS identified in chapter 2 such as; energy briquettes, animal protein, and (vermin-) compost. Therefore, prior to any attempt to investigate actual dewatering, chapter 3 presents dewatering characteristics of FS from lined and unlined pit latrines with a view of comparing the dewaterability of FS from these facilities (Paper ii).

Chapter 4 investigates improvement in dewaterability of FS by use of physical conditioners such as sawdust and charcoal dust, which are cheap and locally available in urban slums of low-income areas of developing country cities such as Kampala (Uganda) (Paper iii).

Chapter 5 assesses and optimises the operating conditions for centrifuge as the selected sustainable technology required for dewatering FS from pit latrines (Paper iv). Chapter 5 used results from chapters 3 and 4 to explore centrifugation as an appropriate technology for dewatering FS from pit latrines. The chapter further assesses the influence of physical conditioners on centrifuge operation conditions. The relationship between chapters 2, 3, 4 and 5 in this study is illustrated in Figure 1.2.

Chapter 6 presents the general discussion of the study. In this chapter, the results from the stand-alone studies presented in the separate chapters 2, 3, 4 and 5 are analysed and integrated to elaborate the key emerging issues from the research.

Chapter 7 concludes the study, by summarising the key findings, and sets forth, the recommendations for policy and further studies.

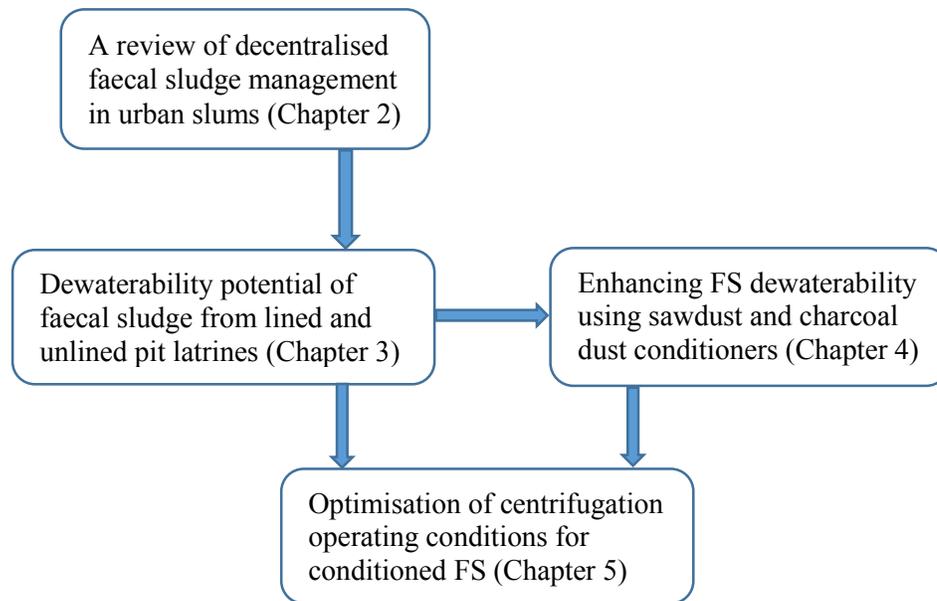


Figure 1.2 Relationship between thesis chapters 2, 3, 4 and 5

1.5 Scope of the Study

The study scope was limited in several aspects. Geographically, it was limited to three slums within Kampala City; *viz*: Bwaise II, Kibuye and Kamwokya (Figure 1.3). These are typical slums in which both lined and unlined pit latrines are the main sanitation facilities (Tumwebaze *et al.*, 2013; Nakagiri *et al.*, 2015). These slums are also characterised by high population and house unit density. On average, the population density of Bwaise II, Kibuye and Kamwokya is 54600, 64200 and 18500, respectively, against the national (Uganda) average figure of 173 persons/km² (MLHUD, 2014; UBOS, 2015). The density of housing units stands at 2200, 5080 and 1240 house structures/km² in Bwaise II, Kibuye and Kamwokya, respectively (MLHUD, 2014). The high population and housing density creates a situation of low/no space availability for construction of new pit latrines, thus increased pressure on the existing ones, increasing the pit filling rates and the associated environmental hazards (Nakagiri *et al.*, 2015). The high housing density, also, signifies presence of narrow passages which limit access to mechanised cesspool trucks to empty the full sanitation facilities present in these study areas. Therefore, such FS remain in these slums with a high potential of environmental pollution and disease prevalence.

In terms of dewatering technology, the study was limited to an investigation of centrifugation because it has a small foot print in terms of area requirement, low operation costs and normally has

a casing to enclose odour in densely populated areas. In addition, conditioning of FS was limited to physical conditioners (leaving out chemical) due to their local availability in urban slums at a low/no cost. Practically, the study was through *in-situ* field measurements and laboratory experiments.

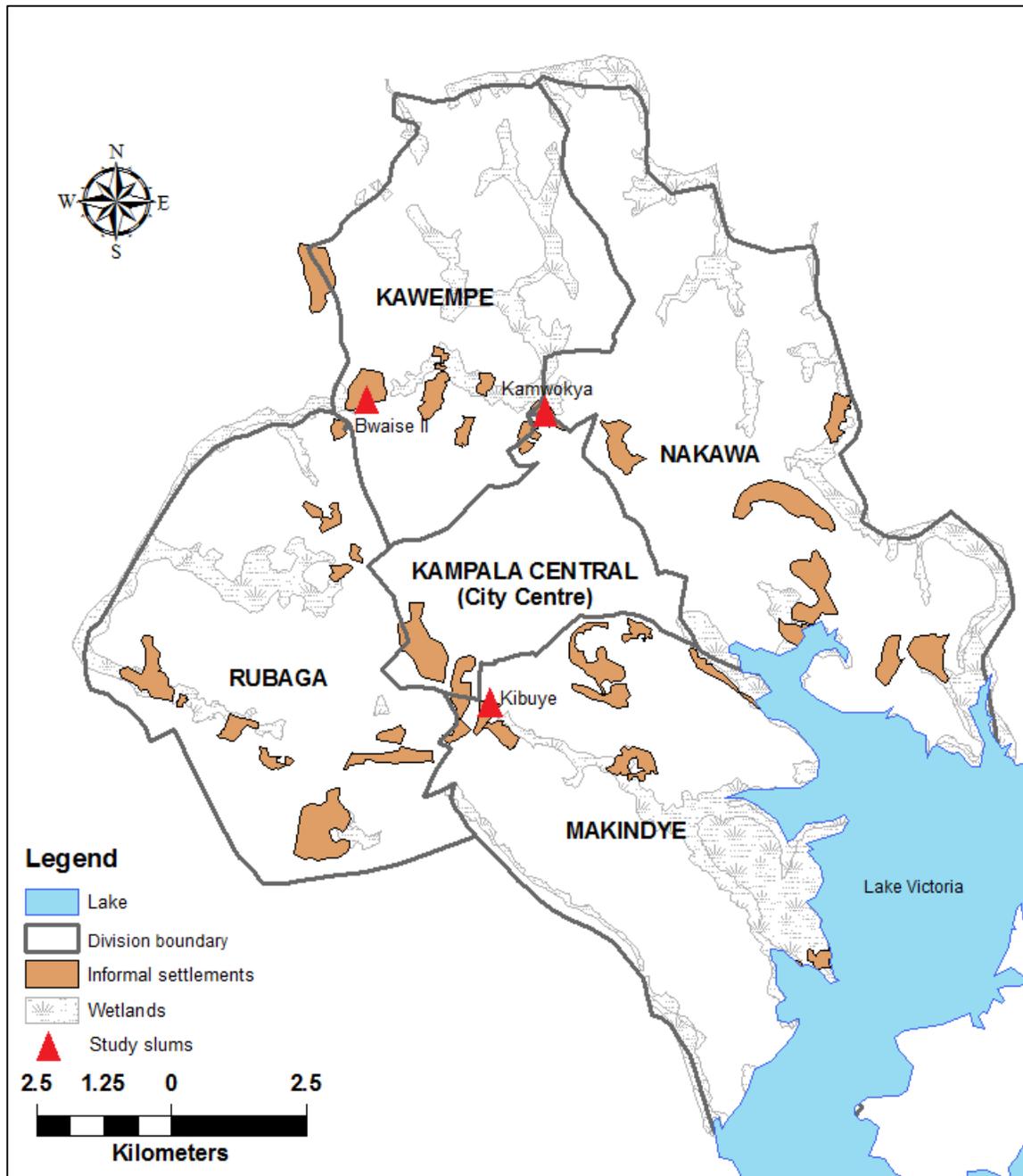


Figure 1.3 Map of Kampala City (Uganda) showing location of study areas (Bwaise II, Kibuye and Kamwokya)

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CHAPTER TWO

2 Decentralised options for faecal sludge management in urban slum areas of Sub-Saharan Africa: A review of technologies, practices and end-uses

This chapter is based on:

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Abstract

Faecal sludge (FS), a product from on-site sanitation systems, poses a management challenge in densely populated urban slums of sub-Saharan Africa (SSA). Currently, FS or its liquid fraction after dewatering is co-treated with sewage in conventional treatment plants. When dewatered, the solids stream is dried and stored further as the terminal treatment or is co-treated directly with organic solid wastes in composting or anaerobic digestion systems. To implement these, FS has to be collected and transported. Also, land is needed, but it is in most cases limited in slums or their vicinity. The collection and transportation of FS from slums is costly due to lack of access, traffic congestion and long travel distances to treatment plants. Worse still, uncollected FS poses health risks and pollutes surface and/or ground water within slums. This review demonstrates that currently utilised technologies and practices fall short in various ways and discusses the possibility of minimising FS management related costs, risks and pollution in urban slums by decentralised treatment and end-use. It also discusses the possible FS-derived end-products and their benefits to urban slum dwellers. Substitution of a part of natural materials (sand and clay) when building and/or biomass (firewood and charcoal) for cooking with FS derived end-products could multiply the benefits of improved sanitation to slum dwellers.

2.1 Introduction

Over 2.7 billion people worldwide rely on on-site sanitation technologies (pit latrines, septic tanks and pour flush latrines) for their sanitation needs. Currently, over 80% of the people in urban areas of Sub-Saharan Africa (SSA) are served by on-site sanitation technologies (Strande *et al.*, 2014). This is likely to continue in the near future because of their low-cost, as people in such settings lack financial strength (Morella *et al.*, 2008). However, the viability of on-site sanitation technologies depends on adequate management of the accumulated faecal sludge (FS). For these, among other reasons, faecal sludge management (FSM) is an emerging field that is currently attracting research interest (Strande, 2014).

In several urban centres of low- and middle-income countries, less than 50% of the daily produced FS is collected (Koné & Strauss, 2004), of which about a half is properly treated (Blackett *et al.*, 2014). The collected FS is either transported to centralised treatment facilities or disposed off into the surrounding environment. The latter is due to long haulage distances, traffic congestion, lack of designated disposal sites and avoidance of fees charged at treatment sites (Strauss *et al.*, 1998; Murungi & van Dijk, 2014). Poor disposal of FS is exacerbated by increased urbanisation under limited infrastructural growth, which is typical of urban slums in low- and middle-income countries. Consequently, large amounts of FS remain uncollected due to high density of housing units which limit access to emptying facilities and the high costs of emptying for the owners of the systems (Murungi & van Dijk, 2014). Most slum dwellers therefore resort to relatively cheap but unhygienic measures of manually emptying and burying FS within the living environment or discharging it in the nearby drains (Kulabako *et al.*, 2010). In some cases, such as Tamale in Ghana, untreated FS is used in agriculture (Cofie *et al.*, 2007). Such indiscriminate disposal practices and end-use of untreated FS have led to excreta related infections through direct contact. Consumption of contaminated crops can also lead to excreta related infections.

The transportation of FS has been reported as the most expensive part of the FSM service chain borne by the owners of the on-site sanitation technologies (Mikhael *et al.*, 2014). For example, in Kampala (Uganda) slums, the medium monthly income is USD 36 per capita (Günther *et al.*, 2011) and the expenditure on emptying and transportation of FS is about USD 50 (5-8 m³ truck) per trip (Murungi & van Dijk, 2014). On several occasions, it takes more than one trip to empty a sanitation

facility, and an average emptying cycle of three months to one year has been reported by Kulabako *et al.* (2010). To address the situation where most of the FS cannot be easily transported from slums to the centralised treatment locations, decentralised treatment and usage of FS products could be an option. In decentralised management systems, FS is emptied, treated and used or disposed off at or near the point of generation. The transportation component is kept at a minimum and the focus is on the necessary treatment and subsequent disposal. Decentralised FSM systems may include use of on-site systems and cluster systems designed to operate at small scale (Massoud *et al.*, 2009). On-site decentralised systems treat FS of individual households, while cluster systems can treat FS from more than one household (Jones *et al.*, 2001).

FS decentralised treatment systems can either be fixed or mobile. For the latter, FS is treated for a particular or group of households and the system is then shifted to another location where such services are needed. This can increase affordability of FS treatment since the initial capital investments in setting up centralised systems are reduced. Furthermore, harnessing the great resources contained in FS, not widely recognised in society at present, would make the same FS properties *e.g.* nutrients that cause environmental problems if not managed correctly to be harvested from the FS. In fact, appreciation of resources from FS in form of utilisable products could create an incentive that would ensure FSM bears its own cost, which is one of the great challenges in FSM. This chapter reviews and analyses technologies and practices suitable for decentralised FSM in urban slums with a focus on SSA. Additionally, possible FS end-uses in urban slums have been reviewed, taking into consideration potential FS-derived products that could replace commonly used products by the slum dwellers.

2.2 Historical background of FS management

Rockefeller (1998) provided a vivid account of the development of FS management in European cities. The use of on-site sanitation technologies evolved with growth in population as communities had to shift from open defecation which was unsightly, caused unpleasant odours and was a key route for disease transmission, to the use of public pits. In several European societies, FS was deposited in cesspools and later collected by scavengers who used to dispose it into streams and rivers, farm land or in open dump sites. To save the cost of emptying, some societies used to dump FS directly in storm sewers, which carried it to rivers upon raining. This situation worsened when

flush toilets were introduced without treatment systems (Tarr & Dupuy, 1988), as cesspools overflowed due to increased wastewater flows. Consequently, this led to connection of cesspools to storm city street sewers. Waterborne disease epidemics, such as the cholera outbreak in European cities in the mid-19th century, led to construction of sanitary sewers for wastewater transportation out of the cities (Tarr & Dupuy, 1988). This practice later polluted the receiving water bodies and motivated introduction of water treatment and consequently wastewater treatment before disposal. While such practices of poor FS disposal are historical and were banned in European cities, today they are commonly found in urban slums of low- and middle-income countries.

FS was used in agriculture as a soil conditioner in India, China, Mexico, Japan and across Asia among others (King, 1972). In Mexico, excreta used to be dried, stored and later crushed and used as fertiliser. Trading in FS fertiliser was common up to mid-19th century, where it was transported from urbanised towns to farming areas due to population increase in cities (Brown, 2003). The use of FS in agriculture led to improved sanitation of the urban centres (Brown, 2003), although this approach was abandoned in the 20th century due to several reasons (Bracken *et al.*, 2007). Firstly, increased urbanisation led to more excreta production (Melosi, 2008), which challenged the logistics of transporting FS based fertilisers from urban to agricultural areas. Secondly, there was a reduction in excreta availability due to use of sewerage sanitation (Rockefeller, 1998). Thirdly, faecal-oral disease epidemics that led to death of people in densely populated cities and the emerged miasma theory which asserted that the diseases were caused by odorous substances, made people abandon trading in fertilisers derived from excreta (Bracken *et al.*, 2007; Melosi, 2008). Fourthly, the mineral fertilisers proved cheaper and simpler to work with as opposed to fertilisers derived from FS (Brown, 2003).

FS recycling in agriculture possess risks due to presence of nematodes (*Ascaris* spp, *Trichuris* spp, *Anylostoma* spp, *Strongyloides* spp) and these, particularly *Ascaris* spp, persist in the environment for a longer time than viruses, bacteria and protozoa. Consequently, nematode eggs became indicators of safety if FS was to be used as a fertiliser. FS treatment was not widely spread although it was done on a small scale.

From history, water pollution and public health were major factors in shifting to sewerage sanitation. However, these problems have not been fully solved since sewerage systems simply move sewage to somewhere else. The discharge of untreated sewage is of great concern around the world due to increased environmental pollution (Baum *et al.*, 2013). The additional challenge is the cost involved in constructing sewerage systems; making it difficult to extend these services to congested slum areas. The capital costs for construction of sewerage system (USD 42.66 capita⁻¹ year⁻¹) was reported to be ten times more than the FSM (USD 4.05 capita⁻¹ year⁻¹) in Dakar, Senegal (Dodane *et al.*, 2012). Many communities in low- and middle-income countries are currently facing similar challenges of disease prevalence and environmental pollution due to poor ways of FS disposal. Development of decentralised ways of FS treatment and safe use of treated FS products could thus contribute towards solving this problem by generating income that would enhance the FSM chain.

2.3 Constituent materials and characteristics of faecal sludge

The constituents of FS depend on among others: diet, lifestyle, habits, health and cultures of sanitation facility users (Still & Foxon, 2012). FS contains excreta (faeces and urine), and may also contain anal cleansing material (toilet and other papers, water, rags, plastics, stones), flushing water (fresh water, grey water), solid and hazardous waste (disposable baby diapers, broken glass, chemicals, sharp metals, pads and condoms) (Still & Foxon, 2012; Niwagaba *et al.*, 2014). In urban slums, lack of proper waste management systems has often led to disposal of greywater, solid and hazardous wastes into on-site sanitation technologies (Katukiza *et al.*, 2012). The presence of such materials alongside FS leads to faster filling rates and renders emptying of pit latrines difficult and hazardous. In places where mechanised emptying exists, residual materials in FS have to be manually removed, which increases emptying charges (Murungi & van Dijk, 2014). This additionally increases health and environmental risks related to disposal of these materials. FS constituents affect the consistency, and this in turn affects its characteristics.

The characteristics of FS depend on various factors *e.g.* origin, ground water infiltration, emptying frequency, user habits, constituent materials, type and location of sanitation facilities (Still & Foxon, 2012; Niwagaba *et al.*, 2014). Consequently, available data on the characteristics of FS are variable (Table 2.1) and generalisations are difficult to make. Attempts to categorise FS basing on origin has resulted into three main FS categories; *septage*, which is often from septic tanks (Strauss *et al.*,

1998); *pit latrine sludge* from pit latrines (Nwaneri, 2009); and *bucket latrine sludge* from bucket latrines. *Public toilet sludge* and *bucket latrine sludge* are in the same category as they are similar in terms of strength (highly concentrated, mostly fresh and stored for days or few weeks). The variation in FS characteristics (Table 2.1) within FS category of a particular origin may be attributed to the above mentioned factors (Section 2.3).

Table 2.1 Characteristics of the three FS categories and sewage (mean and range values)

Parameter	Units	Pit latrine sludge ^{1, 2}	Septage ^{1, 3, 4}	Public toilet sludge or bucket latrine sludge ^{3, 4, 5}	Raw sewage sludge* ^{3, 6}
Total solids, TS	%	3 – 20	<3	≥3.5	<1-9
Total volatile solids	% TS	45 – 60	45-73	70	60-80
COD	mg/L	30,000 – 225,000	10,000	20,000-50,000	500-2,500
COD/BOD		6 – 7	7.14	5	2.5
Total Kjeldhal nitrogen, TKN	mg N/L	3,400 – 5,000	1,000	3,400-3,750	-
NH ₄ -N	mg/L	2,000 – 9,000	120-1,200	2,000-5,000	30-70
Total Phosphorus, TP	mg P/L	450 – 500	150	400	-
Helminth eggs	No. of eggs/g TS	30,000 – 40,000	4,000	20,000-60,000	300-2,000

Notes: ¹ Katukiza *et al.*, 2012; ² Still and Foxon, 2012; ³ Heinss *et al.*, 1998; ⁴Koné and Strauss, 2004; ⁵ NWSC, 2008; ⁶ Tyagi and Lo, 2013

* This can vary greatly depending on the amount of water per capita used in the system.

Generally, sewage sludge has lower concentrations of nitrogen, phosphorus and low numbers of helminth eggs than FS due to dilution effect primarily. To use the FS contents of nitrogen and phosphorus that are beneficial in agriculture, it should be treated. Disposal of untreated FS with high concentrations of organic matter, nutrients and pathogens (Table 2.1) into the environment causes eutrophication and risk of disease transmission.

Pit latrine sludge has a higher concentration of solids and organic contents compared to septage. When unlined, water infiltrates from pits to the surrounding soil, leaving material that has a relatively high concentration of solids in the pit. Comparatively, septage is more stabilised as a result of long detention periods and is also diluted with greywater (Cofie *et al.*, 2006). Organic content decreases with age of the pit contents due to anaerobic and/or aerobic stabilisation processes within the pit (Still & Foxon, 2012). Additionally, pathogen numbers decrease with FS age. In tropical countries, bacteria, viruses and protozoa survive on average for one month in FS while helminth

eggs can survive up to one year (WHO, 2006). However, long storage time of FS is not possible in urban slums due to high user loads of latrines.

2.4 Current practices of faecal sludge management in urban slums

2.4.1 Emptying and transportation of faecal sludge

The selection of an appropriate pit emptying technology depends on pit latrine characteristics such as depth and accessibility, FS sludge characteristics, disposal site and geography of the site (Thye *et al.*, 2011; Mikhael *et al.*, 2014). Often, pit latrines in urban slums are designed and constructed without considering future emptying (Still *et al.*, 2013). Furthermore, pit latrines are commonly dug and constructed by the informal sector workers who may lack technical competency to ensure future emptying possibilities at the construction stage. Pit emptying in urban slums is thus often inadequate due to poor accessibility. There have been several efforts to tackle this problem. The use of portable emptying equipment such as the *Gulper*, Manual Pit Emptying Technology (MAPET) and *Vacutug* are some measures that have been taken to solve this challenge (Thye *et al.*, 2011). However, these techniques have smaller capacities and low speed compared to vacuum trucks, which makes transportation expensive since the disposal sites are usually located far away from slums (Montangero *et al.*, 2002). In Kampala (Uganda) for example, National Water and Sewerage Corporation (NWSC) has proposed collection of FS from the slums by *Vacutugs* or MAPETs and transfer it to a tanker (mobile transfer station) to be towed by a trailer to the treatment plant (NWSC, 2008). A similar model has been successful in urban slums of Maputo in Mozambique.

Manual emptying of pits and vaults is a common practice in urban slums where accessibility by vacuum trucks is not possible. Manual emptying is a basic approach where a person(s) uses simple hand tools like spades and buckets/cans to empty the pit. In some cases, a person(s) emptying uses a ladder to go into the pit (Still & Foxon, 2012). This is usually practiced without personal protective equipment (PPE) like face masks, rubber boots, hand gloves and overalls; making manual emptiers susceptible to faecal related diseases (Murungi & van Dijk, 2014). Failure to use PPE leaves emptiers in direct contact with pathogens, making this practice unhygienic and a health hazard. An examination of face masks of PPE equipped manual emptiers in South Africa, showed presence of different helminth egg species (van Vuuren, 2008). Nevertheless, manual emptiers continue with the practice because of poverty and unemployment. Since these emptiers usually earn money

through emptying and not haulage, they tend to avoid haulage by disposing FS as near as possible to the emptied facility (Klingel *et al.*, 2002). Having treatment sites close to emptied facilities could minimise such indiscriminate practices of FS disposal. In addition, the interaction between emptying, transportation and treatment using decentralised technologies should be considered in order to verify whether emptying frequency, transportation length or treatment feasibility is most important.

2.4.2 Treatment of faecal sludge

FS, or its liquid stream, may be co-treated on a large scale in a sewage treatment plant, in waste stabilisation ponds or treated using constructed wetlands (Ronteltap *et al.*, 2014). The solids fraction may be dried further and stored as the terminal treatment process or co-composted and/or anaerobically digested with organic solid wastes. Centralised co-treatment is practiced in many SSA countries like Uganda, Kenya, Tanzania, Ghana, Senegal and South Africa. Failure of existing sewage treatment plants has, besides operational challenges, been linked to high total solids and nutrient loads from FS (Heinss *et al.*, 1998; Still & Foxon, 2012). Co-treatment is feasible if the treatment plant is available and has been designed to handle a mixture of FS and sewage, but this is not the case in many cities of low- and middle-income countries (Klingel *et al.*, 2002). Moreover, if the resulting sludge is to be used in agriculture, the limiting factor of spreading on arable land would be chemical contamination of sewage.

Co-treatment in waste stabilisation ponds often consists of anaerobic sedimentation followed by either an infiltration pit or a facultative pond which reduces the BOD concentration, and then an aeration/maturation pond which removes pathogens from the effluent (Mara & Pearson, 1986). It is not advisable to only treat the FS stream in stabilisation ponds. This is because FS from urban slums is relatively fresh and thus, has a high ammonia concentration, which is toxic and could inhibit bacteria and algal growth and thereby affecting pond performance (Strauss *et al.*, 1998). Co-treatment of FS in both sewage treatment plants and stabilisation ponds requires large space to be setup. Such space is not available within urban slums and their vicinity. Location of these plants at long distances would increase costs and certainly increase the risk for indiscriminate dumping. In addition, provision of a sewerage system is costly. Decentralised systems where FS is treated within the slums could reduce the cost of FSM.

Co-composting involves aerobic degradation of FS together with the organic fraction of municipal or domestic solid wastes (Cofie *et al.*, 2009) and allows humic substances and nutrients to be recovered safely and used as organic fertiliser. Organic wastes are mixed with FS during co-composting in order to increase C/N ratio from about 6:1 for FS to between 25:1 and 30:1 which is required by composting microorganisms (IWMI & SANDEC, 2002). As solid waste management is another challenge in urban slums, its co-composting with FS is a good option of treating and using the two waste streams. In addition, an optimal moisture content of 50-60% for composting (Klingel *et al.*, 2002) would be conveniently attained at low levels of dewatering FS since it has a relatively high moisture content. However, in an urban setting, the challenge would be the time of six weeks to three months required to get mature and stable compost (Cofie *et al.*, 2009) which translates into large space requirements. Additionally, low or no engagement of slum dwellers in agriculture may limit this application.

The other option for FS treatment/dewatering is the use of constructed wetlands. However, no country in SSA has successfully treated FS using full-scale constructed wetlands. Only experiences from pilot studies have indicated removal efficiencies of over 90% for TS, TVS, TKN, COD and helminth eggs and nutrients such as P and N from the percolate liquid (FS leachate) at loading rates of 200 kg TS/year, although the sewage discharge standards were not met (Kengne *et al.*, 2009b). The nutrient content in bio-solids was comparable to that of poultry manure, hence suitable for agricultural use (Kootatép *et al.*, 2002). The challenge for agricultural use is helminth eggs, which require sludge storage period beyond six months (Kengne *et al.*, 2009a). This additional treatment implies large space requirements.

Energy recovery from FS to meet the energy needs of the high population residing in slums seems to be an attractive venture (Chidumayo *et al.*, 2002). FS treatment technologies for this purpose depend on its heating value, organic content and degree of dewaterability (Elsaesser *et al.*, 2009). Sludge contains free, interstitial, surface and bound water (Chen *et al.*, 2002). Free water can be removed by thickening and then decanting; interstitial water by dewatering and bound water by drying (Elsaesser *et al.*, 2009; Ronteltap *et al.*, 2014). The degree of FS stability influences its dewatering. Fresh FS is more difficult to dewater than digested FS from septic tanks due to the

presence of biodegradable organic constituents. Hence, the dewaterability of FS can be improved by either including a stabilisation stage in FS treatment or blending fresh FS with a stabilised one (Ronteltap *et al.*, 2014). The drying process considerably reduces the moisture content. This leads to reduced FS mass and volume for transportation and storage and thereby reducing the cost; improved energy recovery characteristics; and reduced smell as well as increased pathogen die-off (Niwagaba *et al.*, 2006). This makes FS easier to handle, as utilisation may be done without extra protection. An understanding of the amount of energy required to dry a unit amount of FS from sanitation systems may help in designing drying technologies.

In low- and middle-income countries where FS is treated, dewatering and drying commonly take place on sand beds. Research on improving FS drying was done in Dakar by drying it in greenhouses, where land required for drying was reduced by 20% after turning it on sand beds, hence the high cost of land can be saved by a similar figure (Seck *et al.*, 2015). The thermal drying process is energy intensive and its operation is usually aided by use of solar energy to reduce costs (Chen *et al.*, 2002). For drying high volumes of FS, large space is needed, which cannot be found within urban slums and their vicinity. Low-cost solar collectors which can concentrate solar energy could help to reduce drying time and limit space requirement. Parabolic solar concentrators are reported to raise temperatures to over 100°C (Ouederni *et al.*, 2009).

Furthermore, drying of FS on sand beds increases the inorganic fraction, mainly due to sand, which sticks on the surface of FS cakes directly in contact with it, leading to a high ash content when incinerated or during energy recovery (Kalongo & Monteith, 2008). Application of inorganic coagulants to improve sludge settleability increases the ash content further (Kalongo & Monteith, 2008). Increased ash reduces the energy output per unit weight/volume of FS and increases the disposal costs of generated ash. More so, information on concentration of elements and compounds in FS ash is lacking.

2.4.3 Disposal and end-use of faecal sludge in SSA

In most countries in SSA, FS collected from on-site sanitation technologies is discharged untreated onto surrounding land, watercourses or used untreated in agriculture or aquaculture (Klingel *et al.*, 2002), contributing to health hazards and water pollution. For example, Murray *et al.* (2011b)

reported that only a small fraction (10%) of the collected FS in all major cities of Ghana as being treated. The rest is directly discharged in the ocean. In urban slums of Kampala (Uganda), it has been reported that pit latrines are constructed close to drainage channels wherever possible, to ease manual emptiers' work of FS disposal directly into the channels, once the pit is full (Kulabako *et al.*, 2010). FS is then carried away by flowing water and ends up in surface water bodies, when it rains. In other cases, manual emptiers dispose FS in a pit dug next to a pit latrine (Murungi & van Dijk, 2014; Strande *et al.*, 2014). This does not only lead to groundwater pollution, but also the health and safety of residents in such areas is compromised.

Agriculture being a major land use in SSA has been considered able to absorb all the FS generated in urban slums. The challenge remains its collection, transportation and treatment prior to application on agricultural land. Untreated FS used in agriculture and aquaculture on a small scale has been reported in Tamale, Kumasi and Bolgatanga in Ghana and Mali (Cofie *et al.*, 2007). Such practices exposed farmers to a number of health risks. Some farmers working with raw FS in these areas have reported foul smell, difficulty in transportation, public mockery, foot rot and itching, among others (Cofie *et al.*, 2007). Direct application of FS by some farmers indicates untapped potential of FS as a soil conditioner, but requires extensive management to minimise risks posed when untreated. If these farmers are sensitised on how to sanitise FS on a small scale by themselves, not only will sanitation be improved, but also economic gains from improved crop production will boost their livelihoods.

FS disposal in deep row entrenchment has been demonstrated as a method for using FS in agriculture while minimising the risk for disease transmission. Here, a trench is dug, filled with FS and backfilled with overburden soil. Vegetation is then planted in rows next to the trenches (Still & Foxon, 2012). Trials at Umlazi, South Africa using pit latrine FS have shown enhanced growth of eucalyptus trees; biomass density of those grown on FS being twice as much as those not grown on FS (Still *et al.*, 2012). No pathogen was reported to survive longer than 30 months after burial of FS and no adverse impact on ground water contamination was experienced (Still & Foxon, 2012). However, in an urban slum setting, the challenge would be space limitation for such trenches in order to plant trees and the long-time of 30 months required for FS sanitisation would necessitate large space requirement, which is not available in slums.

2.5 Resource recovery from faecal sludge

Utilisation of treated FS and its products is not currently well developed and profitable (Blackett *et al.*, 2014). Where FS and its products are available, they are landfilled, indiscriminately dumped into the environment, sold at a very low price or given out for free (Diener *et al.*, 2014). This could be because the current available products from FS are of little or no beneficial use. Nutrient recovery from FS to be used as a soil conditioner (one of the FS product) is of less importance to slum dwellers since most of them do not practice agriculture. Production and promotion of products from FS to replace products of high demand can increase the value of FS and its acceptability. Some of the valuable products were identified by Diener *et al.* (2014) and their market potential was determined at an industrial, and not household or slum community level. Identification of small-scale FS uses in a particular slum setting is imperative. Such small usages (Sections 5.1-5.4) when combined can cumulatively create an environment where FS is no longer a management problem, but a raw material for valuable products.

2.5.1 Faecal sludge as a soil conditioner

FS is rich in plant nutrients (nitrogen and phosphorus) and low in heavy metal concentration (Niwagaba *et al.*, 2014), making it suitable for land application. However, FS from areas where products containing heavy metals and washings from hair salons are disposed off in pit latrines could be contaminated (UYDEL, 2006). Unlike nitrogen which is obtained from the atmosphere, phosphorus is largely mined and only available in a few countries; making use of mineral fertilisers very expensive and unsustainable since it is a finite source. Phosphorus is readily available in FS and could be recycled, but is wasted through indiscriminate disposal. To date, tonnes of FS are produced in urban slums due to high population while agriculture, which to a great extent does not replenish the nutrients removed in the soil is widely practiced in rural and peri-urban areas, far from the slums. FS is expensive to transport when used at a far location from the production point thus making its usage as a soil conditioner unsuitable in the context of urban slums. Nikiema *et al.* (2013) transformed FS to fertiliser pellets and produced soil conditioners in form of mineral fertilisers. However, the performance and cost-effectiveness of large scale production of the fertiliser pellets is not yet reported. Involvement of slum dwellers in production and sale of FS derived fertilisers to potential users could be another practical venture. The use of FS derived fertilisers has a positive impact on the environment since it reduces on the energy and costs required to extract, manufacture

and transport mineral fertilisers (Wood & Cowie, 2004; Heinonen-Tanski & van Wijk-Sijbesma, 2005), while at the same time minimising water pollution (Nyenje *et al.*, 2010).

2.5.2 Vermicompost and animal protein from faecal sludge

2.5.2.1. Vermicomposting

Worms feed on FS to grow and multiply, hence increasing their biomass; and the resulting residue (vermicompost) is rich in nitrogen and phosphorus (Otterpohl & Buzie, 2013). The worm biomass can be used as a protein source in poultry and fish feeds while the vermicompost as a soil conditioner (Ndegwa *et al.*, 2000; Lalander *et al.*, 2015). Previous studies have reported reduction in worm biomass due to ammonia toxicity (Yadav *et al.*, 2010). Fresh FS from bucket and public latrines has high ammonia concentrations. This could be reduced through pre-composting. Additionally, the required moisture content (65 to 85%) for worm survival (Loehr *et al.*, 1985) would necessitate FS dewatering by use of bulking agents e.g. coffee husks and saw dust. However, the cost of about 1.2 USD/m³ for the bulking agents in low- and middle-income countries (Diener *et al.*, 2014) can increase FSM costs. Furthermore, the vermicompost stabilisation and sanitisation time of over 3 months (Ndegwa *et al.*, 2000; Yadav *et al.*, 2012) would require space for this technology to be successful in urban slums. There is a need to evaluate whether biomass and vermicompost options would be appropriate in an urban slum setting; availability of market, and other factors such as climate are conducive for worm growth. Investigations into the overall costs required and the revenues generated from sale of worm biomass and vermicompost are required to ascertain whether this technology would make FSM bear its own cost.

2.5.2.2. Black soldier fly

Use of black soldier fly, *Hermetia illucens* L. to feed on FS is another innovative way of reducing FS and generating animal feed protein, as black soldier fly larvae, BSFL (prepupae), and a soil conditioner, as compost residue (Diener *et al.*, 2011; Banks, 2014; Lalander *et al.*, 2014). Additionally, BSFL contributes to sanitisation of FS by reducing *Salmonella* spp numbers, although additional treatment would be required to reduce *Ascaris* eggs to acceptable levels for use of residual compost as a soil conditioner (Lalander *et al.*, 2013). BSFL has a high protein (32-64% dry matter) content, comparable to protein quality in fish meal commonly used for poultry feeds (Oonincx *et al.*, 2015). As a good number of households within urban slums are involved in poultry farming (Correa and Grace, 2014), usage of BSFL for feeds would promote sanitation and consequently

increase farmers' savings. Revenues from sales of this potential animal feed and compost residue, plus costs saved due to reduction of FS quantities could trigger FSM to bear its own cost. However, FS characteristics are highly variable within and between slum communities, this technology should be investigated and its performance evaluated in different slum communities. Additionally, the financial viability and acceptability of BSFL in urban slums needs to be ascertained.

2.5.3 Faecal sludge as a construction material

Increasing urbanisation in low- and middle-income countries has put pressure on non-renewable raw materials for construction. The inorganic content in sewage sludge is beneficial in the production of construction materials (Kalongo & Monteith, 2008). Sewage sludge contains silicate which is characteristic of pozzolanic materials (Hossain *et al.*, 2011). Incineration as one way of sewage sludge disposal, produces incinerator ash, which together with dried sludge are useful primary ingredients in the manufacture of construction materials (Tyagi & Lo, 2013). Some of the construction materials include; artificial light weight aggregates, tiles, cement material and bricks (Tay & Show, 1997). For sewage sludge, a 50% and 20% mixture by weight with limestone and ordinary portland cement respectively yielded a compound with good strength without significant changes in chemical properties (Payá *et al.*, 2002). No literature was found on the use of FS as a construction material.

Construction bricks in low- and middle-income countries are commonly made from soil and clay, and their costs comprise mainly of labour and transportation. A mixture of FS and soil or clay would limit the excessive usage of these non-renewable resources. Up to 20% by weight of the bricks made from sewage sludge exhibited strength which complied with Chinese National Standards (Weng *et al.*, 2003). Bricks from sludge have a low weight due to cavities created after burning the organic matter (Alleman *et al.*, 1990), which is an advantage in reducing the bearing loads from structures. Since FS contains organics, the appropriate mix ratio with clay or soil without compromising strength could be investigated.

2.5.4 Faecal sludge as an energy source

2.5.4.1. Biogas from faecal sludge

The energy potential of FS can be enhanced through biogas production. Biogas can be produced when FS is decomposed anaerobically in an airtight reactor. The gas can be used to complement

energy needs like cooking, lighting and can be converted to electricity (Tumwesige *et al.*, 2014). Bio-methane potential is very low from some FS streams like septage since sludge is already stabilised (Still & Foxon, 2012), but is high from public toilets and bucket latrines because of their freshness due to short retention periods. Since latrines in urban slums have been reported to have high user loads, it is possible to have enough biogas supply for cooking requirements. There needs to be demand for biogas produced in order to present an incentive for a household. A more realistic sales alternative could be commercial food vendors, who have much higher energy demands. Alternatively, conversion to electricity would increase the capital and operation costs, but might produce a more marketable product and thus support a more lucrative business (Murray *et al.*, 2011a). Effectiveness in biogas generation at a household level may need a change in the design of latrine facilities to biogas latrines. However, the expected challenge with biogas latrines may be their operation and maintenance. Furthermore, if a biogas reactor is not air tight and well maintained, it becomes a greenhouse gas source creating rather than solving environmental problems. Greywater containing soap is usually used and if discharged in biogas latrines, affects their functioning due to inactivation of the useful organisms (Alhajjar *et al.*, 1989).

2.5.4.2. *Energy briquettes from faecal sludge*

Energy recovery from FS has of recent been investigated by Murray Muspratt *et al.* (2014) and a calorific value of 17.3 MJ/kg dry solids of FS was obtained, which is comparable with that of other biomass fuels. There is therefore a substantial amount of energy in the carbonaceous component of FS, which can be utilised. This could be of benefit to a large number of people, if availed in form of commonly used fuels like briquettes. Urban slum dwellers have used municipal solid waste (MSW) and charcoal dust as raw materials to produce fuel briquettes, where the former is carbonised using low-cost kilns (Kung *et al.*, 2013). Households involved in the production and purchase of fuel briquettes for own usage save 70% and 30% of their energy needs, respectively (Njenga *et al.*, 2013). Since MSW is used in making carbonised and non-carbonised briquettes and FS has about the same energy content, dried FS is needed as a raw material in the production of fuel briquettes for home use, such as in cooking. Low-cost technologies for briquette production that could easily be adapted by urban slum dwellers need to be investigated. However, combustion of biomass fuels in poorly functioning cooking stoves causes indoor air pollution (Bailis *et al.*, 2005). Therefore, the

production of FS-derived briquettes should be done alongside improved combustion efficiency of cooking stoves.

2.5.5 Summary of pros and cons of FS products

A summary of the benefits and challenges in development and utilisation of the discussed FS products by the urban slum dwellers in low- and middle-income countries of SSA is provided in Table 2.2.

Table 2.2 Summary of pros and cons of potential FS products in an urban slum context.

Potential FS product	Pros	Cons
Soil conditioner	<ul style="list-style-type: none"> • Common application of FS in low- and middle-income countries. Hence, many people's perception are good towards its usage. • Promotes recycling of phosphorus, hence, preventing exploitation of this finite resource. • Limits excess nitrogen and phosphorus loss to water bodies, hence minimising eutrophication. • Low in heavy metal concentration. • FS is readily available due to high population in urban slums. • Revenue generation through sale of soil conditioners. • FS usage, contributes to improved sanitation. 	<ul style="list-style-type: none"> • Limited involvement in agriculture by slum dwellers. • Need to convert FS to a form that can easily be transported to places of use. • Needs proper treatment to prevent excreta related infections during handling. • People's willingness to pay less than production costs. • It is bulky, thus high transportation costs if usage is in a distant location.
Vermicompost	<ul style="list-style-type: none"> • Worms provide the aeration and no need of equipment for turning FS during composting process. • Revenue generated from vermicompost sales as soil conditioner and worm biomass as animal feeds can make FS treatment bear its own cost. • Employment opportunities to slum dwellers. • Part of FS is consumed by worms, thus reducing the amount to be managed. • Resulting worm biomass can be used for animal feed protein (chicken and aquaculture feeds). • Improved public health and decreased environmental pollution. • Vermicompost is odour free and does not attract flies. • Reduced pollutants in vermicompost 	<ul style="list-style-type: none"> • Need to establish market for compost and worm biomass near the point of production to minimise on transportation charges. • Need to pre-compost FS to reduce intoxicating the worms with ammonia. • Vermiculture may be very difficult to maintain in places of very low or very high temperatures. • Required substrate (FS) moisture content may require additional step of FS dewatering. • Capital costs and availability of land for decentralised plant in close proximity to urban slums. • Additional treatment needed for complete sanitisation.
Animal protein	<ul style="list-style-type: none"> • More options for protein sources in animal feeds. • Black soldier flies do not transmit diseases. • Improved sanitation using low-cost technology. • FS compost residue can be used as a soil conditioner. • Does not require a big space for plant setup. Hence, multiple decentralised plants can be setup within the slums. 	<ul style="list-style-type: none"> • Need to change people's attitude so that they can use such an alternative for animal feeds. • Bioaccumulation of pollutants like heavy metals in black soldier fly larvae and subsequent biomagnification in higher trophic levels like chicken and eventually humans.

Potential FS product	Pros	Cons
	<ul style="list-style-type: none"> • Reduced quantities of FS to be managed. • Revenue generation from sales of animal protein and compost residue can make FSM bear its own cost. • More job opportunities to slum dwellers <i>e.g.</i> production and selling of animal feeds. Hence, improved livelihoods of slum dwellers who are low income earners. • Limit importation of animal feeds and thus, prevents surplus nitrogen and phosphorus in form of manure and urine. 	<ul style="list-style-type: none"> • Minimal dewatering of FS from some sources is required.
Construction material	<ul style="list-style-type: none"> • Substitution of non-renewable soil and clay, commonly used in brick making. • Low weight after burning bricks, contributing to reduced structural loads, hence, reduced sizes of structural elements. • Lessening in construction costs. • Improved bond adherence of mortar due to cavities created after burning bricks. • Burning bricks completely eliminates the pathogens in FS. • Creation of jobs for the local population. 	<ul style="list-style-type: none"> • Variations in FS characteristics may produce bricks of inconsistent qualities. • Abundance of unoccupied areas of land outside slum settings creates a sense of raw material availability. • FS is dewatered and dried before mixed with clay or soil, which necessitates additional costs in FS preparation.
Biogas	<ul style="list-style-type: none"> • Used for lighting and cooking by slum dwellers. • Decreased deforestation in search of fuel for cooking. • Effluent slurry can be used as a soil conditioner. • Limited or no direct contact of FS with the public, hence improved health. • Nutrients concentrated in rapidly released form. Therefore, direct utilization of slurry from digesters results in increased crop yield. • No need of additional dewatering step to digest FS, since this occurs at high moisture content (>90%), which is the average moisture content for FS. • Easy acceptability by slum dwellers, since anaerobic technology has been in existence. 	<ul style="list-style-type: none"> • Low methane yield potential in stabilised FS like septage. • Upscaling in urban slums may need changing ordinary latrine designs. • Maintenance and operation for untrained slum dwellers. • A potential source of greenhouse gases if not air tight and is improperly managed. • Additional treatment of effluent slurry for sanitisation, or else can contribute to environmental pollution. • Slurry needs to be dewatered, transformed into a form that is easy to transport to places of need, outside urban slums.
Energy briquettes	<ul style="list-style-type: none"> • FS has a calorific value comparable to other biofuels in use by slum dwellers. • Some slum dwellers are involved in energy briquette production through carbonisation of solid wastes and use of charcoal dust. • Easy adaptation of briquette production technology. • Job creation through production and sale of briquettes. • Revenue generation from sale of briquettes. • Reduction in deforestation rates due to it being an alternative to use of charcoal and firewood. 	<ul style="list-style-type: none"> • Public acceptability in cooking with FS energy briquettes. • Need of additional step(s) in dewatering and drying FS. • Transformation of FS in required form for use on cook stoves may be costly. • Handling of raw sludge poses a health risk for workers.

2.6 Acceptability of faecal sludge products and selection of technologies

Since urbanisation resulted in the collapse of FS trade as manure (Section 2.2), minimisation of haulage distances through decentralised FS treatment, and identification of products of potential use by the slum dwellers in SSA could in future boost FS end-use potential. Conversion of FS to energy is a promising route for reducing biomass fuel (mainly wood and charcoal) dependency by low- and middle-income countries. Processes for conversion of FS to energy include; aerobic fermentation to produce bio-diesel and methanol (Ting & Lee, 2006); pyrolysis, gasification and hydrothermal carbonisation to produce gaseous and liquid fuels with bio-char (Monte *et al.*, 2009); and anaerobic (co-) digestion to produce biogas and slurry. Research into potential of these processes and their applicability to FS as raw material is limited to conditions of urban slums.

For such energy conversion processes to be sustainable, FS products and technologies needed in their development should be affordable, environmentally friendly and socially acceptable. An assessment of costs of the technologies to be installed should be undertaken by considering capital costs, and cost of operation and maintenance. For decentralised systems, operation and maintenance has been reported to be challenging (Massoud *et al.*, 2009). For on-site decentralised technologies such as biogas latrines, operation and maintenance is left to facility owners, who typically pay less or no attention to it until it begins to fail. Therefore, depending on the size of the decentralised system, slum communities may need to employ a fulltime staff to handle emergencies and ensure that the system is properly operated and maintained. For environmental sustainability, the decentralised systems should protect the quality of the environment in places where they are used. The system outputs should be well treated so that the receiving environment is not compromised. Hence understanding the receiving environment is pertinent to design and selection of decentralised treatment technologies.

A common impediment to sanitation and other related technologies is the social and cultural acceptability of products from FS. Cairncross (2003) recommended the marketing of newly developed sanitation technologies to increase social acceptability. Intensive information, awareness-raising and social/commercial marketing campaigns are needed for a paradigm shift in order to develop confidence and skills by the people to maintain FSM technologies and produce FS products (Lüthi *et al.*, 2011). This could be enhanced by early community involvement through assessing the

possible products needed from FS and willingness to produce and use these products (Reymond & Bassan, 2014).

FS management in slums should start at the generation unit (household). Once FS value is appreciated and realised at this most basic level of a community or a nation, FSM can easily take place within the generating communities. It is imperative that locally-made, innovative technologies are found since these can be owned and operated locally within the slum community. These could evolve from existing local technologies, which could be adopted and enhanced for improved FSM. Such management technologies will be sustainable if they are environmentally friendly, economically feasible and socially acceptable (Figure 2.1).

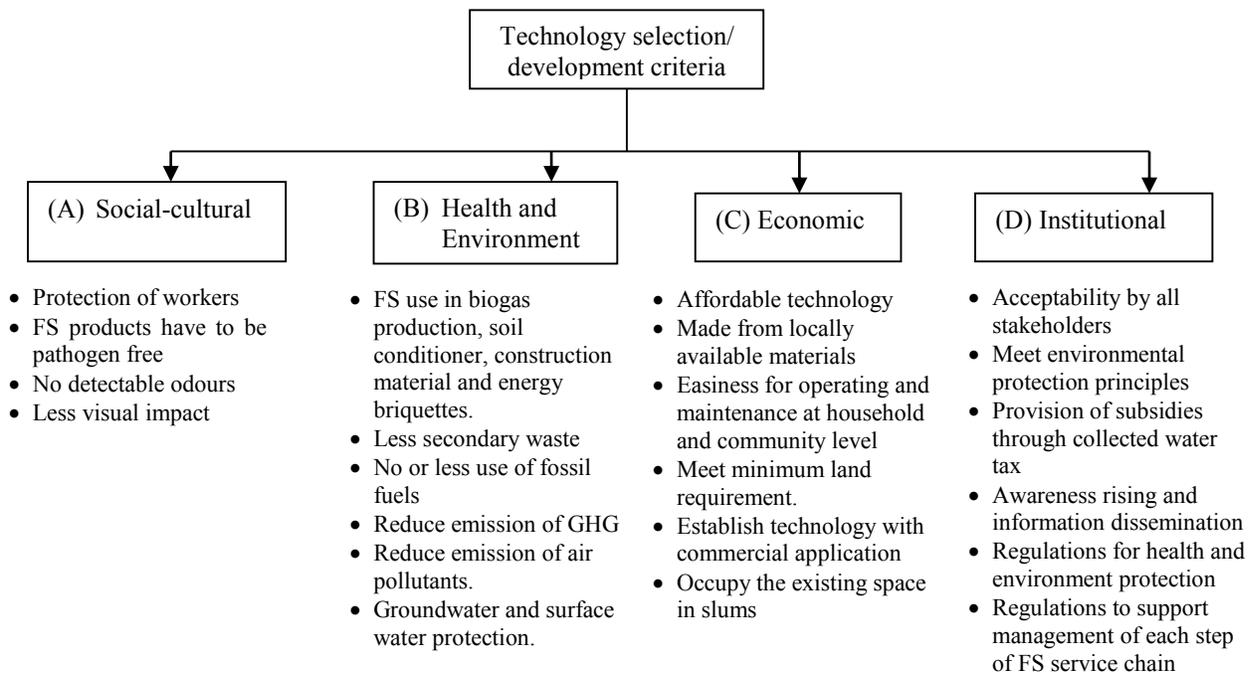


Figure 2.1 Social-cultural, economic, institutional, health and environmental criteria related to technology development for FS management. Adopted with modifications from (Kalongo and Monteith, 2008; Tyagi and Lo 2013, Strande *et al.*, 2014)

The decentralised management of FS will be sustainable if the service chain of emptying, on-site treatment and resource recovery or disposal are identified and the participating stakeholders are coordinated (Bassan, 2014). The stakeholders may be particular government institutions, the private sector, non-governmental organisations (NGOs), households or community. Their roles in FSM should be defined with respect to local context or site (Reymond & Bassan, 2014).

2.7 Knowledge gaps

Several knowledge gaps can be identified along the FSM chain in an urban slum setting, especially the development of technologies for FS conversion to more useful products. The challenge is that most of the FS end-uses in urban slums are still unproven technologies and thus the associated costs cannot easily be determined. Pilot scales are required to verify the concepts, followed by establishment of operational business models relevant to the local context. The ultimate target should be that part of revenue generated from FS product sales can help finance less-profitable sections of FSM chain, thereby causing FSM to bear its own costs.

Next, dewatering, drying, resource and energy recovery are attracting the interest of many researchers. Dewatered and dried FS is a prerequisite for FS conversion to many useful products (Table 2.2). Dewatering and drying FS by use of sand beds attracts a low applicability potential in urban slums since it requires large space and takes a long time. Sand drying beds increase the sand content of dried FS which lowers the output energy per unit weight of dried FS, if used as a fuel. There is need to investigate low-cost compact technologies of drying FS which do not use sand beds and where FS drying using solar energy is enhanced by using solar concentrators.

Dewatering and drying of FS yields leachate because FS contains over 80% water (Table 2.1). Therefore, the process of obtaining dried FS solids for resource recovery or disposal yields FS leachate (liquid stream), which is hazardous and heavily polluted with large amounts of organic matter, nutrients and pathogens. Owing to various ways of FS solid-liquid separation, studies on characterisation and distribution of contaminants in the two streams for FS from different sources is lacking. Their characteristics influence the selection of treatment technologies and proper ways of disposal. FS solid-liquid streams can be a potential source for ground and surface water contamination, if they are not properly collected, treated and safely disposed off. The organic and nutrient content of FS leachate are comparable to leachates from municipal solid waste landfill sites (Tatsi *et al.*, 2003). Wiszniowski *et al.* (2006) discussed various means of treating landfill leachate. Research into application of these different treatment technologies to FS leachate can be useful. Additionally, high levels of pathogen concentration in FS leachate would necessitate research into different feasible ways of its disinfection.

FS dewatering and drying is complex due to the different forms of water (free, interstitial and bound) present. Modelling drying process of FS could provide information on the behaviour and nature of different water types and their movement through the FS structure. An understanding of such mechanisms, and the knowledge of moisture distributions within FS is helpful in process design, FS handling and energy saving.

Research into simpler technologies of converting FS into physical forms of mineral fertiliser with or without nutrient enhancement should be investigated. If carried out, this can promote easy transportation of this fertiliser to areas of need and it would also enhance ease of application. Additionally, research into low-cost technologies of extracting non-renewable phosphorus is also still lacking.

Many end-products like energy briquettes, biogas, bio-diesel, methanol, gaseous and liquid fuels, fertiliser pellets and construction materials can be derived from FS and these can substitute other products in common use. The market potential of particular products from FS in site specific areas need to be determined before the products are fully developed. Furthermore, an understanding of the feasibility of manufacturing these products from FS at a decentralised scale should be investigated. Following production of biogas from FS, slurry results. However, the digester operation conditions are inadequate in production of sanitised slurry. Investigations into different ways of slurry sanitisation and its potential usage/disposal under conditions of urban slum setting are pertinent. Similarly, in the production and use of fuel briquettes, besides calorific value, the extent of indoor air quality should be investigated. Furthermore, optimal selection or design of the cook stove to be used with FS fuel briquettes and suggestions for improvement in efficiency are necessary.

2.8 Conclusions

The increasing rate of urbanisation amidst persistent poverty in SSA suggests that urban slums are a reality and are unlikely to disappear soon. Urban slums generate enormous quantities of FS. Slums are unique and current approaches to FSM are failing to cope.

Radical changes in operational strategies and subsequent decentralised management of the generated FS should be developed. The current practices of abandoning full pits or emptying in environment are generally poor, emptying technologies for pits in slums are available and more under development/modification, treatment technologies are limited to centralized ones and utilisation of treated FS and its products is not currently developed in slums.

Simple on-site beneficial low-cost technologies to produce high value FS derived products will propel slum residents to manage their own FS, create business and employment. FS wastes which potentially cause environmental pollution and spread of various diseases should instead be used as raw materials of useful products. In return the environment is protected and people's lives and resources that would be spent treating excreta related diseases are saved.

The success of technologies/options and end-uses for FSM discussed in this paper will depend on the local context. To achieve a paradigm shift and make FS and its products acceptable by the potential customers in urban areas and to induce the demand for such products, there is need for intensive information, awareness raising and social/commercial marketing campaigns. Slum dwellers need to be provided with access to finances, education and information required to influence their environmental space, which is an important step towards sustainable FS management. Change of people's behaviour and understanding of barriers that prevent them from using FS and its products have to be addressed. This would motivate the slum dwellers to participate in production and trading of FS products, and consequently lead to generation of revenue that could propel FSM generate its own cost.

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CHAPTER THREE

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

This chapter is based on:

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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 chapter therefore explores the applicability of dewatering as the first and critical step in decentralised 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 percent 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 (1,122 and 1,485 seconds 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 ≤ 1 mm. The results from this study suggested that FS from pit latrines in Kampala can be conveniently dewatered without thickening, thereby reducing costs of FS management.

3.1 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 centralised plants for appropriate treatment (Koné & Strauss, 2004; Blackett *et al.*, 2014). The rest is either unemptied or disposed of indiscriminately onto surrounding land, water courses or unsafely used in agriculture/aquaculture (Klingel *et al.*, 2002; Murungi & 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 & 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 and space availability in slums may necessitate modified/specialised 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 decentralised treatment (Chapter 2). The first stage in developing decentralised 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 off or utilised in the slum areas to minimise 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 off or converted into useful products within slum areas, which reduces management costs (Novak & 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 due to their low cost. 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 m² of land is required for a sand bed that performs three dewatering cycles per month with an average load of 15 m³ of FS per cycle and a depth of 30 cm (Dodane & 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, quantity and characteristics of FS, space availability and capital costs among other factors (Metcalf and Eddy, 2003). For decentralised dewatering of FS in urban slums, it is pertinent to understand the dewaterability characteristics of FS from sanitation facilities such as pit latrines commonly used in such areas. Characteristics of FS may vary with location, type, design and construction of pit latrines (Still & 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 & 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 chapter 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.

3.2 Materials and methods

3.2.1 Study area and faecal sludge sampling

The FS samples used in this study were collected during the period of September 2015 to December 2015 from three different slum clusters found within Kampala city (Uganda), namely Bwaise II, Kibuye and Kamwokya (Figure 1.3). 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-motorised 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 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-mechanised technologies like the *gulper*, where the operators fluidise 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) (Figure 3.1), was used to obtain FS samples. When the container of the sampler was inserted at the required depth (surface, middle or bottom of the pit), 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. FS samples were collected and analysed during the period of September 2015 to December 2015.

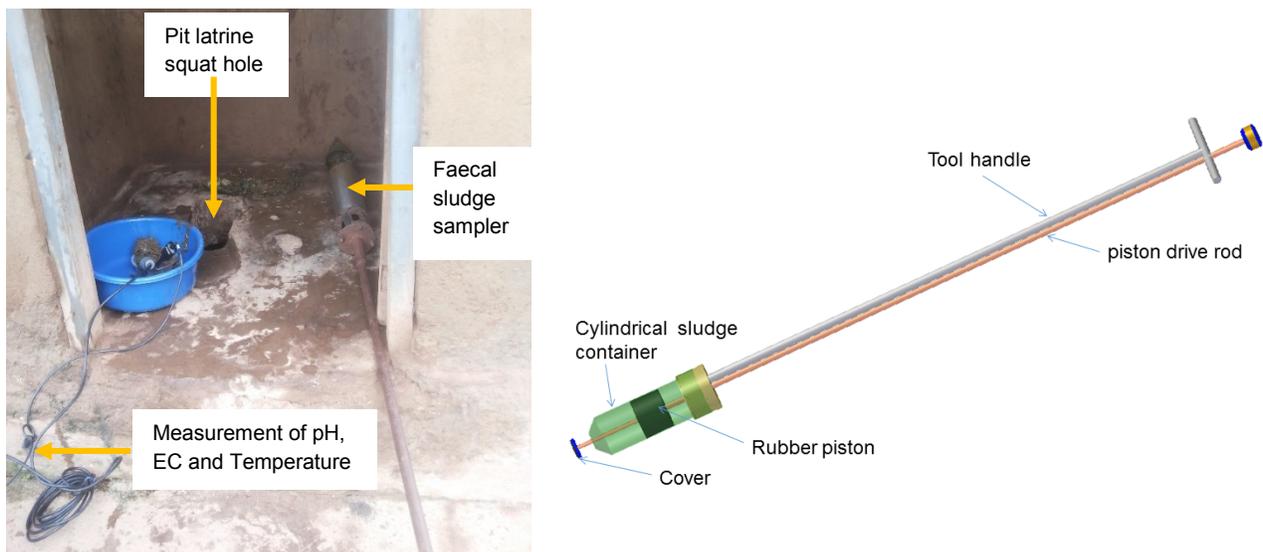


Figure 3.1 A fabricated multi-stage sampler used in obtaining faecal sludge samples from a pit latrine through a squat hole (left) and schematic diagram of a faecal sludge sampler (right)

3.2.2 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 chemical oxygen demand (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.

3.2.3 Characterisation 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 (NH₄-N) (Han & 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 NH₄-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.

3.2.4 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.

3.2.5 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).

3.2.6 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 statistically 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 %.

3.3 Results

3.3.1 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 3.1).

Table 3.1 Characteristics of faecal sludge from lined and unlined pit latrine from three slums

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

Note: *significant difference between characteristics of FS from lined and unlined pit latrines at $p = 0.05$ using ANOVA. SD means standard deviation

The low TVS proportions in FS from unlined pit latrines (50.0 \pm 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 \pm 0.3) than that of lined (1.5 \pm 0.4) indicates longer retention time (higher age) of FS from unlined pit latrines (Gebauer & 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 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.

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 3.2). A Tukey HSD 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 3.2).

Table 3.2 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	Kibuye	Kamwokya	<i>p</i> - value
			Mean \pm SD	Mean \pm SD	Mean \pm SD	
Lined pit latrine FS	Temperature	°C	22.8 \pm 1.6	23.1 \pm 1.1	23.7 \pm 0.8	0.674
	pH		7.2 \pm 0.4 ^a	7.6 \pm 0.2 ^b	7.7 \pm 0.2 ^b	0.011*
	Conductivity	mS cm ⁻¹	17.3 \pm 9.0	22.7 \pm 3.0	14.7 \pm 7.8	0.114
	COD	mg/L	107,137 \pm 32,542 ^a	75,120 \pm 28,778 ^a	20,794 \pm 8,456 ^b	0.000*
	TS	g/L	75.1 \pm 19.8 ^a	61.9 \pm 22.3 ^a	21.4 \pm 10.1 ^b	0.000*
	TVS	%TS	70.4 \pm 12.8 ^a	68.5 \pm 3.9 ^a	53.0 \pm 6.9 ^b	0.002*
	Moisture content	% (wet basis)	92.1 \pm 2.0	92.8 \pm 1.6	N/A	0.513
	Sand content	%TS	27.3 \pm 9.4	29.7 \pm 16.1	38.7 \pm 12.8	0.250
	Unlined pit latrine FS	Temperature	°C	22.4 \pm 0.2	22.5 \pm 1.1	23.7 \pm 0.9
pH			7.4 \pm 0.3	7.8 \pm 0.3	7.7 \pm 0.1	0.237
Conductivity		mS cm ⁻¹	9.9 \pm 4.8	15.4 \pm 8.1	12.3 \pm 4.2	0.535
COD		mg/L	140,607 \pm 42,881	156,553 \pm 46,953	107,960 \pm 40,122	0.363
TS		g/L	166.1 \pm 51.7	237.7 \pm 117.2	139.6 \pm 41.3	0.274
TVS		%TS	65.5 \pm 12.5	50.1 \pm 2.3	38.4 \pm 16.0	0.069
Moisture content		% (wet basis)	84.5 \pm 1.1	82.3 \pm 8.3	N/A	0.740
Sand content		%TS	37.8 \pm 11.5	57.8 \pm 12.5	54.3 \pm 12.6	0.170

Note: *significant difference in characteristics of FS from lined and unlined pit latrines among slums at $p = 0.05$ using ANOVA. SD means standard deviation. Means with different letters are significantly different from each other. N/A-not analysed.

3.3.2 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 (Figure 3.3). 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 ($p = 0.104$) (Figure 3.2). 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.

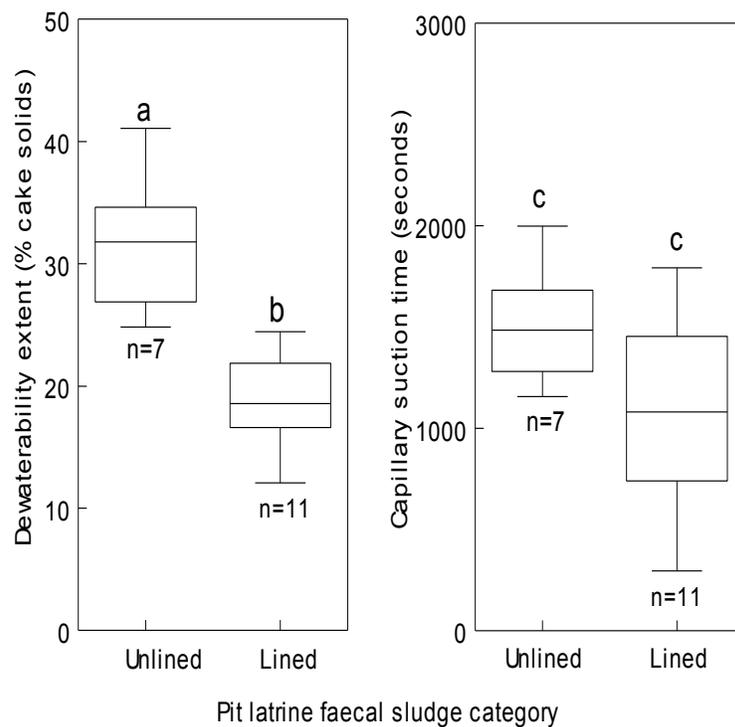


Figure 3.2 Dewaterability extent (left) and dewaterability rate as CST (right) of FS from lined and unlined pit latrines. Graphs with different letters are significantly different from each other at $p=0.05$. Box represents 50% of the data points and line in boxes represents the mean. n is the sample size

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 3.3). 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.

Table 3.3 Multiple comparisons of means \pm standard deviation for FS dewaterability rate and extent grouped by slum

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

Note: 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.

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 3.4). 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 3.4).

Table 3.4 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

Note: *Significant correlation coefficients at $p = 0.05$

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

3.3.3 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 (Figure 3.3). 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 (Figure 3.3).

Particle sizes bigger than 5 mm were not considered in this study as these were initially screened out before analysis. This is because particle 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.

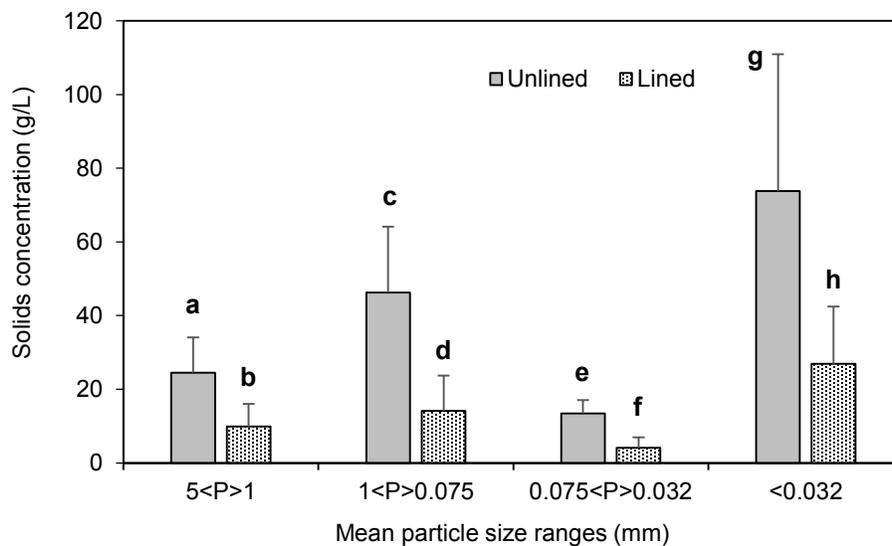


Figure 3.3 Comparison of solids concentration in lined pit latrine FS (n=21) and unlined pit latrine FS (n=9) for a given particle size range. For example; 5<P>1 denotes solids passing 5 mm sieve and retained by 1 mm sieve; and <0.032 denotes solids passing 0.032 mm sieve). Graphs with different letters are significantly different from each other at p=0.05

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 3.5). Solids of a size <0.032 mm in

FS from unlined pit latrine were significantly different among slums. A Tukey HSD post hoc multiple comparison revealed that the TS at particle size <0.032 mm was 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 HSD 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 3.5). This was due to lower initial total solids of FS from lined pit latrines in Kamwokya.

Table 3.5 Mean TS concentration \pm 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	Kibuye	Kamwokya	p- value
		TS (g/L)	TS (g/L)	TS (g/L)	
Unlined pit latrine FS	5<P>1	27.2 \pm 5.1	17.7 \pm 9.9	28.6 \pm 11.8	0.367
	1<P>0.075	41.8 \pm 16.5	58.9 \pm 30.2	42.3 \pm 13.3	0.589
	0.075<P>0.032	14.6 \pm 0.9	14.3 \pm 5.9	11.7 \pm 2.3	0.667
	<0.032	123.7 \pm 7.7 a	74.5 \pm 23.3 b	39.8 \pm 4.5 b	0.005*
Lined pit latrine FS	5<P>1	14.6 \pm 6.2 a	8.6 \pm 2.6 a	6.8 \pm 5.8 b	0.029*
	1<P>0.075	19.0 \pm 8.4 a	18.4 \pm 9.8 a	6.8 \pm 5.5 b	0.012*
	0.075<P>0.032	5.2 \pm 2.7 a	6.4 \pm 1.8 a	1.5 \pm 0.7 b	0.000*
	<0.032	36.3 \pm 15.5 a	35.4 \pm 6.6 a	10.13 \pm 6.6 b	0.000*

Notes: *Statistically significant using ANOVA at $p = 0.05$; TS is total solids concentration. Means with different letters are significantly different at $p = 0.05$ for a particular particle size range.

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 <1mm (Figure 3.4a). 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.

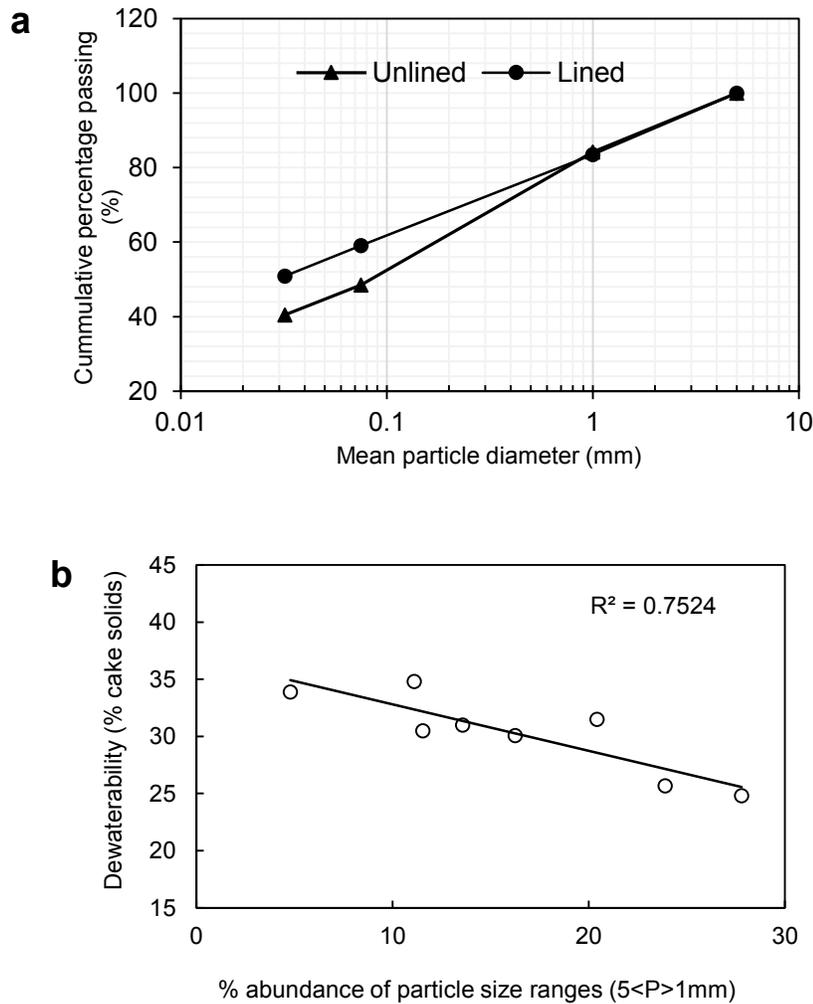


Figure 3.4 (a) Normalized particle size distribution of FS from lined and unlined pit latrines; and (b) Pearson correlation between dewaterability extent and change in proportion of particles for size range (5<P>1mm) of FS from unlined pit latrine.

3.3.4 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. 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 (Appendix A). 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 (Figure 3.5b). 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.

3.4 Discussion

3.4.1 Characterisation of faecal sludge from pit latrines vs 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.* (2009a). Such pH values (7.5–7.7) are of advantage if FS dewatering is to be enhanced using coagulants. Coagulants destabilise 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 & 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 minimised 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 [$\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$] and ferrous sulphate [$\text{Fe}_2(\text{SO}_4) \cdot 3\text{H}_2\text{O}$] 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 mg/L 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 & 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 (1,000-1,500 s) was far higher than those for commonly reported wastewater activated sludge (120-250 s) (Chen *et al.*, 1996; Lee & 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, 2007b). 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 particles 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 & 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 & Fang, 2002; Neyens & Baeyens, 2003), resulting in low dewaterability extent.

3.4.2 Particle size distribution versus faecal sludge dewaterability extent

Variation in particle size of sludge solids has been reported to influence its dewaterability (Karr & 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 & 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, 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 & 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, 2007b). 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 & 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 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 & 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.

3.4.3 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 off.

The total solids from characterisation 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 an average range of 12-35 gTS/L to 60-70 gTS/L for 7 days in Dakar (Senegal) (Dodane & 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 necessitate 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 decentralised 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 decentralised 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, 2007a). Similarly, belt presses work well with flocculated sludge to avoid blinding of the filter belt and enhance gravity drainage (Wakeman, 2007a). 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, 2007a). 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 less than 5 mm and solids content in the range of 7.6 to 16.6 %, the appropriate dewatering centrifuge types could be either a decanter or basket centrifuge.

3.5 Conclusions

- 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, and coffee or rice husks.
- The dewaterability characteristics of sewage sludge have been extensively published, but that of FS are 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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CHAPTER FOUR

4 Enhancing faecal sludge dewaterability and end-use by conditioning with sawdust and charcoal dust

This chapter is based on:

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Abstract

Faecal sludge (FS) treatment in urban slums of low-income countries of sub-Saharan Africa is poor or non-existent. FS contains over 90% water and therefore dewatering it within slums decreases transport costs, facilitates local treatment and end-use. This chapter was designed to enhance the dewatering efficiency of FS, using two locally available physical conditioners (sawdust and charcoal dust), each applied at dosages of 0, 25, 50, 75, 100 and 125% TS. The optimum dosage for both conditioners occurred at 50 and 75% for cake moisture content and capillary suction time, respectively. The dewatering rate improved by 14.3% and 15.8%, whereas dewatering extent (% cake solids) improved by 22.9% and 35.7%, for sawdust and charcoal dust, respectively. The dewatering in FS conditioned with sawdust and charcoal dust was mainly governed by absorption and permeation (porosity), respectively. The calorific value improved from 11.4 MJ kg⁻¹ by 42 and 49% with 50% TS dosage of sawdust and charcoal dust, respectively. The FS structure also became porous after dewatering which hastens the subsequent drying and/or composting processes. Due to comparable performance in dewatering, sawdust or charcoal dust, whichever is locally available, is suitable for treatment of FS in low-income urban slum settlements.

4.1 Introduction

Lined pit latrines are used by over 75% of slum population in Kampala, Uganda (Tumwebaze *et al.*, 2013). Therefore, dewatering (solid-liquid separation) forms a crucial part in decentralised treatment of faecal sludge (FS) from lined pits since it contains over 92% water (Chapter 3). Dewatering reduces solid fraction volumes and subsequently the costs of transportation and handling (Qi *et al.*, 2011). Furthermore, FS from lined pits exhibited a low dewatering extent (low percent dry solids in dewatered cake) (Chapter 3).

Chemical conditioners and plant extracts have been used to improve the dewatering rate (rate at which water filters through the FS sample) (Gold *et al.*, 2016), but no improvement in dewatering extent is reported. Physical conditioners such as coal fines, char, sawdust, bagasse, rice husks, rice bran and wheat dregs have been reported to improve dewatering extent of sewage sludge. They enhance the mechanical strength of sludge through formation of a rigid lattice structure to improve permeability within sludge solids, hence allowing water to easily flow out of the porous sludge structure (Qi *et al.*, 2011). Also, physical conditioners have a low moisture content compared to FS, which leads to reduction in cake moisture through absorption. They are generally more attractive from the economic and environmental points of view, since they are often waste materials from domestic and agricultural activities or cheap process by-products, therefore cost effective when applied in dewatering enhancement. Additionally, some of these physical conditioners are carbon-based, hence preferred if the dewatered sludge is to be used for energy recovery purposes (Qi *et al.*, 2011; Luo *et al.*, 2013). Diener *et al.* (2014) reported energy recovery from FS as a viable venture that can incentivise FS management to bear its own cost.

In this chapter, sawdust and charcoal dust were investigated as suitable physical conditioners for improving dewaterability and also improve energy potential of the resulting FS from urban slums. Sawdust and charcoal dust from Bwaise slum (Kampala) were used because they are biodegradable, readily available in urban slums at low or no cost. Since a large number of slum dwellers depend on wood charcoal as their major cooking fuel, there is production of high volumes of charcoal dust (a waste from wood charcoal). The other physical conditioners such as coffee, palm, ground nuts and rice husks, as well as bagasse were not considered because they are costly to transport since they are generated in areas with large scale agricultural activities (Byrne *et al.*, 2015). For example, these

conditioners are obtained at long distances in relation to Kampala slums, where a lot of FS that needs localised handling to reduce haulage costs is generated. In addition, the current competition for these wastes as fuel sources to generate heat in a number of industries and agricultural production (e.g. poultry and piggery farming; some on a commercial scale) has made them expensive (Diener *et al.*, 2014). Also, application of sawdust and charcoal dust conditioners maintains potential utilisation value of the resulting FS after dewatering. Sawdust and charcoal dust possess calorific values of about 20 and 28 MJ kg⁻¹, respectively (Diener *et al.*, 2014), but FS has a lower calorific value in the range of 12-17 MJ kg⁻¹ (Murray Muspratt *et al.*, 2014; Seck *et al.*, 2015), which is expected to be improved by sawdust and charcoal dust conditioning. The improvement in energy content could be a driver for sustained end-use, hence improved sanitation through management of not only FS, but also the sawdust and charcoal dust wastes from the surrounding environment of urban slums.

Over 70% of the urban households in a number of low-income countries of SSA rely on wood charcoal (carbonised wood product) as the main source of cooking fuel (Ferguson, 2012). The population growth in SSA is likely to raise the demand of wood charcoal, yet about 5 to 20% of the charcoal volume is wasted in the form of charcoal dust, formed either during parking, transportation and/ or storage (Basu *et al.*, 2012). Some charcoal dust is currently mixed with binders to make fuel briquettes, while the rest ends up in municipal solid waste (Eichner *et al.*, 2006). Also, sawdust is a globally abundant organic waste from timber sawmills. In fact, the wood loss in form of sawdust is estimated at 18 to 20% of the log volume in some SSA countries such as Uganda (Zziwa *et al.*, 2006). Part of sawdust is currently used to provide energy at household and industrial scale (Diener *et al.*, 2014) as well as bedding layer in rearing of chicken, while a fraction of it joins the municipal solid waste stream (Komakech *et al.*, 2014).

Sawdust on the other hand has been used in a number of studies to remove toxic substances, such as heavy metals, colour and others, from water and wastewaters (Shukla *et al.*, 2002). Furthermore, pre-conditioning of domestic and industrial wastewater sludge with sawdust to improve dewaterability has been studied (Luo *et al.*, 2013). However, charcoal dust is equally important but its potential as a conditioner in the treatment of wastewater sludge is untapped. Application of sawdust and charcoal dust in dewatering of FS is also not yet reported.

The objective of this chapter was therefore to determine how the dewaterability of FS from pit latrines in urban slums can be enhanced with sawdust and charcoal dust as physical conditioners. Additionally, characterisation of dewatered FS in terms of the energy beneficiation resulting from the use of these conditioners was done. The results provide information that could be used in the practice of FS conditioning while managing sawdust and charcoal dust wastes in urban slums.

4.2 Materials and Methods

4.2.1 Collection and preparation of faecal sludge samples

Faecal sludge samples were collected from Bwaise, a typical urban slum in Kampala with limited access to mechanized pit emptying. The location coordinates of Bwaise are: 00 21 00N, 32 33 40E (Latitude: 0.3500; Longitude: 32.5610). Faecal sludge from lined pit latrines was used in this study because lined pit latrines are used by more than 75% of urban slum population in Kampala (Tumwebaze *et al.*, 2013). Grab samples were obtained from various layers (top, middle and bottom) of a pit latrine through a squat hole by using a multi-stage sampler (Figure 3.1). These were mixed into a composite sample that was collected in a 30 L HDPE plastic container and then transported to the Public Health and Environmental Engineering Laboratory at Makerere University, where they were stored at 4°C prior to further processing and analysis. The preparation of FS samples before analysis involved removal of extraneous material by passing it through a 5 mm sieve (Burton, 2007).

4.2.2 Collection and preparation of physical conditioners

Charcoal dust was obtained from charcoal outlets within the Bwaise slum, while sawdust was obtained from a timber sawing mill in the same slum area. Charcoal dust and sawdust particles were sieved to a size less than 2.36 mm for uniformity, oven dried for 24 hours and stored in a vacuum desiccator, to keep it dry during analysis (Luo *et al.*, 2013). The particle size distributions of sawdust and charcoal dust used in the study were determined by gradation using standard sieves ranging from 2.36 mm to 0.075 mm (Table 4.1). The density of sawdust and charcoal dust was determined by packing a measured weight of the conditioner into a graduated cylinder. The cylinder was tamped on the bench top until no further volume reduction of conditioner was observed. This volume was recorded and the density was calculated.

Table 4.1 Particle size distribution of sawdust and charcoal dust conditioners

Particle size (mm)	Sawdust		Charcoal dust	
	Mass retained (%)	Cumulative mass passing (%)	Mass retained (%)	Cumulative mass passing (%)
2.360	0.0	100.0	0.0	100.0
1.180	36.6	63.4	31.4	68.6
0.600	37.4	26.0	22.6	46.0
0.425	11.6	14.4	9.4	36.6
0.300	7.2	7.2	8.9	27.7
0.212	3.6	3.6	6.4	21.3
0.150	1.6	2.0	5.2	16.1
0.750	0.8	1.2	7.2	8.9
Pan	1.2	N/A	8.9	N/A

4.2.3 Characterisation of faecal sludge

Raw FS from lined pit latrines was characterised for: total solids (TS), total volatile solids (TVS), pH, electrical conductivity (EC), moisture content, dewatered cake solids, bulk density, ash content, calorific value and crude protein (Table 4.2).

Table 4.2 Characteristics of raw faecal sludge samples

Parameter	Unit	Range values
pH		7.6 – 8.5
EC	mScm ⁻¹	5.8 – 9.4
Total solids (TS)	g/L	15.0 – 32.2
Moisture content	%	96.7 – 98.4
Volatile solids (VS)	%TS	30.2 – 60.7
Ash content	%TS	39.3 – 69.8
Cake solids	%	14.0 – 28.2
Bulk density	kgm ⁻³	995 – 1002
Crude protein	mg/gTS	50.8*
Gross calorific value (dry basis)	MJ kg ⁻¹ (d.b)	11.4*

Note: *mean value

TS, TVS and ash content were determined according to standard methods for examination of water and wastewater (APHA/AWWA/WEF, 2012). The TS concentration was determined gravimetrically by taking the weight of the oven dried sample at 105°C for 24 hours and expressed as a fraction of wet sample volume. TVS was determined by taking the weight difference between oven dried solids and the 2-hour 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 hours. Gross calorific value was determined on dry samples after TS analysis, where approximately 1 g of sample was combusted in an oxygen bomb calorimeter (IKA Model C2000, Germany). Crude protein, an indicator for extracellular polymeric substances (EPS), was determined by multiplying

a factor of 6.25 to the difference between total nitrogen (TN) and ammonium-nitrogen (NH₄-N) (Han & Anderson, 1975). Three replicates were analysed for each sample to verify the reproducibility of the experimental results.

4.2.4 Physical conditioning and dewatering of faecal sludge

The physical conditioner (sawdust or charcoal dust) was added to 500 mL of FS in dosages of 0, 25, 50, 75, 100 and 125 %. The dosage ranges are inferred from those used in conditioning of sewage and industrial wastewater sludge using physical additives such as sawdust (Lin *et al.*, 2001; Luo *et al.*, 2013). The conditioned FS mixture was agitated at a speed of 60 rpm and time of 20 minutes (Luo *et al.*, 2013), using a Stuart flocculator (Jar test), model SW6. The sawdust or charcoal dust dosage was expressed as the weight ratio of conditioner to FS dry solids. For each dosage, analysis was replicated three times to attest reproducibility of the experimental results.

4.2.5 Dewatering performance of conditioned faecal sludge

Dewatering performance of conditioned FS was determined in terms of capillary suction time (CST) (time for water to filter through the FS sample) and percent moisture content in dewatered FS cake after centrifugation, representing dewaterability rate and dewaterability extent, respectively. A high CST value and high cake moisture content are reflections of poor FS dewaterability (rate and extent, respectively). CST was measured in triplicate using a CST instrument (Type 304M, Triton, England, UK) equipped with an 18 mm diameter reservoir funnel and chromatography paper, as described in the standard method (APHA/AWWA/WEF, 2012).

Dewatering extent was determined using a batch type laboratory centrifuge (MISTRAL1000 type, UK), where 50 mL of FS sample was centrifuged at 3,000 rpm for 20 minutes, corresponding to gravitational force of 1,500 *g* (Jin *et al.*, 2004). After centrifugation, percent moisture content (wet basis) in centrifuged cake was determined from the wet and oven dried (105°C) cake weights. The volume and turbidity of decanted off supernatant (leachate) were determined using a measuring cylinder and a spectrophotometer (Hach DR 2800, UK), respectively. The other parameters namely volatile solids and ash content of the centrifuge dewatered FS cake were determined following standard methods (APHA/AWWA/WEF, 2012). In order to compare the microstructure of the original raw FS and the conditioned FS mixtures, a digital microscope was used. Micrographs were captured after visualising the samples, placed on a microscope slide.

4.2.6 Data analysis

Statistical analysis was carried out using SPSS version 21.0 for Windows. Data were tested for normality using the Shapiro-Wilk test and homogeneity of variance by the use of Levene's test in SPSS. Descriptive statistics were used to describe the characteristics of FS and conditioners. Significant differences in treatments using sawdust and charcoal dust were evaluated using the Analysis of Variance (ANOVA) at 5% significant level.

4.3 Results and Discussion

4.3.1 Characterisation of sawdust and charcoal dust

Most of the characteristics of sawdust and charcoal dust used in this study were comparable to published literature from different tree species in different countries (Table 4.3). This implies that the results from this study are transferrable to similar conditioners in different locations. In cases of no literature for charcoal dust, wood charcoal literature was used, since charcoal dust is derived from wood charcoal. Charcoal dust had a higher calorific value than sawdust, mainly because of its higher fixed carbon content (Demirbas, 2004; Pastor-Villegas *et al.*, 2006). However, some charcoal dust can be mixed with extraneous materials like soil, depending on the source, which may increase the ash content and thus lower the calorific value. Volatile solids in charcoal dust are lower than those in sawdust due to their removal during the wood carbonisation process.

Table 4.3 Characteristics of physical conditioners (sawdust and charcoal dust)

	Present study		Published data		
	Unit	Sawdust	Charcoal dust	Sawdust	Charcoal dust*
Specific gravity		0.065	0.053	N/A	N/A
Bulk density (loose)	kgm ⁻³	173.9±10.8	868.5±7.8	180-635 ^a	N/A
Water content (wet basis)	wt%	18.4±1.3	11.6±0.4	11-13 ^c	5.2 ^d
TVS	wt%	79.0±1.0	61.3±2.2	77-82 ^{a, c}	20-23 ^{b, d}
Ash content	wt%	2.5±0.6	24.7±3.1	0.4-2.8 ^a	3.8 ^d
Gross heating value (dry basis)	MJ kg ⁻¹	19.7±0.1	23.7±0.7	14-21 ^{a, c}	23-28 ^e
Aluminum oxide (dry basis)	%	N/A	N/A	4.2-9.5 ^{a, c}	10.8 ^d
Silicon oxide (dry basis)	%	N/A	N/A	10.8-49 ^{a, c}	29.5 ^d
Crude protein	mg/g solids	2.6	10.3	N/A	N/A

Notes:

* Values used are for wood charcoal since charcoal dust is a waste from wood charcoal, N/A – not available

^a Demirbas (2004).

^b Pastor-Villegas *et al.* (2006).

^c Abreu *et al.* (2010)

^d Arthur *et al.* (1948)

^e Diener *et al.* (2014)

4.3.2 Effect of physical conditioners on faecal sludge characteristics

There was an increase in TVS and a decrease in ash content for FS conditioned with both sawdust and charcoal dust (Figure 4.1 b and c). However, sawdust conditioned FS depicted higher TVS and lower ash content values than charcoal dust for all dosages. These are relevant characteristics if conditioned FS is to be used in energy recovery, as depicted by increasing calorific value of conditioned FS with increasing dosages (Figure 4.1a). The low calorific value of unconditioned FS in this study (11.4 MJ kg^{-1}) could be due to the presence of high ash content ($\sim 40\% \text{ TS}$) as this indicates the incombustible fraction of FS. This is comparable to a study by Seck *et al.* (2015), whose calorific value of FS was 12.2 MJ kg^{-1} with an average ash content of $41.7\% \text{ TS}$. The authors further realised an increment of 6% in ash content after dewatering of FS on sand beds. Therefore, avoiding FS contact with sand during dewatering reduces the ash content of the resulting cake. Additionally, usage of sawdust or charcoal dust significantly lowered the ash content through dilution effect, hence increment in energy potential of the resulting material.

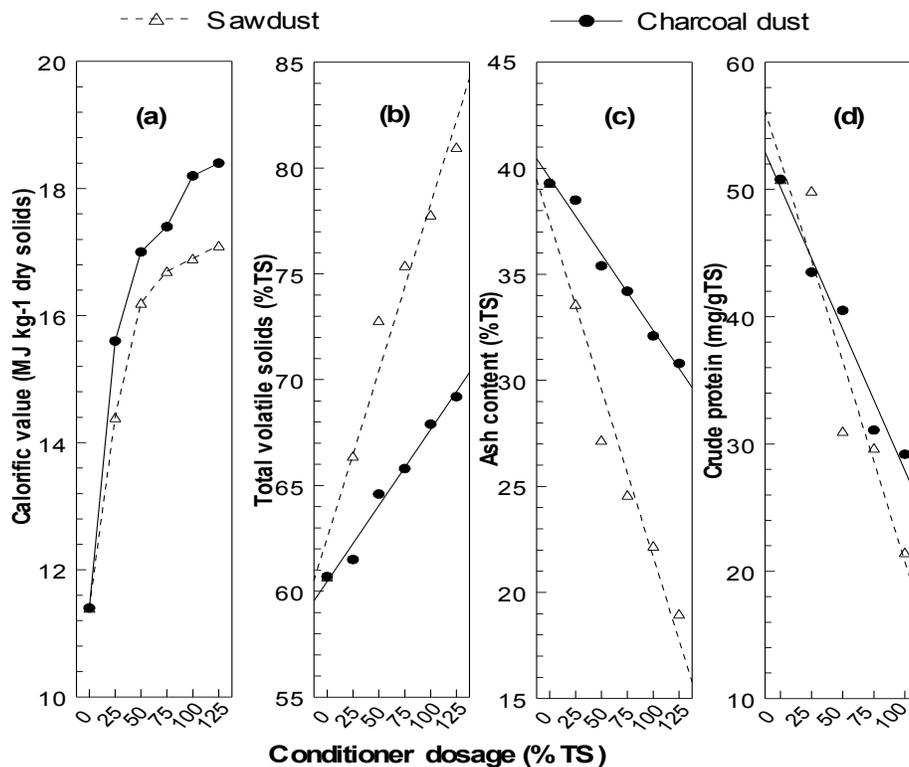


Figure 4.1 The effect of physical conditioner dosage on (a) calorific value, (b) volatile solids, (c) ash content and (d) crude protein of FS

FS conditioned with charcoal dust depicted higher calorific values, although not significantly different from sawdust ($p = 0.410, 0.082, 0.388$ and 0.122) for corresponding dosages (25, 50, 75 and 100%). This reflects a comparable performance in energy recovery when either of the conditioner is used. Additionally, multiple comparisons of average calorific values at different dosages using Tukey HSD revealed no significant difference ($p > 0.05$) beyond 25 and 50 % TS dosage for charcoal dust- and sawdust-conditioned FS, respectively. The gross calorific value of FS improved by 42 and 49%, when conditioned with 50% TS dosage of sawdust and charcoal dust, respectively. Finally, increased conditioner dosages lowered crude protein content in FS (Figure 4.1d). Crude protein is a component of EPS, with a high water-holding capacity. Therefore, a reduced protein fraction in sludge improves dewaterability efficiency (Mikkelsen & Keiding, 2002).

4.3.3 Effects of physical conditioners on dewatering of faecal sludge

The cake moisture content decreased significantly with conditioner dosage of up to 50% TS. Beyond this dosage, charcoal dust-conditioned centrifuge cake had significantly lower moisture content than a sawdust-conditioned one ($p < 0.05$) (Figure 4.2a). The cake moisture content significantly decreased from 86% to 80.8% ($p = 0.000$) and 82.8% ($p = 0.001$), when conditioned with 50% TS of charcoal dust and sawdust, respectively. A linear regression showed a very strong positive relationship between cake moisture and crude protein content when conditioned with sawdust ($R^2 = 0.92, p = 0.009$) and charcoal dust ($R^2 = 0.96, p = 0.004$). The decrease in cake moisture with sawdust addition was comparable to results obtained by Lin *et al.* (2001), who reported the sawdust dosages (0, 90, 100, 200 and 300%) with sludge cake moisture contents of 88.6, 85.3, 80.4, 77.2 and 74.8%, respectively. Additionally, Ding *et al.* (2014) also noted a decrement in cake moisture from 91.3 to 88.5%, when sawdust was increased from 0 to 100%, respectively. Also, a decrease in filter cake moisture from 87 to 75% was reported when coal fly ash dosage was varied from 0 to 100% (Chen *et al.*, 2010).

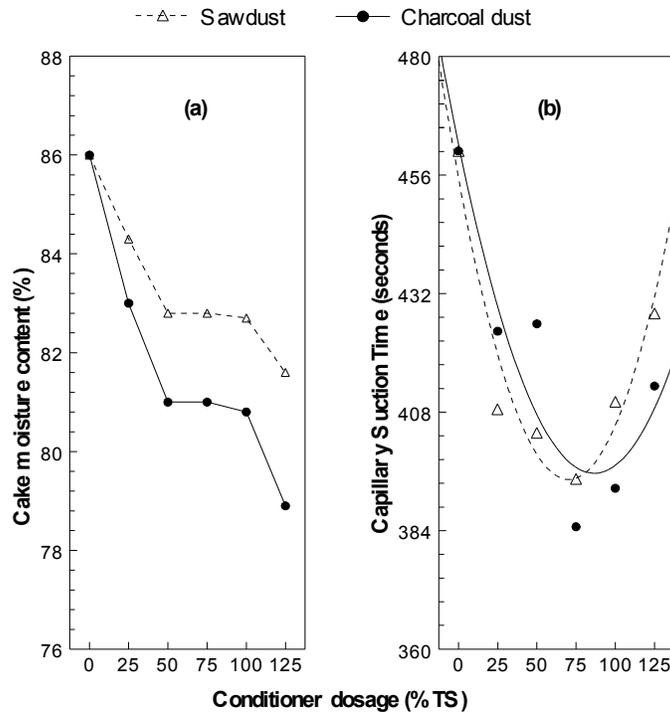


Figure 4.2 The effect of conditioner dosage on (a) dewatered cake moisture content and (b) capillary suction time

On the other hand, capillary suction time (CST) decreased (FS dewaterability rate improved) when the doses of sawdust or charcoal dust were increased to 75% TS (Figure 4.2b). CST was reduced by 14.3 and 15.8% for sawdust and charcoal dust, respectively at 75% dosage, compared to non-conditioned FS. The presence of aluminium and silicon elements in sawdust and charcoal dust (Table 4.3) are responsible for increment in dewatering rate, since these are known to cause agglomeration and thus increase in rate of settling. However, an increase in CST beyond the 75% dosage was recorded. A similar trend was reported by Luo *et al* (2013), where optimal sawdust dosage for sludge from textile dyeing industry was 60%, beyond which an increase in CST was realised. Secondly, Jing *et al.* (1999) reported a high dewaterability rate improvement of 60% when 170% dosage of sawdust was used. This high improvement could be due to higher doses and larger particle sizes of sawdust used (1 to 5 mm) as opposed to the one with high proportion of fines used in this study (<2.36 mm).

The results generally suggested that the added sawdust and charcoal dust created voids within the FS cake, which permitted the passage of water. This was supported by the visible voids in the microstructure of conditioned FS compared to raw FS (Figure 4.3). Therefore, the presence of

physical conditioners improved the cake porosity by forming channels or pores between the sawdust or charcoal dust particles and FS particles because of different particle size distributions, thus also, the increased CST.

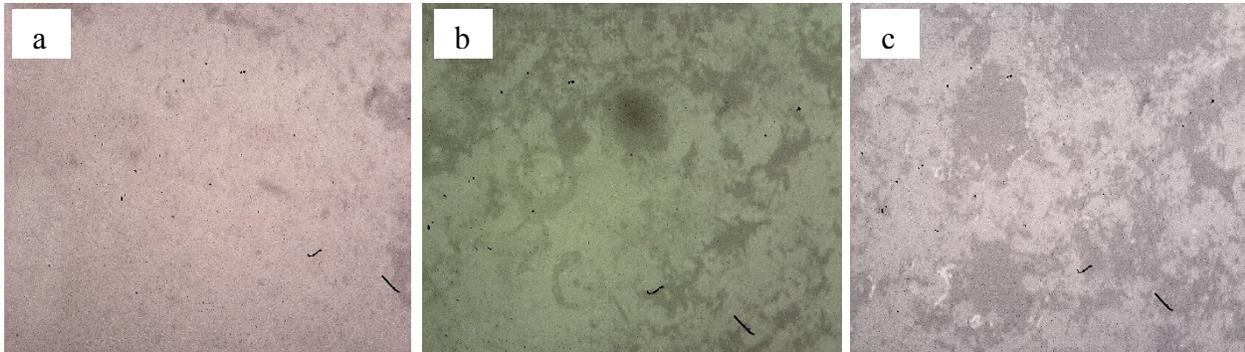


Figure 4.3 Micrographs of raw FS (a), FS conditioned with 75% sawdust (b) and with 75% charcoal dust (c): magnification x100

4.3.4 Effect of dewatering on leachate production

Increasing the dose of sawdust or charcoal dust decreased the cake moisture content, but did not increase volume of centrate /leachate (liquid stream after centrifugation) yielded (Figure 4.4b). In fact, these conditioners consistently reduced the volume of leachate recovered. Significant reduction ($p < 0.05$) in leachate production was realised after 50 and 75% TS dosage of charcoal dust and sawdust respectively. This decrease with higher dosages could be attributed to absorption of free water from FS into sawdust or charcoal dust, hence less free water available for release from FS. A similar observation of decrease in leachate volume at higher sawdust dosages was reported by Lin *et al.* (2001).

A linear regression revealed a very significant ($R^2 = 0.89, p = 0.000$) and a moderate positive ($R^2 = 0.56, p = 0.005$) correlation between cake moisture content and leachate volume when conditioned with sawdust and charcoal dust, respectively. This implied that more free water absorption took place in sawdust- than charcoal dust-conditioned FS. For example, at 50% dosage of charcoal dust conditioner, there was significant low cake moisture content and at the same time no significant reduction in leachate volume. Therefore, cake moisture content reduction in FS conditioned with charcoal dust was mainly governed by permeation due to the created rigid porous structure that allows escape of water.

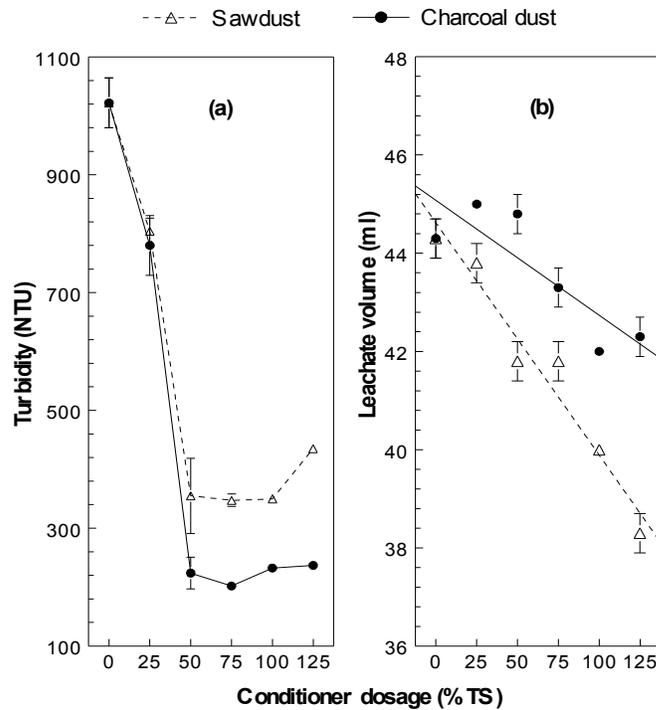


Figure 4.4 Effect of conditioner dosage on (a) leachate turbidity and (b) leachate volume.

It suffices to note that the leachate turbidity significantly decreased by 65.3 and 78%, when conditioned with sawdust and charcoal dust, respectively, at dosages of 50% TS (Figure 4.4a). Chen *et al.* (2010) varied coal fly ash dosage from 0 to 1,000% in conditioning sewage sludge and obtained least turbidity at 100% dosage. At a dosage of 50% and beyond, the turbidity for charcoal dust-conditioned FS was significantly lower than that of sawdust-conditioned FS because wood charcoal has potential of adsorbing toxic substances such as heavy metals and organic compounds (Pulido-Novicio *et al.*, 2001). More so, charcoal dust contained a higher proportion of finer particles (Table 4.1), leading to an increase in surface area, thus more adsorption potential for suspended solids, and hence the recorded low turbidity. The attained turbidity levels with charcoal dust conditioner were below the Ugandan effluent discharge standards of 300 NTU, implying improved quality of leachate after dewatering. However, at dosage higher than 100% TS, the turbidity slowly increased with increasing conditioner dosage.

4.3.5 Implications for subsequent faecal sludge management options in urban slums

Various FS management strategies in an urban slum setting are suggested based on the study findings (Figure 4.5). If the dewatered FS is to be used as a fuel, energy for drying is required and

then the dewatered cake has to be transformed into briquettes for easy usage and handling (Chapter 2). Fortunately, the created porous structure after physical conditioning mean less energy required to dry conditioned FS than the raw FS. The dried conditioned FS can be carbonised to produce char, bound and compacted into briquettes. Both the drying and carbonisation processes are very effective if one is to ensure destruction of pathogens present in conditioned FS, due to high temperatures involved (Niwagaba *et al.*, 2006; Ferguson, 2012), making such briquettes easy and safe to handle/use in homes. The emissions such as carbon monoxide, carbon dioxide, methane, hydrogen and ethane occur during different carbonisation stages, leading to reduced volatile compounds (organic compounds), increased fixed carbon, and hence increased calorific value of the resulting char (Demirbas, 2004). Therefore, usage of carbonised conditioned FS reduces the harmful emissions compared to burning of raw conditioned FS in home stoves. The resulting ash content of about 25 and 34 % TS for sawdust- and charcoal dust-conditioned FS, respectively, after energy recovery can be transported and sold to farmers to recover nutrients such as nitrogen, phosphorus, potassium, calcium and magnesium for their crops. This can therefore improve soil physical and nutritional properties. Unlike, wastewater sludge, the concentration of heavy metals (such as copper, zinc, lead and arsenic) in FS from Ghana and Burkina Faso is significantly lower (Bassan *et al.*, 2013; Appiah-Effah *et al.*, 2015). For Bwaise slum, the heavy metals from automotive garages are mainly disposed off in drainage trenches, than pit latrines (Nyenje *et al.*, 2013). Therefore, the resulting ash after recovering heat from FS can be safely used in soil improvement.

Increasing sawdust or charcoal dust dosages leads to increase in weight of resulting sludge. Therefore dosages of > 75% (dry weight) should be avoided if dewatered sludge is to be transported from urban slums and disposed of at either landfills or conventional treatment plants, whichever is nearer. Alternatively, if the space and time in the slums allow, then composting could be done. The increased porosity after conditioning FS allows easy passage of air within the FS structure, hence increased rate of composting. However, this would require more bulking material (sawdust or charcoal dust) dosage to lower moisture content (<60%) to acceptable levels for composting. Addition of conditioners such as sawdust in dosages of >300% after dewatering have been found to be sufficient in achieving successful composting (Lin *et al.*, 2001).

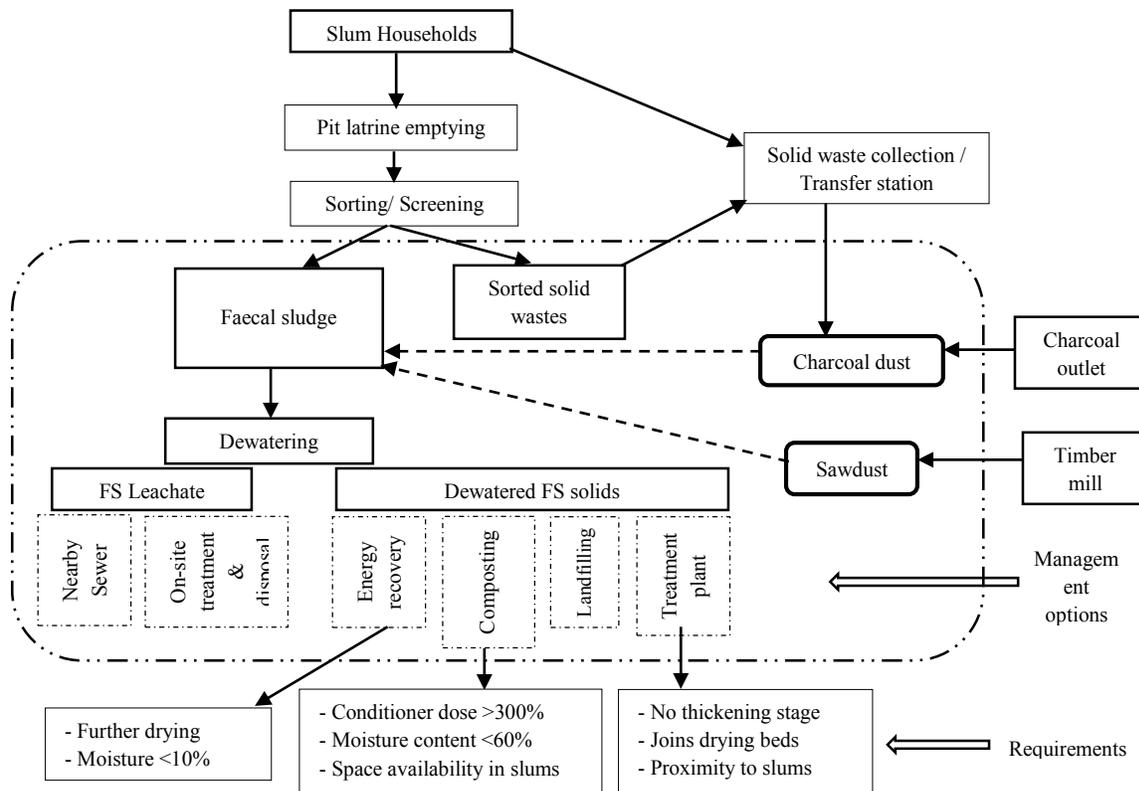


Figure 4.5 Propositional faecal sludge management system technology scheme in urban slum based on use of sawdust and charcoal dust conditioners.

4.4 Conclusions

The effect of sawdust and charcoal dust conditioners in enhancing FS dewaterability has been investigated. The investigations demonstrate the potential of conditioning FS followed by dewatering as well as potential end-use, could make the use of FS products or their sales subsidize the costs of FS management, thereby reducing financial inputs by the low-income urban slum residents. The capillary suction time of FS decreased by 14.3 and 15.8% when conditioned with 75% of sawdust and charcoal dust, respectively. Additionally, the moisture content in dewatered cake decreased by 4.6 and 6.4% when conditioned with 50% sawdust or charcoal dust, respectively, and these are comparable to values in the literature when sawdust is used in conditioning sewage sludge. As a demonstration, 100 litres of FS, with total solids concentration of 25 g/L at conditioner dosage of 50% TS, translates into a requirement of 1.25 kg solids of conditioner. The conditioned FS structure became porous after dewatering, and this potentially translates into less time and energy for subsequent drying, compared to unconditioned FS.

After dewatering, the leachate characteristics improved in terms of turbidity, due to the adsorptive nature of the conditioners. This could reduce the cost of treating the leachate to safe levels before discharge. Also, the calorific value of dewatered FS increased by 42 and 49% when conditioned with 50% TS dose of sawdust and charcoal dust, respectively, hence improvement in energy recovery potential. This may promote its use as an alternative fuel to increase the proportion of home-grown energy sources, and thus achieving the aim of energy conservation.

This study did not vary physical characteristics of conditioners such as particle sizes, hence their contribution to dewaterability should be studied. Different sources of conditioners may affect conditioner characteristics like charcoal dust from retail outlets may differ from that at households. Similarly, sawdust from different tree species may possess different characteristics. These may be studied and their contribution to FS dewatering determined.

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CHAPTER FIVE

5 Optimisation of centrifuge operating conditions for dewatering physically conditioned faecal sludge from urban slums

This chapter is based on:

Semiyaga, S., Okure, M. A. E., Niwagaba, C. B., Nyenje, P. M. & Kansiime, F (2017). Optimisation of centrifuge operating conditions for dewatering physically conditioned faecal sludge from urban slums. *Environmental Technology and Innovation* 8, 28-39. Doi: 10.1016/j.eti.2017.03.005.

Abstract

Decentralised faecal sludge (FS) dewatering in urban slums using centrifugation technology has potential to reduce public health risks and environmental pollution caused by indiscriminate disposal of untreated FS. A laboratory-scale centrifuge was applied to optimise dewatering of FS from lined pit latrines, conditioned with sawdust and charcoal dust. Response surface methodology and central composite design were used to construct and model relationships between independent variables (FS volume, centrifugation time and speed) and the dependent variable (per cent cake solids) for unconditioned and conditioned (sawdust and charcoal dust) FS. The results demonstrated that the centrifugation technology can yield more per cent cake solids at reduced speeds when physically conditioned. Rotational speed was a significant parameter ($p = 0.0020$) for unconditioned (original) and charcoal dust conditioned FS ($p = 0.0019$). Significant parameters for sawdust conditioned FS were speed ($p = 0.0001$) and quadratic effect of time ($p = 0.0494$). An optimal centrifugation time of 20 minutes and centrifugation container volume of 70-80% full of FS for conditioned FS were obtained. The centrifugation speeds tested in this paper provide critical information for proto-type design of a hand-powered centrifuge, the operating conditions and its subsequent set up. This can serve as an option for dewatering FS from commonly used sanitation facilities in urban slums, thereby enabling decentralised treatment to reduce costs of FS management and support resource recovery at the source.

5.1 Introduction

Over 70% of the urban population in sub-Saharan Africa (SSA) reside in slum areas (UN-HABITAT, 2006). In most slum areas, infrastructure such as roads is lacking due to high density of housing units, hence making it costly and difficult for emptying trucks to access sanitation facilities (Chapter 2). The high faecal sludge management (FSM) cost and limited access could be solved by managing FS at or near the point of generation within urban slums (decentralised level) (Chapter 2). However, this calls for technologies that can be used in FSM at a decentralised scale. Technologies such as *gulper*, *vacutags*, and others, have been developed to empty and collect FS from slums (Still, 2012). However, these technologies cannot solve all challenges of the FSM services chain such as the treatment and disposal or end-use of FS.

Since FS from lined pit latrines is over 90% water, dewatering presents an important first step of treating it effectively (Chapter 3). A new pit latrine design incorporated with a removable dewatering unit (metal cage with filter bags) could be an innovative approach to reduce the cost of dewatering, emptying and subsequent transportation of FS (Hamawand & Lewis, 2016). The containers can easily be collected from places with limited access in slums. However, the high percentage of filled-up pit latrines, reported at 66 % in the slums of Kampala (Nakagiri *et al.*, 2015), and the limited space for new ones, would call for technologies of managing/dewatering FS from the already existing filled-up latrines. Technologies commonly used in dewatering sewage sludge at a centralised scale include; thickening tanks, sand beds, filter presses and centrifuges (Pan *et al.*, 2003). The sand bed and filter press technologies have a challenge of large space requirement which may be limited in urban slum settings. Centrifugation technology has a small foot print in terms of area requirement, low operation costs and normally has a casing to enclose odour in densely populated areas (Broadbent, 2001; Drury *et al.*, 2002). In addition, dewatering or sedimentation can be achieved faster due to enhancement of gravitational acceleration by centrifugal acceleration resulting from circular rotational motion of the centrifuge (Garrido *et al.*, 2003). Such characteristics make centrifugation an appropriate dewatering technology for urban slums.

Centrifugation is based on the principle that when a suspension such as FS is swirled at a particular rotational speed, the denser solids move through a fluid in the direction tangential to the direction of rotation, under centrifugal acceleration (Vesilind & Zhang, 1984). A driving force for water

removal from settled FS sets up, which reduces the cake moisture content (or increasing per cent dry cake solids) in the settled solid fraction of FS. However, the use of rotational speed to hasten dewatering during centrifugation requires mechanical energy say from electric motors, hence, high operational and maintenance costs. This further limits their widespread application in some slum areas with no connection to the electricity grid.

Industrial /commercial centrifuges have been classified into sedimenting or filtering centrifuges, with underlying principles of gravity sedimentation and pressure filtration, respectively (Buerger & Concha, 2001). Extensive usage of sedimenting centrifuges has been reported, and it has been found that suspensions containing considerable amount of fine solids of less than 45 μm easily clog filtering centrifuges (Buerger & Concha, 2001). FS from pit latrines in Kampala slums contain over 70% fine particles of less than 45 μm (Chapter 3), justifying the need for sedimentation centrifuge type.

Data from batch laboratory-scale centrifugation studies have been used as a basis for design equations of large-scale continuous centrifuges or to know the performance of existing centrifuges, given the type of feedstock to be centrifuged (Brar *et al.*, 2006). Continuous commercial centrifuges are designed on mechanical basis and cannot be easily modified. Indeed, centrifuge design is impossible in the absence of laboratory centrifugation studies. The performance of a commercial continuous centrifuge is governed by equation (1) (Brar *et al.*, 2006).

$$\Sigma = \frac{Qt\omega^2}{g \ln(R_0/R_1)} \quad (1)$$

Where Σ is the centrifuge parameter, dimension L^2 (m^2); Q is the feedstock flow rate (l/d), which is proportional to volume; t is the centrifugation time (s); g is the acceleration due to gravity (9.81 ms^{-2}); ω is the rotational speed (rads^{-1}); R_0 is the maximum rotor radius (cm); R_1 is the minimum radius of liquid interface (cm). However, since some parameters are constant, volume of FS, rotational speed and time are the major operational parameters pertinent for the batch centrifugation process (Buerger & Concha, 2001).

Cake solids formation depends on both centrifugation operating conditions such as rotational speed, time, nature of FS material centrifuged, as well as the form of material pre-treatment such as using

conditioners. Centrifugation has a drawback of achieving dewatering at very high rotational speeds. Pre-treatment of FS with chemical conditioners improves the dewatering rate or rate of cake formation (Gold *et al.*, 2016). However, physical conditioners improve the extent of dewatering (cake dryness or per cent cake solids) and partly the dewatering rate (Qi *et al.*, 2011). Dewatering rate is the rate at which water filters out of FS, while dewatering extent is the per cent dry solids in FS cake (Peng *et al.*, 2011). The physical conditioners, being at lower moisture content absorb moisture from FS (Chapter 4) and also enhance the mechanical strength of the resulting cake by formation of rigid lattice structures which improve porosity of sludge cake; hence easing flow of water out of the cake (Qi *et al.*, 2011).

Sawdust and charcoal dust are wastes from timber saw mills and wood charcoal, respectively. They have advantages of being biodegradable, readily available in urban slums at low or no cost, and the dewatered cake has improved utilisation potential especially during energy recovery (Diener *et al.*, 2014). Sawdust and charcoal dust can improve dewatering extent and, hence a probable reduction in rotational speed required for centrifugation. However, when FS is conditioned and centrifuged, the centrifugation operation conditions of FS volume, rotational speed and time act differently and can affect one another. Consequently, optimisation of these factors is necessary in order to determine the best response in terms of per cent cake solids achieved. In addition, centrifuges have been used in centralised wastewater treatment plants, but no studies exist on decentralised centrifugation of FS from pit latrines in slums areas.

This chapter was therefore carried out to determine the effect of sawdust and charcoal dust conditioning on optimum centrifugation operation parameters of FS. This study is considered of benefit to the process design and sizing efficient equipment pertinent in dewatering of FS from the sanitation facilities commonly used in urban slums, such as pit latrines. FS from lined pit latrines was considered in this study. This is because FS from lined pits has a lower dewatering extent compared to FS from unlined pit latrines (Chapter 3).

5.2 Materials and methods

5.2.1 Collection of FS samples

FS samples for the study were collected from Bwaise (Figure 1.3), a typical urban slum in Kampala (Uganda) with limited access to mechanised pit emptying. A fabricated multi-stage sampler (Figure 3.1) was used in obtaining FS samples from five purposively selected pit latrines. Grab samples of one litre were obtained from each of the three layers (top, middle and bottom) of each pit latrine through a squat hole and were mixed into a composite sample. Composite samples were obtained from five pit latrines and put in a 30 litre HDPE plastic container. The container was immediately transported to the Public Health and Environmental Engineering Laboratory at Makerere University. While in the laboratory, the samples were stored at 4°C until they were analysed. Prior to preparation and subsequent experiments, FS samples were removed from the refrigerator and left to attain room temperature.

5.2.2 Preparation of FS samples

Preparation of FS samples before analysis involved passing them through a 5 mm sieve to remove the extraneous materials (Chapter 3). The raw FS samples from lined pit latrines were characterised for total solids (TS), total volatile solids (TVS), ash content, pH, electrical conductivity (EC), sand content and bulk density (Table 5.1). TS, TVS and ash content of FS were determined according to standard methods (APHA/AWWA/WEF, 2012). EC and pH were measured using a calibrated portable meter (Hach HQ30d Flexi model). The TS concentration was determined gravimetrically by taking the weight of an oven dried sample at 105°C for 24 hours and expressed as a fraction of raw sample volume. TVS was determined by taking the weight difference between oven dried solids and the 2-hour muffle furnace ignited sample at 550°C and expressed as a percentage of TS. Ash content was the residue weight after ignition in the furnace at 550°C for 2 hours, also expressed as a percentage of TS. Sand content was determined using the acid method; where ash was washed with 0.1 M HCl solution into ash-less filter papers. The paper and content were ignited in a furnace at 550°C for 2 hours and the residue was taken as sand content, expressed as a percentage of TS. Three replicates were analysed for each sample to attest the reproducibility of the experimental results.

Table 5.1 Characteristics of original faecal sludge samples from pit latrines

Parameter	Unit	Mean values \pm <i>SD</i>
pH		8.77 \pm 0.03
Electrical conductivity	mS cm ⁻¹	7.66 \pm 0.09
Temperature	°C	24.4 \pm 0.6
Total solids (TS)	g/L	31.0 \pm 0.8
Moisture content	%	97.0 \pm 0.1
Total volatile solids (TVS)	%TS	58.6 \pm 0.5
Ash content	%TS	41.4 \pm 0.5
Sand content	%TS	31.2 \pm 5.6
Bulk density	kgm ⁻³	1240 \pm 0.3

Notes: *SD* standard deviation.

5.2.3 Faecal sludge conditioning

Preliminary conditioning experiments were performed on FS by varying sawdust and charcoal dust conditioner dosages from 0, 25, 50, 75 and 125 % (weight of dry conditioner as a ratio of FS dry solids). Sawdust and charcoal dust dosage of 75 % FS total solids had the optimal dewaterability efficiency (for both indicators of dewatering rate and dewatering extent) (Chapter 4). Therefore, in this study, FS was conditioned with sawdust and charcoal dust dosages of 75 % TS. Charcoal dust was obtained from charcoal outlets within Bwaise slum, while sawdust was obtained from a timber sawing mill in the same slum area. Charcoal dust and sawdust particles were sieved to a size less than 2.36 mm to limit variability, oven dried for 24 hours and stored in a vacuum desiccator, for consistency in dry weight during analysis (Luo *et al.*, 2013). The characteristics and particle size distribution of sawdust and charcoal dust are presented in Tables 5.2 and 5.3, respectively.

Table 5.2 Characteristics of physical conditioners (sawdust and charcoal dust)

	Unit	Sawdust	Charcoal dust
Specific gravity		0.065	0.053
Bulk density (loose)	kgm ⁻³	173.9 \pm 10.8	868.5 \pm 7.8
Water content (wet basis)	wt%	18.4 \pm 1.3	11.6 \pm 0.4
TVS	wt%	79.0 \pm 1.0	61.3 \pm 2.2
Ash content	wt%	2.5 \pm 0.6	24.7 \pm 3.1
Gross heating value (dry basis)	MJ kg ⁻¹	19.7 \pm 0.1	23.7 \pm 0.7
Crude protein	mg/g solids	2.6	10.3

Table 5.3 Particle size distribution of sawdust and charcoal dust conditioners

Particle size (mm)	Sawdust		Charcoal dust	
	Mass retained (%)	Cumulative mass passing (%)	Mass retained (%)	Cumulative mass passing (%)
2.360	0.0	100.0	0.0	100.0
1.180	36.6	63.4	31.4	68.6
0.600	37.4	26.0	22.6	46.0
0.425	11.6	14.4	9.4	36.6
0.300	7.2	7.2	8.9	27.7
0.212	3.6	3.6	6.4	21.3
0.150	1.6	2.0	5.2	16.1
0.750	0.8	1.2	7.2	8.9
Pan	1.2	N/A	8.9	N/A

5.2.4 Centrifugation experimental design

A laboratory based electrical centrifuge (MISTRAL1000 type, UK) equipped with four centrifuge cells of 50 mL capacity each, with a respective rotational speed and time limit of 6,000 rpm and 99 seconds was used in the study. The criteria for selection of centrifuge was based on availability and ability to vary rotational speed, rotational time and the volume. Centrifugation experiments were carried out by varying independent variables (factors) of FS volume, rotational speed and time to obtain the dependent variable of percent cake solids (dewatering extent) for different factors. A predetermined FS volume was centrifuged at a particular speed for a known time. The dry solids of the settled dewatered cake obtained at oven temperature of 105°C and expressed as a percentage of wet dewatered cake was taken as per cent cake solids. The following minimum and maximum values of factors were used; volume (30-50 mL), speed (600-1800 rpm, with respective centrifugal accelerations of 60-540 g) and time (10-30 minutes).

Combinations of different factors were determined using the central composite design (CCD) and response surface methodology (RSM) in JMP software package, version 10 (SAS Institute). CCD and RSM were used for constructing and exploring approximate relationships between the independent variables of the centrifugation process (i.e. FS volume, speed and time) and the response variable (per cent cake solids). The mentioned range values for the factors were entered in JMP software and 16 runs were automatically generated (Table 5.4) with different combinations of volume, speed and time.

Table 5.4 Central composite design for experimental variables (volume, rotational speed and time) and response (% cake solids)

Run No.	Volume (mL)	Speed (RPM)	Time (min)	Cake solids (%)		
				Original FS	Sawdust conditioner	Charcoal dust conditioner
1	30	600	10	8.7	11.2	12.1
2	30	600	30	9.1	11.9	14.8
3	30	1200	20	10.9	14.1	18.9
4	30	1800	10	12.3	14.9	17.6
5	30	1800	30	12.0	15.6	16.8
6	40	600	20	9.5	14.0	14.5
7	40	1200	10	10.8	13.4	15.3
8	40	1200	20	11.0	14.1	16.7
9	40	1200	20	14.1	15.3	18.2
10	40	1200	30	12.2	14.9	17.4
11	40	1800	20	13.8	16.7	19.2
12	50	600	10	10.1	12.6	13.6
13	50	600	30	9.5	11.7	14.1
14	50	1200	20	12.2	15.3	17.8
15	50	1800	10	13.2	15.6	15.8
16	50	1800	30	13.2	16.5	19.6

The objective was to maximise the per cent cake solids for the various combinations of independent variables. The values of per cent cake solids shown in Table 5.4 were obtained experimentally for 16 runs of original FS (FS without conditioners), 16 runs (each) of sawdust and charcoal dust conditioned FS. Experiments were carried out using two replicates, hence, each per cent cake solid value reflecting average of the replicates.

5.2.5 Data analysis

Statistical design of experiments and data analysis was performed using the statistical software package JMP, version 10 (SAS Institute) for the regression analysis of the data and to estimate the coefficient of regression equations. The experimental data obtained (Table 5.4) was modelled by the system described through an empirical second-order equation (equation 2). Second order model gives a good estimate of the response surface and can be used to locate optimum response (% cake solids) and at the same time explain the centrifugation process.

$$Y = \beta_0 + \sum_{i=1}^k \beta_i x_i + \sum_{i=1}^k \beta_{ii} x_i^2 + \sum_{i=1}^k \sum_{i \neq j=1}^k \beta_{ij} x_i x_j + \varepsilon \quad (2)$$

Where, Y is the predicted response or dependent variable (% cake solids); β_0 is a constant coefficient (intercept); β_i , β_{ii} and β_{ij} refer to the regression coefficient for linear, quadratic, and interaction effects (between factors i and j), respectively; x_i and x_j are the independent variables (i.e. FS volume, centrifugation speed and time); k is the number of factors (independent variables) and ϵ denotes the random error of prediction (residuals).

The estimates of the model coefficients were calculated by least squares multiple regression. Analysis of variance (ANOVA) was used for model adequacy and analysis of experimental data to obtain the interaction between the independent variables and the response. The statistical significance of the model was checked by Fisher's F-test and the quality of model fit was expressed by the regression coefficient R^2 . The significance of the model terms in equation 2 were evaluated at p -values ≤ 0.05 (95 % confidence interval). The mathematical equations for original and conditioned FS which relate factors and the response were developed. Thereafter, the non-significant model terms ($p > 0.05$) were eliminated to obtain reduced model equations. The validity of the reduced model equations (after dropping the non-significant terms) were checked by computing the model residuals and examining the normal probability plots. A reduced model was considered valid when the residual plots were very close to a straight line (normally distributed). Lastly, canonical curvature analysis was performed to predict the shape of the curve generated by the multiple regression models. Three-dimensional (3D) surface plots and their respective two-dimensional (2D) contour plots were obtained for the original and physical conditioned (sawdust and charcoal dust) FS, based on response (% cake solids) and the independent variables (FS volume, centrifugation speed and time).

5.3 Results

5.3.1 Statistical analysis of models for original and conditioned FS

The regression coefficient (R^2) values for models of original, sawdust and charcoal dust conditioned FS of 0.84, 0.94 and 0.88, respectively, indicate that respective 84, 94 and 88 % of the variations in per cent cake solids (response) can be explained by the factors of FS volume, speed and time. Models for conditioned and original FS used were significant ($p = 0.005$ and 0.034 for sawdust and charcoal dust conditioned FS, respectively) (Table 5.5). The probability of lack of fit (PLOF) for original and conditioned FS were more than 0.05, implying that the second-order model fits the

experimental data well and thus its application is eligible to interpret the response values of per cent cake solids. Additionally, the sawdust conditioned FS model was better explainable by variables because of the higher R^2 and $Adj R^2$. Concurrently, a relatively lower coefficient of variation (CV) for the same model of 11.8 % indicated a more precise and reliable model.

Table 5.5 ANOVA and model fitting results for the response (% cake solids) for original and conditioned FS

	P	R^2	Adj. R^2	CV (%)	RMSE	MOR	PLOF	F-value
Original (FS only)	0.067	0.84	0.61	15.0	1.07	11.4	0.98	0.08
FS + Sawdust	0.005*	0.94	0.85	11.8	0.65	14.2	0.78	0.51
FS + Charcoal dust	0.034*	0.88	0.70	13.3	1.20	16.4	0.57	1.34

Notes: P – probability; PLOF – probability of lack of fit; CV – coefficient of variation; RMSE - root mean square error; MOR – mean of response; *Statistically significant at $p < 0.05$.

The coefficient estimates of the regression terms for original and conditioned FS were obtained from JMP software output (Table 5.6); resulting in the equations (3, 4, and 5) for original, sawdust and charcoal dust conditioned FS, respectively. The response (% cake solids), denoted as Y, while the factors of FS volume, speed and time were coded as x_1 , x_2 and x_3 , respectively.

$$Y=12.16+0.52x_1+1.76x_2+0.09x_3+0.04x_1x_2-0.09x_1x_3-0.01x_2x_3-0.42x_1^2-0.32x_2^2-0.47x_3^2 \quad (3)$$

$$Y=14.99+0.40x_1+1.79x_2+0.29x_3+0.05x_1x_2-0.18x_1x_3+0.23x_2x_3-0.43x_1^2+0.22x_2^2-0.98x_3^2 \quad (4)$$

$$Y=17.75+0.07x_1+1.99x_2+0.83x_3+0.03x_1x_2+0.30x_1x_3-0.03x_2x_3+0.44x_1^2-1.06x_2^2-1.56x_3^2 \quad (5)$$

Table 5.6 Model parameter estimates and ANOVA results for response surface second-order model terms for per cent cake solids

	Model term	Coefficient estimate	Degrees of freedom	Sum of squares	F-value	P-value (P>F)
Original	Intercept	12.16				<0.0001*
	X ₁	0.52	1	2.70	2.34	0.1766
	X ₂	1.76	1	30.98	26.86	0.0020*
	X ₃	0.09	1	0.08	0.07	0.7999
	X ₁ X ₂	0.04	1	0.01	0.01	0.9245
	X ₁ X ₃	-0.09	1	0.06	0.05	0.8254
	X ₂ X ₃	-0.01	1	0.00	0.00	0.9748
	X ₁ X ₁	-0.42	1	0.46	0.39	0.5530
	X ₂ X ₂	-0.32	1	0.26	0.23	0.6502
	X ₃ X ₃	-0.47	1	0.57	0.50	0.5079
FS + Sawdust	Intercept	14.99				<0.0001*
	X ₁	0.40	1	1.60	3.78	0.1000
	X ₂	1.79	1	32.04	75.62	0.0001*
	X ₃	0.29	1	0.84	1.98	0.2085

	Model term	Coefficient estimate	Degrees of freedom	Sum of squares	F-value	P-value (P>F)
	X ₁ X ₂	0.05	1	0.02	0.05	0.8352
	X ₁ X ₃	-0.18	1	0.25	0.58	0.4758
	X ₂ X ₃	0.23	1	0.41	0.96	0.3660
	X ₁ X ₁	-0.43	1	0.50	1.17	0.3201
	X ₂ X ₂	0.22	1	0.12	0.29	0.6102
	X ₃ X ₃	-0.98	1	2.56	6.03	0.0494*
FS+ Charcoal dust	Intercept	17.75				<0.0001*
	X ₁	0.07	1	0.05	0.03	0.8598
	X ₂	1.99	1	39.60	27.49	0.0019*
	X ₃	0.83	1	6.89	4.78	0.0714
	X ₁ X ₂	0.03	1	0.01	0.00	0.9549
	X ₁ X ₃	0.30	1	0.72	0.50	0.5061
	X ₂ X ₃	-0.03	1	0.01	0.00	0.9549
	X ₁ X ₁	0.44	1	0.52	0.36	0.5694
	X ₂ X ₂	-1.06	1	2.94	2.04	0.2034
	X ₃ X ₃	-1.56	1	6.38	4.43	0.0801

Notes: * statistically significant at $p < 0.05$

When the significance of each term's contribution to the three model equations (3, 4 and 5) was determined, it suffices to note that the intercept coefficient terms for all the three models were highly significant ($p < 0.0001$ for equations 3, 4 and 5, each). The linear coefficients of speed significantly contributed to % cake solids for all the three models ($p = 0.0020$, 0.0001 and 0.0019 for original, sawdust and charcoal dust conditioned FS, respectively). However, the quadratic effect of time had significant contribution ($p = 0.0494$) to % cake solids for only sawdust conditioned FS.

After elimination of non-significant terms, reduced model equations for original and charcoal dust conditioned FS were still valid, since residual plots were close to a straight line (Appendix B). Unlike for sawdust conditioned FS, the significant terms of speed and time² had plots quite away from the straight line. An adjustment was therefore made to avoid eliminating the terms for speed² and the interaction of speed and time. This produced a plot, where the residual plots were very close to the straight line (Appendix B). After eliminating model terms and checking for validity, the following reduced equations 6, 7 and 8 for original, sawdust and charcoal dust conditioned FS respectively were generated. These can be reliably used to produce % cake solids for different factor consideration.

$$Y = 12.16 + 1.76x_2 \quad (6)$$

$$Y=14.99+1.79x_2+0.23x_2x_3+0.22x_2^2-0.98x_3^2 \quad (7)$$

$$Y=17.75+1.99x_2 \quad (8)$$

5.3.2 Effects of parameters on process optimisation

The regression model equations were graphically represented on three-dimensional (3D) surface and two-dimensional (2D) contour plots for the original, sawdust and charcoal dust conditioned FS from pit latrines. This was to visualise the relationship between interaction of independent variables and the corresponding per cent cake solids yield under these conditions.

When the original FS was centrifuged under varying conditions of volume, speed and time, the mean of % cake solids for all runs was 11.4 % (Table 5.5). Increase in time from 5 to 20 minutes at volumes of 20 mL or speed of 400 rpm only improved cake solids from 8 to 9 %. Increase in volume (40-50 mL) by about twice at the same time of 20 minutes increased cake solids from 8 to 12.3 % (Figure 5.1). Time increase beyond 20 minutes generally reduced the per cent cake solids. The converging of contours reflected interactions between; volume and time (elliptical contours reflect a perfect interaction between volume and time), volume and speed; and time and speed, although the interactions were not significantly changing the per cent cake solids ($p > 0.05$). However, visualising the way the various factors influence the dewatering process helps to improve the centrifuge design.

Furthermore, at optimal rotational time of 20 minutes and volume of ~ 45 mL, the average % cake solids of 11.4 (Table 5.5) could be achieved at a speed of 920 rpm. Increase in speed from 400 to 2000 rpm linearly improved % cake solids at slight quadratic effects of volume and time (Figure 5.1b and c). Similarly, increasing speed from 920 to 2000 rpm at constant time of 20 minutes improved % cake solids from average of 11.4 to 14.1 % (Figure 5.1c).

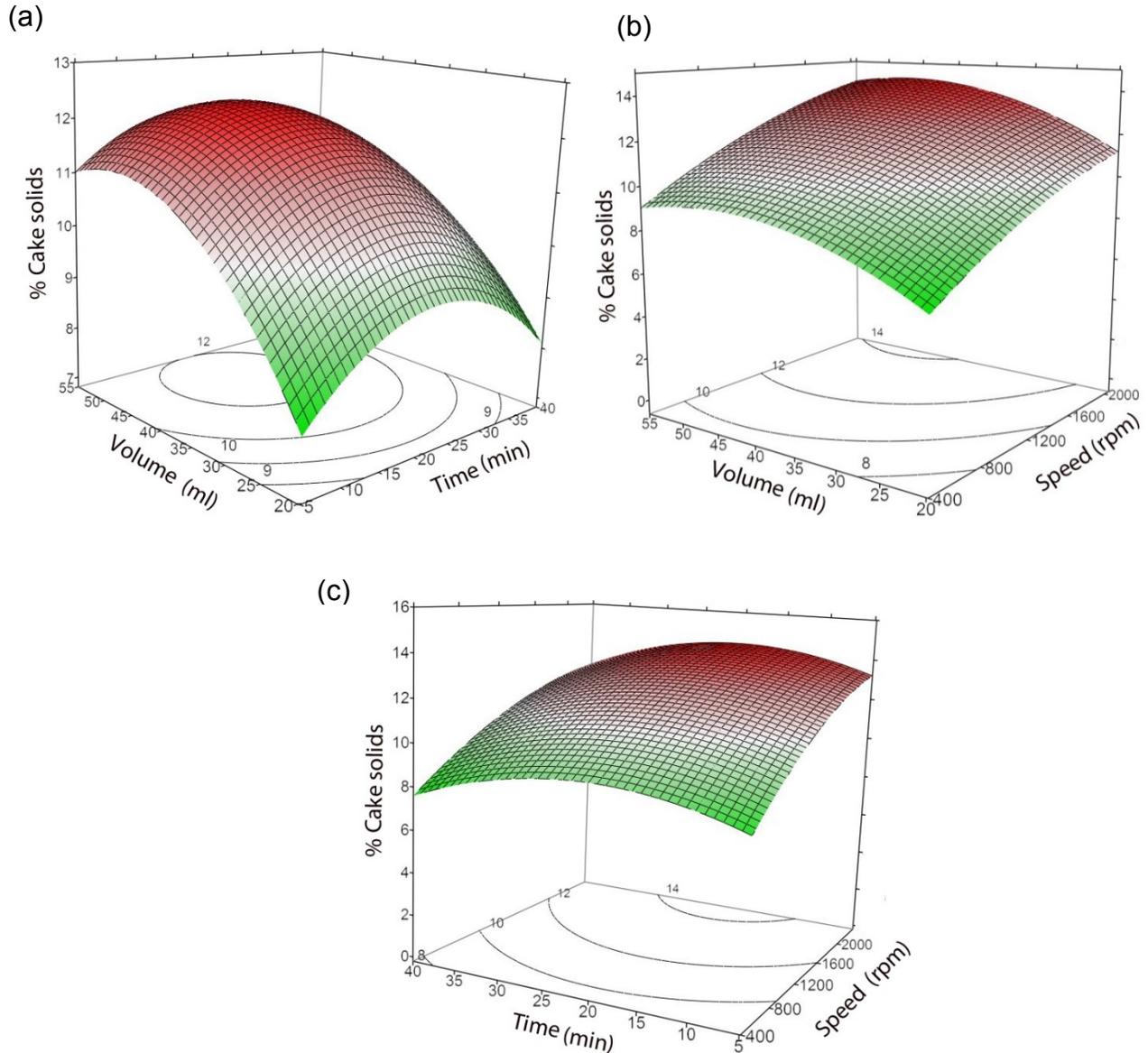


Figure 5.1 Three-dimensional surface plots of per cent cake solids for unconditioned FS from lined pit latrine (original) as a function of: (a) volume and time; (b) volume and speed; (c) time and speed. Below each graph is a 2D contour plot showing interaction between the two variables.

When 75 %TS dosage of sawdust conditioner was mixed with FS, the mean of % cake solids for all runs increased to 14.2 %. Increase in time at volumes of 20 mL or speed of 400 rpm improved cake solids from 9.3 to 12.5 % from 5 to 20 minutes, respectively. Increase in volume (40-50 mL) by about twice, at the same time of 20 minutes, increased cake solids from 9.3 to 15 % (Figure 5.2a). Time increase beyond 20 minutes generally reduced the per cent cake solids. The 2D contours reflect some interactions between; volume and time (also, the elliptical contours reflect a perfect interaction

between volume and time), volume and speed; time and speed. The speed and quadratic effect of time were significantly contributing to the per cent cake solids for sawdust conditioned FS ($p = 0.0001$ and $p = 0.0494$, respectively). At optimal time of 20 minutes and volume of ~ 45 mL, the average per cent cake solids of 14.2 (Table 5.5) could be achieved at speed of 890 rpm. Similarly, the 11.2 % cake solids at a rotational speed of 920 rpm in the original FS can be achieved at virtually no rotation, but only through sedimentation or absorption effect. Increase in speed from 400 to 2000 rpm linearly improved per cent cake solids at slight quadratic effects of volume and time (Figure 5.2b and c). Similarly, increasing speed from 890 to 1800 rpm, at a constant time of 20 minutes, improved per cent cake solids from average of 14.2 to 17.0 % (Figure 5.2c).

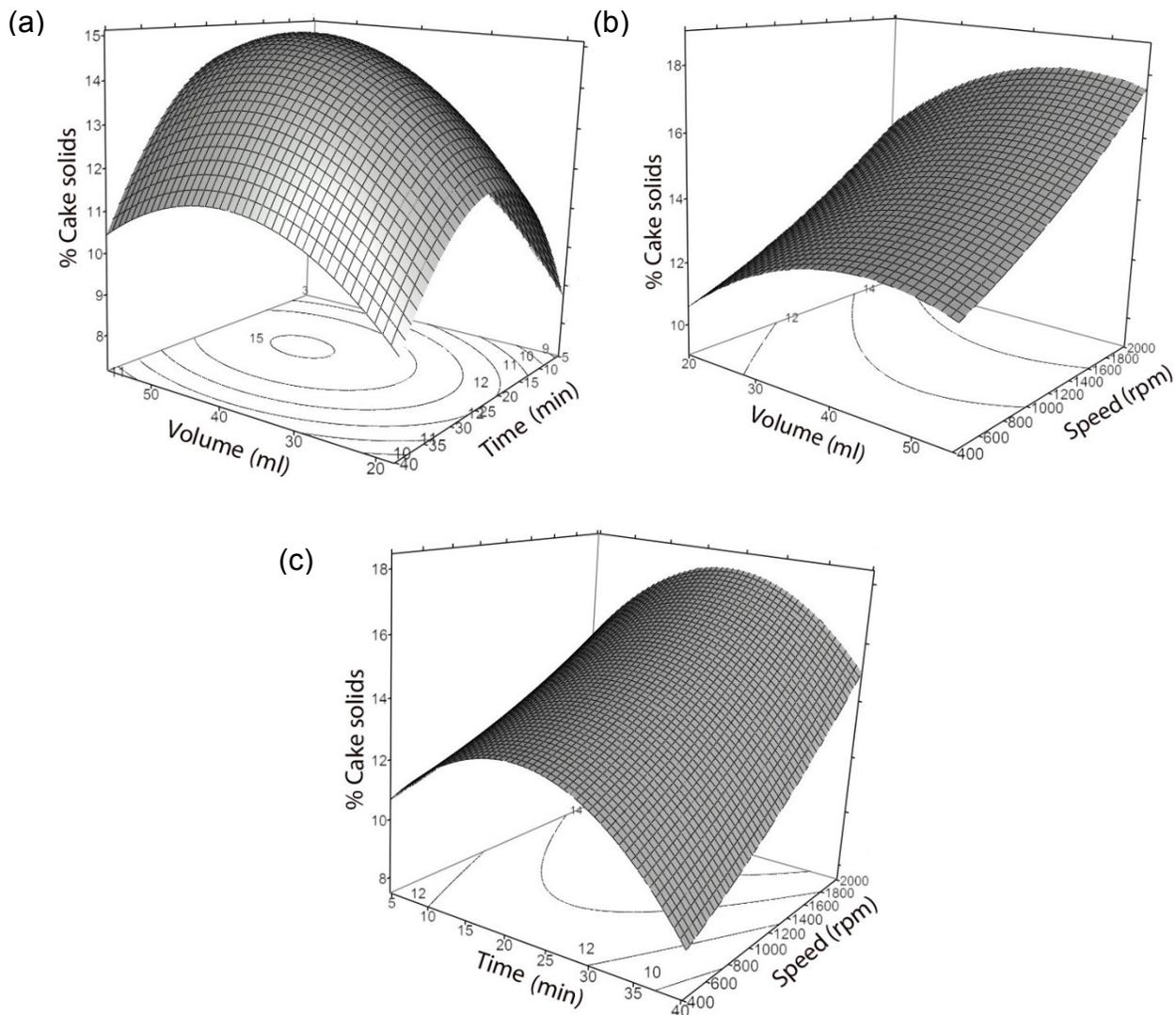


Figure 5.2 Three-dimensional surface plots of per cent cake solids for sawdust conditioned pit latrine FS as a function of: (a) volume and time; (b) volume and speed; (c) time and speed. Below each graph is a 2D contour plot showing interaction between the two variables.

A 75 % TS dosage of charcoal dust conditioner mixed with FS increased the mean of per cent cake solids for all runs to 16.4 % (Table 5.5). Per cent cake solids increased at lower and higher volumes, with the least observed values at intermediate volumes at all times. However, the maximums at lower (<30 mL) and higher volumes (>42 mL) and minimum at intermediate volume (35 mL), all occurred at time of 20 minutes (Figure 5.3a). Thus, some interactions of volume and time were realised at lower and higher volumes, although not significant ($p = 0.506$). A similar effect on volume interaction with speed was observed at lower and higher volumes ($p = 0.955$), with a saddle point at 35 mL. Higher cake solids (>20 %) were achieved at a speed of 1600 rpm with lower or higher volumes (Figure 5.3b). There was an almost perfect interaction between speed and time (elliptical contours), though it was not significant ($p = 0.954$). The quadratic effect of time was reflected; with the maximum being 20 minutes. The optimum cake solids of 13.3 % could be obtained at maximum time of 20 minutes at volume and speed of 35 mL and 400 rpm, respectively. However, cake solids increased to an optimum of 18.7 % at a speed of 1600 rpm, beyond which per cent cake solids decreased.

At optimal time of 20 minutes and volume of 35 mL, the average per cent cake solids of 16.4 (Table 5.5) could be achieved at speed of 870 rpm. Consequently, increasing speed from 870 to 1600 rpm at constant time of 20 minutes improved per cent cake solids from average of 16.4 to 18.6 % (Figure 5.3c). For comparison with the original FS, average 11.2 % cake solids at speed of 920 rpm can be achieved at about 160 rpm, when conditioned with charcoal dust.

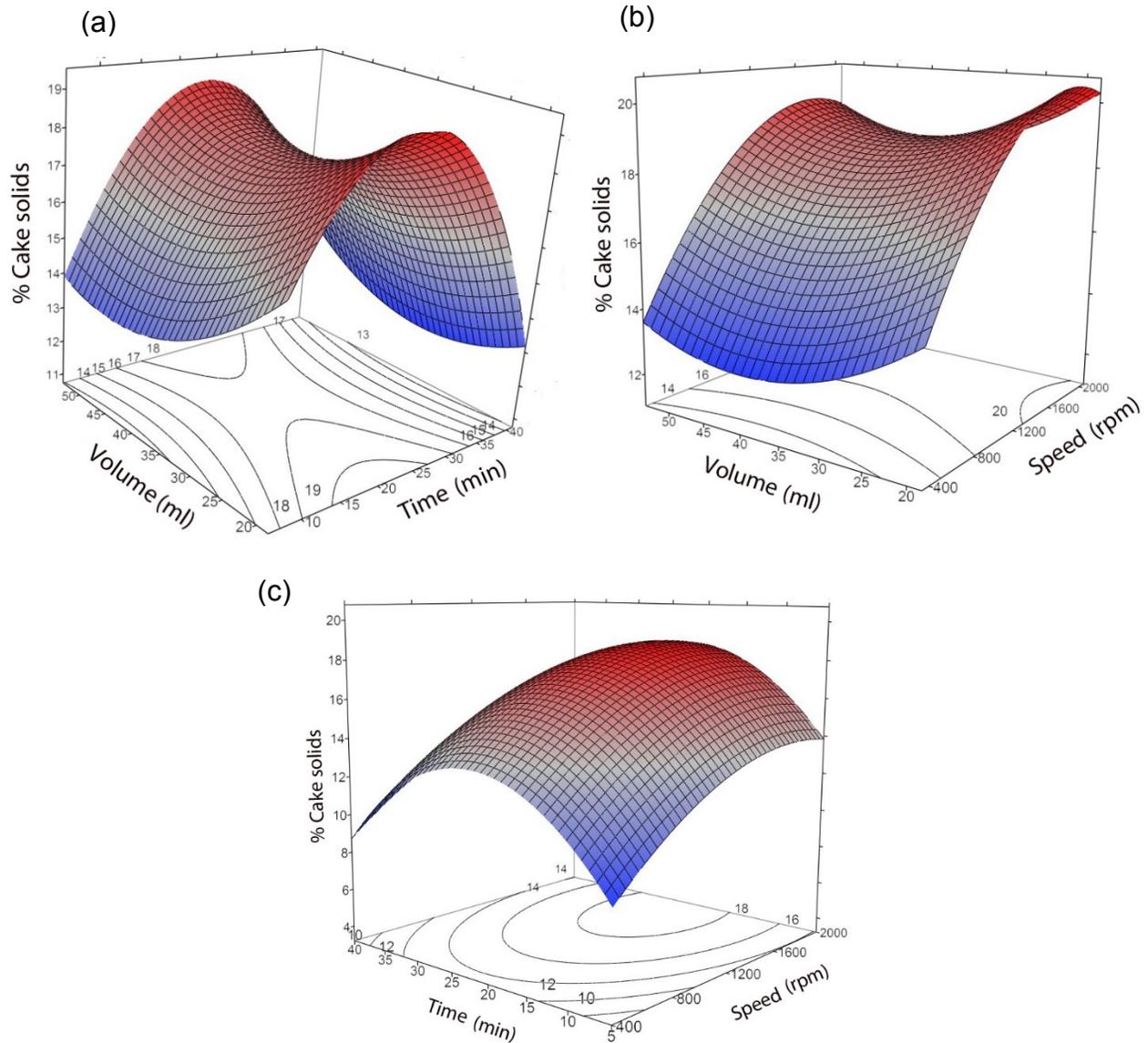


Figure 5.3 Three-dimensional surface plots of per cent cake solids for charcoal conditioned FS from pit latrine as a function of: (a) volume and time; (b) volume and speed; (c) time and speed. Below each graph is a 2D contour plot showing interaction between the two variables.

5.4 Discussion

5.4.1 Use of sawdust and charcoal dust conditioners in centrifugal dewatering of FS

The average per cent cake solids for original FS, sawdust and charcoal dust conditioned FS were 11.4, 14.2 and 16.4, respectively. Per cent cake solids increased by 24.6 and 43.8 % when conditioned with 75 %TS of sawdust and charcoal dust, respectively. The cake solids increase in FS conditioned with charcoal dust is much higher than the observed 28.2 % increment by Albertson and Kopper (1983), when sewage sludge was conditioned with coal fines. The interaction effects

for volume and time in original and sawdust conditioned FS signified sedimentation of particles with time. However, the quadratic effect of time, where it takes 20 minutes for cake solids to increase to maximum and thereafter decreases, was significant for sawdust conditioned FS. Centrifugation beyond 20 minutes resulted in re-suspension of settled solids probably due to high absorptive nature of sawdust (Lin *et al.*, 2001; Luo *et al.*, 2013). The result therefore suggests that sawdust significantly re-absorbed moisture during batch centrifugation to decrease the per cent cake solids after 20 minutes. Therefore, the quadratic effect of time needs to be considered during the operation of a centrifuge by limiting centrifugation time.

The use of sawdust and charcoal dust conditioners improved the cake solids recovery due to water absorption and increased porosity of FS cake. The decrease in moisture content of conditioned FS cake after dewatering is comparable to that of sewage sludge cake, when sawdust and coal fly ash additives were increased from 0 to 100 % (Lin *et al.*, 2001; Chen *et al.*, 2010; Ding *et al.*, 2014). The particles of sawdust/charcoal dust are bridged between FS solids, creating voids for water to flow out of the cake. This improvement in porosity makes subsequent management options for separated FS solid and liquid streams simpler. For example, the drying process of solid fraction quickens, since the convective heat from surrounding air could easily be conducted to the interior of the FS cake, thus increasing the interior temperature which affects the diffusion of water and vapour from the interior to the surface, and later evaporated to the ambient (Lei *et al.*, 2009). This can be achieved by conventional drying of FS on sand beds, enhanced by greenhouse effect or use of solar dryers (Murray Muspratt *et al.*, 2014). The later enhanced technologies could be more feasible in an urban slum setting due to space limitations. Further, the improved porosity of FS cake can enhance the composting process through increased internal spaces for air flow (Lin *et al.*, 2001). Subsequently, usage of sawdust/charcoal dust conditioned FS as an organic soil amendment improves soil productivity, not only because of nutrients present in FS, but also increased aeration and water holding capacity of soils due to improved porosity (Kelley & Martens, 1984).

5.4.2 Effect of rotational speed on cake solids yield

Generally, the higher the centrifugation speed, the more the centrifugal acceleration and hence faster sedimentation rate of solids for the original and sawdust/charcoal dust conditioned FS. This is in agreement with a study by Garrido *et al.* (2003) who reported increased sedimentation with

centrifugation rotational speed. In addition, conditioned FS contains larger and more particles than original FS (Table 5.3), hence the increased sedimentation rate of conditioned FS, since larger particles tend to settle out quicker (Chu & Lee, 2002). Moreover, the particles of sawdust and charcoal dust are bridged between the original FS particles. These break the capillary water between FS particles, hence, creating voids (Schubert, 1984).

Further rotational speeds set up centrifugal compaction of settled solid particles causing more water to be released, hence the observed drier cake after physical conditioning with sawdust/charcoal dust. However, charcoal dust conditioned FS yielded dryer cake solids than sawdust (16 and 14% cake solids, respectively) at similar rotational speeds. This could be because the density of charcoal dust (869 kgm^{-3}) is much higher than that of sawdust (174 kgm^{-3}) (Table 5.2), since Vesilind and Zang (1984) reported centrifugal compaction to be a function of particle density. Hence, more compaction takes place in charcoal dust conditioned FS and consequently more per cent cake solids yield. Therefore, the observed increase in per cent cake solids with speeds in original and sawdust conditioned FS could be due to increasing compaction of FS cake. An interesting result is for charcoal dust conditioned FS, where an optimum speed of 1600 rpm occurred, beyond which per cent cake solids reduced. The higher density of charcoal dust particles could have caused the sedimentation and compaction processes to be completed by this speed. FS conditioning results therefore depict increased capacity of centrifuges to handle more FS volumes and hence significant reductions in space requirements in urban slums.

5.4.3 Implications on faecal sludge management in urban slums

A typical centrifuge is known to consist of a rotor, spin by a drive motor which is powered by electrical supply that makes it to rotate (Gutierrez, 2005). The observed reduced centrifugation speeds after modifying FS properties with the sawdust/charcoal dust conditioners can be realised by hand-powered centrifuge devices. Here, a user physically spins the device and energy is transformed into rotation of the rotor through gears. This could help in dewatering of FS from slum areas that are not supplied with electricity, or where the use of electricity to run the centrifuge is more expensive as compared to hand-powered. In some cases, cycle-powered centrifuge devices could also be appropriate, where the pedalling actions of bi/tricycles are transformed into rotor motion. Never-the-less, hand/cycle-powered centrifuge devices could become energy intensive in times

where people have to operate them for long durations, owing to large volumes of emptied FS. In such cases, the centrifuge design could be modified to allow a 12 volts DC battery power source (Turvaville *et al.*, 1999) to rotate the devices in slum areas. The DC battery can be recharged from places with electricity and used for running centrifuge or usage of DC solar batteries charged by solar panels could be appropriate since solar energy is available in most of the low-income countries. Local fabrication of hand/cycle powered centrifuge devices can provide a low cost technology that is easily adoptable by low-income urban slum population.

After centrifugation, the separated liquid fraction (centrate/leachate) could be further treated in a low-cost crushed filter (sand, soil or lava rock) unit such as that developed by Katukiza *et al.* (2014a) to reduce the pollutant loads from wastewater in urban slums. The treated centrate is likely to suit non-portable purposes such as irrigation of tower gardens for urban agriculture (Kulabako *et al.*, 2011), or mortar additive for construction purposes (Katukiza *et al.*, 2014a). This has the potential to improve health and increase environmental protection that would otherwise emanate from indiscriminate disposal of untreated FS in a slum environment. The dewatered solid fraction can be transformed into a number of products utilisable by the slum population (Chapter 2).

Implementation of centrifugation technology in dewatering FS at household or community level in slums requires FS emptying and treatment of the separated FS streams, before and after centrifugation, respectively. People/slum dwellers are involved during execution of these activities at all stages of emptying, dewatering and treatment/end-use of liquid and solid streams. Since raw emptied FS contains high pathogen load (Still & Foxon, 2012), this poses health risks to the users of the centrifugation technology. Therefore, a need for further investigation on the fate of pathogens such as *E.coli* and helminth eggs across centrifugal dewatering process in an urban slum setting is necessary in order to protect the operators of this process and subsequent processes/handling and/or reuse downstream.

5.5 Conclusions

The centrifugation rotational speed has been identified as a key design parameter. In addition, the centrifugation time significantly influenced dewatering of sawdust conditioned FS. The effect of time on percent cake solids yield was quadratic, with an optimum value at 20 minutes.

Centrifugation beyond this time further reduced per cent cake solids due to re-absorption of moisture by the dewatered cake conditioned with sawdust/charcoal dust.

When FS was conditioned with charcoal dust, the saddle point created at midway volumes (35 to 40 mL) suggested that operating a centrifuge when full or less than half-full would yield higher cake solids. For original and sawdust conditioned FS, optimum cake solids were obtained between volume of 40 to 45 mL. Therefore, making the centrifuge container full lowered the per cent cake solids. Charcoal dust conditioned FS exhibited an optimum per cent cake solids yield at a speed of 1600 rpm, but cake solids were linearly increasing with speed for original and sawdust conditioned FS. Rotational speed required to achieve a certain per cent cake solids reduced with addition of sawdust and charcoal dust. Such low rotational speeds can be achieved by hand/cycle powered centrifuge devices, fabricated locally, thereby, providing a low cost technology adaptable for dewatering FS in low-income urban slums. The next stage is to develop a pilot-scale centrifuge unit and test it with FS from sanitation facilities commonly used by urban slum dwellers, such as pit latrines.

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CHAPTER SIX

6 General Discussion

6.1 Introduction

Poor and inadequate sanitation has remained one of the key challenges in slums of low-income countries and is responsible for increased risks to public health and environmental pollution (Fuhrimann *et al.*, 2014). Proper management of FS can improve sanitation of urban slum dwellers through reduced faecal contamination into the environment (Lilford *et al.*, 2016). The chemical oxygen demand (COD) of FS from pit latrines is very high (65,521-132,326 mg/L) (Chapter 3) compared to that of greywater from slums (2,000-6,000 mg/L (Katukiza *et al.*, 2015)) and is much higher than the acceptable discharge standard of COD<100 mg/L by NEMA (Uganda). This is an indicator of a very high pollution potential, when untreated FS is discharged onto land or in surface water open drainage channels within slums, as often practiced. Exposure to surface water open drainage channels has been reported to be the highest contributor to measured disease burden of 680 disability-adjusted life years (DALYs) per 1000 persons per year in Bwaise III slum, Kampala (Katukiza *et al.*, 2014b). In addition, inadequate access to sanitation is responsible for disease burden of 40 and 17 DALYs per 1000 persons per year for sanitation workers and children living in slums on Kampala, respectively (Fuhrimann *et al.*, 2016).

Limited interventions in sanitation improvement in Kampala slums, by the municipality (*e.g.* Kampala Capital City Authority, KCCA, Uganda), non-governmental organisations (NGOs), and others, have mainly focused on provision of sanitation facilities such as public pit latrines. This is in addition to privately owned household pit latrines, although access to these facilities is still inadequate (Tumwebaze *et al.*, 2013). The high user loads of the existing inadequate pit latrines in slums due to high population density of over 50,000 persons per km² (Section 1.5) has increased the filling rates. This creates the need for frequent emptying and subsequent treatment of the FS in these facilities.

Similarly, minimal interventions have been made towards management of FS along the service chain of emptying, transportation, treatment, end-use and/or disposal in slums. This is a major challenge, mainly in slum areas where full sanitation facilities are not accessible by the commonly used equipment such as vacuum trucks due to limited access. An NGO; Water For People (WFP)

developed an emptying technology known as the *gulper* (Figure 6.1A), which, after testing in Tanzania, South Africa and Uganda proved to be successful in emptying dense FS from lined and unlined pits in slum areas inaccessible by vacuum trucks (Still, 2012). The business of FS emptying and subsequent transportation using various means such as pick-up trucks and tricycles, in Kampala, has been ventured into by companies such as *Sanitation Solutions Group* and other private entities (Figure 6.1B). However, these have singled out transportation as the most expensive part, covering 65 % of the total expenses and costs are directly borne by the slum dwellers (Sanitation solutions, 2015). The low ability to pay for such sanitation services by the slum dwellers results into unhygienic practices of improper disposal of FS (Murungi & van Dijk, 2014; Ezeh *et al.*, 2016).

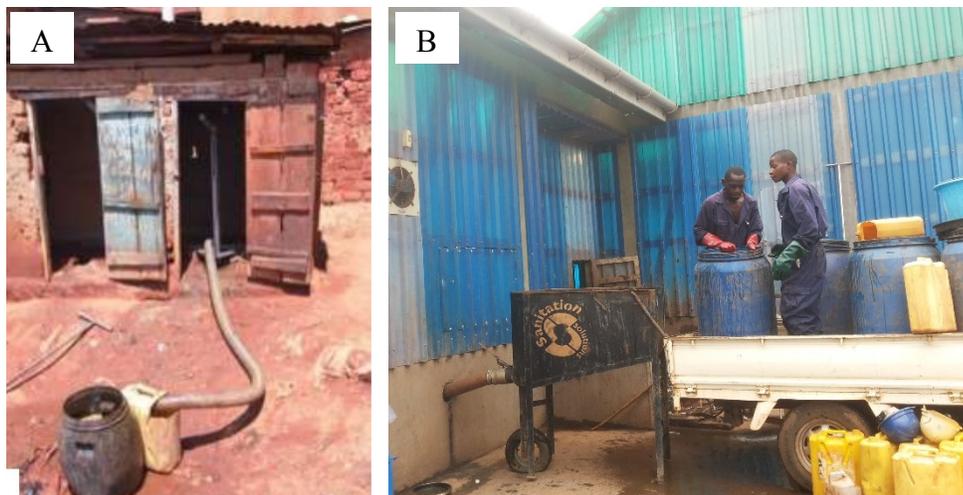


Figure 6.1 (A) The gulper emptying a pit latrine in Kampala (WFP, 2014) and (B) a truck transporting FS to a wastewater and faecal sludge treatment plant in Lubigi (Kampala, Uganda). FS is discharged into the plant through an inlet designed by Sanitation Solutions Group.

6.2 Decentralised faecal sludge management to support end-uses in urban slums

The decentralising of FSM services and recovery of resources for beneficial use by slum dwellers helps to minimise transportation costs and may potentially increase the amount of FS collected from sanitation facilities (Chapter 2) due to increase in accessibility and improved FS valorisation (Schmitt *et al.*, 2016). For example, Lusaka Water and Sewerage Corporation in Zambia delegated Kanyama Water Trust (KWT), a community based organisation (CBO) in Kanyama peri-urban slum (Lusaka-Zambia) to manage FS at a decentralised level. KWT managed to empty over 600 pit latrines (500 m³ of FS) in 17 months using manual emptiers with simple modified garden tools, and

further transported the FS to transfer stations within the vicinity of the slums by help of hand carts at 60 USD for 1.44 m³ (Mikhael & Drabble, 2014; Holm *et al.*, 2015).

However, FS amounts collected can be increased if emptying and transportation costs are lowered through transformation into valuable products such as energy briquettes, soil conditioner, animal protein, biogas and construction material (Chapter 2). These products can be sold and the revenue generated can subsidize the emptying costs. Lowering emptying costs is pertinent, since maintenance of full pit latrines such as those in Kampala slums is mainly a responsibility of landlords, who mainly reside in affluent areas outside the slums (Tumwebaze *et al.*, 2013). Since the landlords' aim is to maximise profits from the rented housing units, little attention is paid to servicing of full pits, leaving them full and hence, worsening the sanitation conditions for the slum dwellers (Katukiza *et al.*, 2010). Once resources/products from FS are acceptable and profitable to the slum dwellers, trading in them could increase the amounts of FS emptied from sanitation facilities in slums and promote safe management. *Sanivation* (<http://www.sanivation.com/>), an NGO in Naivasha (Kenya) which produces briquettes from FS and realises income through sales to slum dwellers and neighbouring communities, who have accepted to use the briquettes made out of FS as cooking fuel.

FS can be emptied and processed from slum areas and resources recovered from it can be utilised outside the slums, where the demand is high. An example is a project called Faecal Management Enterprises (FaME) that was conducted in Kampala and Dakar (Senegal) in 2011-2013. Here, FS use as an industrial fuel was successfully piloted in model clay and cement kilns and the outputs of FS use as fuel were comparable to those of commonly used biomass fuels. However, the study estimated the available FS quantities from FS treatment plants in Kampala to be too low compared to the available market in industries, when such a project is scaled up (Gold *et al.*, 2014). Since 60 % of Kampala population resides in slums (UN-HABITAT, 2007), where over 70 % of pit latrines are full and remain unemptied (Nakagiri *et al.*, 2015) due to lack of proper access for mechanical emptying trucks, decentralised FS management would help increase emptied quantities for reuse, to rectify such an envisaged challenge.

6.3 Characteristics of faecal sludge from sanitation facilities in urban slums

Urban slums in many SSA countries such as Uganda, Kenya, Rwanda, Tanzania, Malawi, South Africa and Zambia depend on both lined and unlined pit latrines for excreta disposal (Nakagiri *et al.*, 2016). The intrinsic characteristics of FS from pit latrines can inform the potential management option (s). FS from lined pit latrines had significantly high levels of moisture compared to that from unlined pits (chapter 3). The unlined pits leach out the water in FS, provided the pit is above the water table and the surrounding soil is permeable. However, the moisture content of FS from unlined pit latrines in this study (83.4 %) is comparable to that of fresh excreta (faeces and urine) of about 81 % (Nwaneri, 2009). This means that a number of sampled unlined pit latrines in urban slums had little leaching effect into surrounding soils, probably because soils are clogged or are of low permeability. Nyenje *et al.* (2013) reported clay soil and shallow water table in Bwaise slums. The clay soils could impede infiltration of leachate from unlined pit latrines while the shallow water table in such slums present a high risk of groundwater pollution. FS from unlined pit latrines in South Africa is reported to contain moisture content as low as 70 % (Still & Foxon, 2012). Such FS can be treated for subsequent disposal/reuse without a dewatering step.

The solids concentration in matrix of FS from both lined (51.4 g/L) and unlined (177 g/L) pit latrines reflects a potential for recovery of large quantities of bio-solids (Chapter 3). Bio-solids are of great importance for resource recovery/reuse, since, most products from FS are generated from the solid fraction (Chapter 2). Similarly, the high sand content in FS from unlined pit latrines (>50% TS) (Chapter 3) leads to increase in porosity, creating easy water movement and hence, FS dries quicker on sand beds/solar dryers. Shortage of space in slums call for usage of solar dryers, since they enhance drying through the trapping of solar energy and require a small area. The subsequent use of FS is influenced by the type of pit latrine. Therefore, the highly degraded FS from unlined pit latrines reflected by relatively low COD/TVS ratio of 2.0 is correlated to low calorific value and bio-methane potential, hence low energy recovery potential. Therefore, transformation of this FS category into products/resources where volatile solids is not a prerequisite *e.g.* construction material and soil conditioner, could be appropriate. FS from unlined pits in South Africa is buried as a soil conditioner in deep row trenches and vegetation planted next to trenches to uptake nutrients from the FS (Still & Foxon, 2012). Another example is from Kanyama (Zambia), where FS from unlined pits is processed into soil conditioner, bagged and sold to farmers (Mikhael & Drabble, 2014).

However, the recovery of soil conditioner from FS has been regarded non-profitable, mainly from urban slums, where minimal farming is practiced (Chapter 2). Therefore, the use of lined pit latrines, not only safely contains FS to prevent pollution, but also produces FS with high TVS, thereby increasing prospects for energy recovery from FS.

6.4 Emptying technologies of pit latrines in urban slums

Over 66 % of the existing pit latrines in Kampala slums are full and overflowing (Nakagiri *et al.*, 2015). Full pit latrines worsen the problem of poor human excreta disposal into the surrounding environment and the higher user loads on the remaining facilities lead to increase in fill up rates. Unlike unlined pit latrines, the high moisture content of 92 to 98 % of FS from lined pit latrines in this study (Chapter 3 and 4), makes it easier for emptying by mechanised vacuum technologies. Public pit latrine FS in many towns of Ghana is reported to have moisture content of a similar range to that from lined pit latrines in this study and is emptied by vacuum cesspool emptier trucks (Appiah-Effah *et al.*, 2014). However, lack of access paths for mechanised vacuum cesspool trucks in many urban slums could promote use of *vacutags* and the *eVacs* (Figure 6.2), which are vacuum-based technologies, powered by generators to empty FS from the pits (Still, 2012). These can easily be moved from one location to another in urban slums. In addition, the high moisture content of FS from lined pit latrines also support the use of manually-powered *gulper* technology (Figure 6.1), which is a low-cost technology, since it does not require fuel to operate and can easily be moved from one location to another.



Figure 6.2: *Vacutag* (left) and the *eVac* (right) for vacuum emptying of FS in areas with narrow streets (Still, 2012)

The relatively low moisture content (83 %) of FS from unlined pit latrines (Chapter 3) does not permit usage of vacuum emptying technologies, unless large amounts of water are added to fluidise FS in the pits. It is expensive to add water, yet it has to be removed during the first step of treatment referred to as dewatering. Indeed, water coverage in many slum areas is low and where available, is expensive (Katukiza *et al.*, 2012), which eventually leads to an expensive emptying process. This is worse for FS from unlined pits, which is much dryer than the one observed in this study (moisture content less than 83 %). Such FS was found in slums, but not considered in this study, since the major focus was on dewatering, thus considering low moisture FS to be already dewatered in due course of infiltration into the surrounding soils (Chapter 3). Such dewatered FS has been reported in latrine facilities in South Africa, Zambia and Malawi. From these countries, FS has been emptied by removing a manhole cover or breaking part of the pit, to gain access to pit content. Modified garden tools such as rakes and shovels with long handles are then used to remove FS from pits and empty into drums for subsequent transportation (Still, 2012; Holm *et al.*, 2015).

In addition, limited road access in slums does not only affect pit latrine emptying, but also solid waste management, mainly collection and transportation. This has caused slum dwellers to dispose of solid waste in pit latrines, thus worsening the filling problem (Katukiza *et al.*, 2012; Nakagiri *et al.*, 2015). A study by Zziwa *et al.* (2016) reported FS from slums to be composed of 20 to 40 % solid wastes such as clothes, polyethylene bags, blankets, sanitary pads, diapers, old batteries, glasses and paper. The deposition of solid wastes in the pits should be discouraged, by for instance, awareness raising on latrine practices, followed by monitoring and law enforcement to ensure that solid wastes are managed separately from pit latrine FS. However, the urban authorities have to put in place appropriate solid waste management measures such as temporary storage facilities and frequent collection of the stored wastes. The presence of solid wastes in FS increases risks of blocking pipes of vacuum technologies and unblocking them is reported to be time consuming and labour intensive (Still, 2012). Therefore, solid wastes have to be raked out before vacuum emptying and this has been reported to hike the emptying costs by about 15 % (Murungi & van Dijk, 2014). This partly explains why emptying FS from slum areas with limited access is costly. Actually, the most feasible emptying technology in such settings which is manual emptying aided with modified garden tools has always been more expensive than using vacuum cesspool trucks. For example, emptying with a vacuum cesspool truck costs about 13 USD/m³, while manual emptying aided with

garden tools or *gulper* in Lusaka (Zambia), Lilongwe (Malawi) and Kampala costs about 42 USD/m³. Unfortunately, people in such settings are poorer, living with many full pit latrines, mainly because, emptying charges required are extremely high. Therefore, decentralised FS management with a focus on valuable resource recovery in slums could help in generating revenue that could incentivise the less privileged parts of the FS management service chain such as emptying (Chapter 2). This is because slum dwellers would see their FS as a resource and as a result manage it properly in anticipation of financial benefits. For example, it is anticipated that one proper management strategy would be to avoid depositing solid wastes in the pit latrines.

6.5 Treatment of faecal sludge from urban slums

In centralised treatment, FS goes through screening pre-treatment to remove large sized solid wastes, often deposited in sanitation facilities. Thickening is then practiced to increase the solids concentration, followed by dewatering to separate FS into solid and liquid fractions for further treatment or stabilisation (Ronteltap *et al.*, 2014). However, treatment technologies at decentralised level in slums would differ from the commonly applied centralised ones, due to lack of space and difference in FS characteristics. The presence of large amounts of solid waste in FS from urban slums (Section 6.4) requires screening using a mesh of 5 mm aperture (Chapter 3). The screenings could be managed through drying and subsequent incineration. However, as explained above (Section 6.4), the combined improvement of solid waste collection, alongside FS management, is likely to result into FS with less solid wastes, which can likely eliminate this challenge. It is also hoped that when FS is viewed as a resource, solid waste disposal into pit latrines would be avoided as this would reduce the quality of FS.

Conventionally, FS is thickened to increase the solids concentration after screening (Dodane & Bassan, 2014). FS, mainly from septic tanks has been reported to increase in solids concentration, after thickening, from 12-35 gTS/L to 60-70 gTS/L for 7 days in Dakar (Senegal), while 150 gTS/L has been achieved in Accra (Ghana), after 8 weeks of thickening (Strauss *et al.*, 1998; Dodane & Bassan, 2014). The presence of high TS content in FS from lined (51.4 ± 29.2 g/L) and unlined pit latrines (177 ± 78.1 g/L) in this study (Chapter 3) reveals no need of the thickening stage since TS concentration of FS from pit latrines is in the range of observed TS after thickening.

Additionally, the TS concentration of FS from lined pits increased from 32 gTS/L to 56 gTS/L after optimal sawdust/charcoal dust conditioner dosage of 75% TS (Chapter 4). Such physical conditioning further increases the total solids concentration of FS, which further justifies the elimination of thickening stage in the treatment of physically conditioned FS from lined pit latrines in urban slums. Consequently, the capital costs, space, time and labour required for construction and operation of the thickening tanks for FS from pit latrines from Kampala slums would not be necessary, hence, reduction in the steps essential for decentralised FS treatment.

6.5.1 Dewatering of faecal sludge from urban slums

High moisture content of FS from lined (92.4 ± 1.5 %) and unlined (83.4 ± 5.0 %) pit latrines in this study depicted a need to consider dewatering as a pertinent stage in treatment of FS, mainly from lined pit latrines (Chapter 3). In this study, dewaterability or dewatering performance was indicated by two variables; that is dewatering rate (the rate at which water filters out of the FS/water matrix) and dewatering extent (per cent cake solids in the FS sludge cake, after dewatering by centrifugation). The results showed that the dewatering rate of FS from lined and unlined pit latrines was not significantly different (Chapter 3), although about 4 times higher compared to that of sewage sludge (Lee & Liu, 2000). This implies that the water takes longer time to filter out of FS, which is disadvantageous for decentralised FSM in slums since it translates into large space requirement as a result of long FS processing times. Therefore, ways of improving the dewatering rate of FS from pit latrines are necessary, as discussed in section 6.5.2.

On the other hand, the dewatering extent of FS from unlined pits (31.8 %) was higher than that of lined pit latrines (18.6 %) (Chapter 3). Results from centrifuge dewatering experiments showed that TVS and sand content were the most dominant FS characteristics affecting dewatering extent of FS from lined pit latrines ($R^2 = -0.459$, $p = 0.016$ and $R^2 = 0.719$, $p = 0.001$, respectively). The higher TVS and protein content of FS from lined pit latrines in Kampala slums was moderately related to low dewatering extent (Chapter 3). This is similar to a recent study by Shi *et al.* (2016) who also identified TVS and sand content, as the most dominant characteristics affecting dewatering extent of sewage sludge ($R^2 = -0.838$, $p = 0.000$ and $R^2 = 0.610$, $p = 0.016$, respectively). Higher TVS and protein content are indicators of high extracellular polymeric substances (EPS), which are hydrophilic (water loving) in nature, leading to FS structure retaining water, hence, the low

dewatering extent (Niu *et al.*, 2013). This implies, more water could be released from lined pit latrine FS by improving its structure, as discussed in section 6.5.2.

Conversely, initial total solids (TS) content of FS was the characteristic found to be affecting dewatering extent of FS from unlined pit latrines ($R^2 = 0.768, p = 0.004$). The initial TS of FS from unlined pits is a reflection of dewatered FS when inside the pits, mainly due to infiltration action of leachate into the surrounding soil, hence, no need of improving the dewatering extent. However, leachate infiltration into the soils results in environmental pollution (Nyenje *et al.*, 2013), thus, the disqualification of unlined pit latrines from the recently developed minimum standards of permitted toilet/latrine designs in Kampala (KCCA, 2016). Never-the-less, over 20 % of slum population in Kampala are currently using unlined pit latrines (Tumwebaze *et al.*, 2013), hence, the already accumulated FS in them has to be managed, as discussed in section 6.3.

6.5.2 Conditioning to improve FS dewatering performance

The low dewatering performance of FS from lined pit latrines was improved by use of conditioners (Chapter 4). Chemical conditioners, which are inorganic or organic coagulants/flocculants (such as ferric chloride, aluminium sulphate, lime, *Moringa oleifera*, chitosan and polyelectrolytes) have been reported to improve the dewatering rate of sludges (Jin *et al.*, 2004; Gold *et al.*, 2016). On the other hand, physical conditioners (such as sawdust, coal dust, wheat dregs and gypsum) have been reported to enhance both dewatering extent and rate of sludges (Qi *et al.*, 2011). These often being waste materials and available in urban slums at low or no cost favours their application potential for conditioning FS from pit latrines located in slums.

Results from this study showed that variation in particle sizes of FS from lined pit latrines had no effect on dewatering extent (Chapter 3), implying that chemical conditioners, which work by increasing particle size may have no impact on improving dewatering extent of FS from pits. In addition, the presence of high proportion of colloidal and supra-colloidal particles in FS from lined pits (Chapter 3) reduces the dewatering extent due to blinding of pores between FS solids, making FS structure to retain water. Mowla *et al.* (2013) reported an increase in the bound water content of bio-sludge due to the presence of fine particles, which migrate into the cake pores, consequently, leading to reduced dewatering extent. Application of chemical conditioners agglomerates fine

particles into large flocs for easy separation from the sludge. However, sludge flocs are highly compressible during the compression stage of mechanical dewatering, where the growth in sludge cake causes blockage of the sludge cake voids leading to subsequent low dewatering extent (Novak & O'Brien, 1975). A study by Smollen and Kafaar (1997) found negligible improvement in dewatering extent of bio-sludges when conditioned with polyelectrolyte and dewatered with a laboratory based centrifuge. Also, conditioning of FS from septic tanks with locally produced conditioners in Senegal; such as *Moringa oleifera* seeds and press cake, *Jatropha calotropis* leaves, *Jatropha curcas* seeds and chitosan increased dewatering rates by 59 – 97 % (Gold *et al.*, 2016). This explains why chemical conditioners are better in enhancing dewatering rate, but not dewatering extent. Dewatering extent is pertinent in decreasing initial FS volumes for easy transportation, treatment and subsequent disposal. This is usually achieved by using physical conditioners (Qi *et al.*, 2011).

Physical conditioners, on the other hand, form rigid lattice structures (Skelton builders) to enhance the mechanical strength, leading to improved permeability within FS solids, hence allowing water to flow through the porous structure leading to improved dewatering extent. The selection of sawdust and charcoal dust as physical conditioners in this study (Chapter 4) was due to their availability in urban slums at low or no cost and they are carbon based, implying dewatered solids have low ash content and high calorific value, which characteristics are relevant for energy recovery from FS (Qi *et al.*, 2011). Indeed, the calorific value of FS increased by 42 and 49 % with addition of 75 % (FS solids) dosage of sawdust and charcoal dust, respectively; while ash content reduced by 40 and 16 %, respectively, at the similar dosages (Chapter 4).

Application of 75 % dosage of sawdust and charcoal dust conditioners improved dewatering extent of FS from lined pit latrines by 22.9 and 35.7 %, respectively (Chapter 4). The added physical conditioners reduced crude protein content (synonymous to reduction in EPS) by 49 % and 35 % at 75 %TS dosage of sawdust and charcoal dust, respectively. Reduced EPS is linked to improvement in dewatering extent due to the sludge structure releasing trapped water (Mikkelsen & Keiding, 2002). The structure of FS became more rigid and porous when conditioned, as reflected by the microscopic structures (Chapter 4), leading to release of more water and, hence, improvement in dewatering extent. Similar results of improved porosity and dewatering extent have been reported

when physical conditioners such as wood chips, wheat dregs, lignite, sawdust and coal fly ash are mixed with sewage sludge (Lin *et al.*, 2001; Luo *et al.*, 2013). Improved porosity increases the subsequent drying or composting processes of conditioned FS. Therefore, investigation to the contribution of sawdust/charcoal dust conditioners on drying and/or composting of the dewatered FS, was pertinent.

The dominant process in sawdust conditioned FS dewatering was absorption, as the high moisture content in FS cake could be explained by 89 % reduction in leachate production, but this was only 56 % for charcoal dust conditioned FS (Chapter 4). Lin *et al.* (2001) observed reduced cake moisture content with increasing dose of wood chip or wheat dregs and concluded that the water from sludge was permeated into the physical conditioners. Addition of other agricultural waste such as rice shell or bagasse to sludge from brewery wastewater caused a decrease in cake moisture content (Lee *et al.*, 2011). Conversely, charcoal dust conditioned FS dewatered to a greater extent than sawdust conditioned, which could imply that porosity/permeation is a more dominant factor in dewatering extent of FS and this was more expressed by charcoal dust than sawdust (Chapter 4). A study by Thapa *et al.* (2009) reported markedly improved permeability of sewage sludge when conditioned with lignite. The permeability increased with increasing mass proportion of lignite and decreased with increasing compression pressure. Therefore, the selection of dewatering technology could often be limited to devices operating at relatively low pressures or short compression times (*e.g.* belt presses or centrifuges), due to limited reported benefit from application of high pressures (Qi *et al.*, 2011).

6.5.3 Dewatering technologies for urban slums

Dewatering is usually applied after thickening stage, which has potential to be eliminated when dealing with FS from pit latrines in urban slums (this section). Dewatering can be done either by using sand beds where water freely drains off or mechanically by using centrifuges, filter presses and screw presses (Ronteltap *et al.*, 2014). Sand bed technology is cheap and widely used in centralised FS treatment plants, though the natural operations (filtration and evaporation) and dependence on weather conditions translate into large space requirement, making them inappropriate at decentralized slum levels which are usually congested. Centrifuges and presses are compact technologies and have a potential in dewatering sludges faster due to added force from the

mechanical equipment (Anlauf, 2007). The small space requirement of these technologies make them appropriate for application in urban slums. Murray Muspratt *et al.* (2014) reported an 85 % reduction in land requirement when FS was conditioned with a polymer followed by pressing. However, mechanical dewatering technologies have constraints of high capital, operation and maintenance costs, the need to add flocculants/conditioners and the dependency on electricity (Ronteltap *et al.*, 2014); making them expensive, which could limit their application in slums where low-income earners live. Therefore, application in slums would require lowering costs through considerations such as localised fabrication using available materials, use of locally available conditioners (Chapter 4) and possibility of operating them without connection to electricity (Chapter 5).

The study into particle size distribution of FS from lined pits depicted 38 % of the particles to undergo natural gravity sedimentation (Chapter 3). Therefore, usage of mechanical dewatering technologies that apply sedimentation mechanism such as centrifugation can explore this phenomenon. Furthermore, centrifugation technology operates by enhancing sedimentation, through use of centrifugal force, which causes more solids to settle and drives out more water from settled sludge, thus improvement in dewatering (Buerger & Concha, 2001). The higher initial solids content (7.6 to 16.6 %) and very high proportion of fine particles of FS from pit latrines (Chapter 3) point at centrifugation being more appropriate for dewatering such FS (Broadbent, 2001). Furthermore, Wakeman (2007) reported that centrifuges handle sludges with higher solids content and are not affected by the presence of fine particles.

6.5.4 Dewatering by centrifugation

Centrifuges are classified into sedimenting or filtering and choice of selection largely depends on particle size and initial solids content of sludge to be dewatered (Broadbent, 2001). Buerger and Concha (2001) recommended use of sedimentation centrifuges for dewatering sludge with large proportion of particles finer than 45 μm , since filtering centrifuges are susceptible to clogging due to presence of finer particles (Buerger & Concha, 2001). Results from chapter 3 showed that over 38 and 70 % of the particles of FS from lined pit latrines in Kampala slums were settleable and finer than 45 μm , respectively. Therefore, sedimentation centrifuge type is the appropriate option in a bid to avoid high maintenance costs that would be spent on filtration centrifuges.

Furthermore, the utilisation of centrifugation speed reduces the time needed to achieve the required dewatering extent, hence, a need for small area foot print for treatment facilities. Models for centrifugal dewatering of FS conditioned with 75 %TS dosages of sawdust and charcoal dust were developed, where per cent cake solids (dewatering extent) was the response while FS volume, centrifugation speed and time were the independent variables considered. The models showed that speed was a significant factor for centrifugal dewatering of charcoal dust conditioned FS. Due to absorptive nature of sawdust conditioner, speed and quadratic effect of time were found to be the significant factors in sawdust conditioned FS. Hence, centrifuging sawdust conditioned FS for a longer time (>20 minutes) causes re-suspension and hence, subsequent reduction in dewatering extent (Chapter 5). This also implies the separated water should be removed from the container as soon as the centrifuge stops running to prevent re-soaking of sawdust conditioned FS. Additionally, during operation of the centrifuge, the volume of container should be made 70 to 80 % full of conditioned FS, as dewatering extent was noted to decrease beyond this capacity.

6.6 Implications of centrifugation on FS management service chain in urban slums

The proposed dewatering by centrifugation has influence on the entire FSM service chain covering emptying, transportation, treatment and end-use. Given the high density of housing in urban slum settlements and the nature of FS the pit latrines, emptying can be done manually by use of *gulper* technology or modified garden tools such as spades and forks (Figure 6.3). A proposal for decentralised management of FS comprises of a centrifuge placed at a household level to dewater emptied FS or placed at transfer station, where FS from a group of households is transported in drums using handcarts/tricycle (Figure 6.3). A centrifuge can be mounted on a handcart or tricycle for easy mobility from a household/transfer station to another, within a slum setting.

After dewatering, the liquid stream (centrate/leachate) could be discharged to a sewer line and co-treated with wastewater in centralised treatment plants, for slum areas that have connection to sewer lines. However, the quality of leachate has to be compatible with characteristics of wastewater received at the treatment plant. Further, the organic composition of leachate such as tannin and lignin, obtained mainly from sawdust conditioner need to be examined and their implication to processes of wastewater treatment plant determined. For slums with no sewers in the vicinity (as the case for the majority of slums in SSA), the liquid fraction could be further treated using low-cost

locally available technologies to reduce pollutant loads. For example use of a two-step larva rock filter developed by Katukiza *et al.* (2014a), which was reported to significantly reduce greywater pollutant loads from Bwaise slum to discharge standards. Thus, the resulting effluent could be safely discharged to open drains, used in groundwater recharge, and/or used for non-portable purposes such as irrigation of tower gardens for urban agriculture (Kulabako *et al.*, 2011), or mortar additive for construction purposes (Chapter 2).

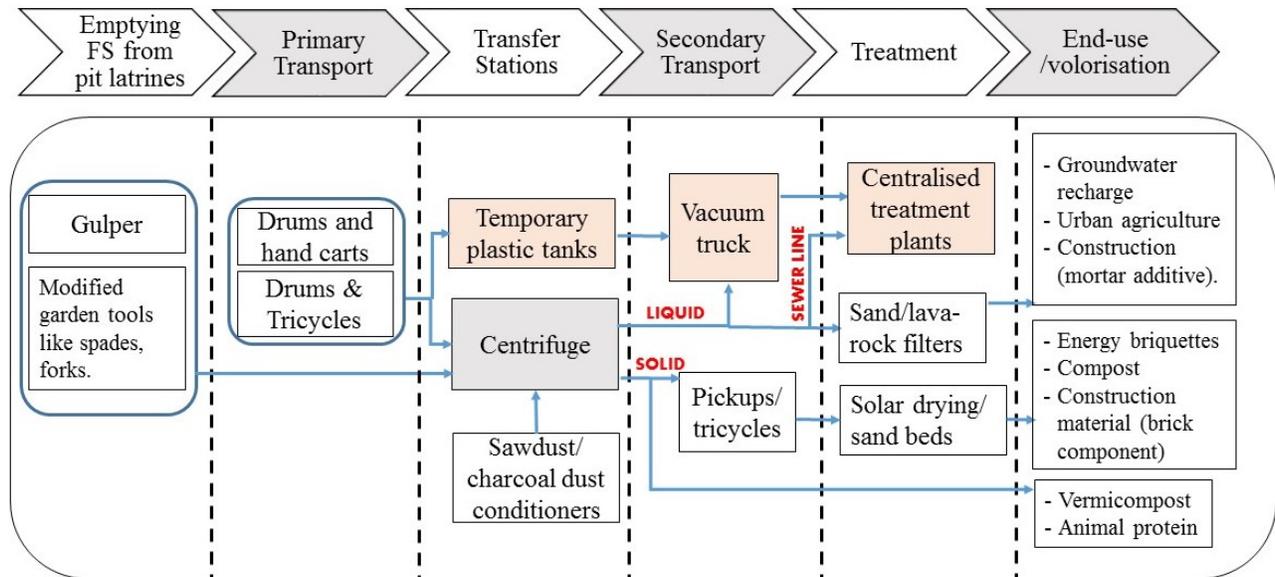


Figure 6.3 Proposed service chain for managing FS from pit latrines in urban slums following centrifugation

The dewatered solid stream on the other hand, can be transformed into a number of products/resources utilisable by urban slum dwellers, such as soil conditioner, vermicompost, animal protein, construction material and energy briquettes, whichever may deem fit for a particular slum community/area setting (Chapter 2). However, in some cases where FS is used as a soil conditioner/compost, it has proved to be less profitable, since low economic value is attached to organic fertilisers and farming is not readily practiced in urban slum settings (Nikiema *et al.*, 2013). The increased cost to poultry feeds would make animal protein from FS a viable venture, though this has not been tried (Chapter 2). High energy demand for lighting and heating at both household and industrial scale makes energy recovery from FS to be a very promising profitable venture that could propel the less privileged parts of the FSM service chain (Diener *et al.*, 2014). Sanivation, an NGO based in Naivasha (Kenya), dealing in production FS briquettes realised that they burn longer

with low carbon emissions and are 40% less expensive compared to charcoal (<http://www.sanivation.com>).

In addition, the sawdust/charcoal dust conditioners have demonstrated effectiveness not only in improving solid-liquid separation, but also enhancement in energy recovery from FS, through increased calorific value and reduced ash content of the residue (Chapter 4). This makes energy briquettes from conditioned FS competitive over wood charcoal. Thus, energy recovery from FS would partly replace the charcoal and firewood used by over 90 % of the Uganda population for cooking and heating, amounting to over 4 million tonnes of annual wood consumption, which accounts for over 70 % of deforestation (Ferguson, 2012). Furthermore, physical conditioners increase porosity for easy motion of air through the FS structure, which improves subsequent drying and composting processes. However, for composting, more conditioner dosages have to be considered to lower the FS moisture content from over 90 % to <60%. Studies have reported sawdust dosage of >300 % for successful composting (Lin *et al.*, 2001).

During centrifugal dewatering, FS conditioned with sawdust/charcoal dust took less time than unconditioned one to attain the same dewaterability extent (Chapter 5), hence increased capacity of centrifuges to handle more FS, therefore, significant reductions in space requirements in urban slums. In some cases where large FS volumes are rendering use of hand/cycle-powered centrifuges labour-intensive, a 12 volts-DC battery power source could be included in the design. The findings from this study can be used to design and operate a hand/cycle-powered centrifuge proto-type in dewatering FS from pit latrine facilities in slums, where electricity is absent or expensive to use. This will enable decentralised FS treatment and support resource recovery at the source, thereby achieving adequate sanitation and improved quality of life of slum dwellers.

6.7 Gaps to scale-up for local reuse

The implications are based on experiments carried out using a laboratory-based centrifuge. Electricity was the energy source used for powering the centrifuge. A domestically-based centrifuge will need to be designed and tested and the actual power requirement is determined. To implement centrifugation technology in dewatering FS at household or community level in slums, there is need to empty FS and treat the separated streams of FS, before and after centrifugation, respectively. To

support job creation and improve livelihoods, slum dwellers should be involved during execution of these activities at all stages of emptying, dewatering and treatment/end-use of liquid and solid streams.

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CHAPTER SEVEN

7 Study Conclusions and Recommendations

7.1 General conclusions

The following are the main conclusions from this research in line with the set objectives:

Specific objective 1: A review of practices, technologies and end-uses of FS in urban slums

- Faecal sludge management in slums is poor and wanting. From the review of literature on decentralised management of FS, the common practice when pit latrines are full is to discharge emptied FS into the surrounding environment. The major technologies used in slums where mechanised trucks do not reach are emptying equipment such as *gulper* and MAPET; and subsequent transportation using tricycles/pickup trucks. Technologies for use after emptying FS, at various stages like dewatering, treatment and resource recovery at decentralised level are lacking. The major promising end-uses are the ones that convert FS to energy. Decentralised management to reduce transport costs, supported by local re-use are key in achieving sustainable local use of FS.

Specific objective 2: Dewatering characteristics of FS from pit latrines

- The design and/or construction of pit latrines (lined or unlined) has an influence on the FS characteristics and, consequently affects dewatering efficiency of FS. The dewatering rate of FS from unlined pits was not significantly different from that of lined pit latrines ($p = 0.104$), but the dewaterability extent of FS from lined pit latrines (18.6 %) was significantly lower ($p = 0.000$) than that of unlined pit latrines (31.8 %).
- The low dewatering extent of FS from lined pit latrines was significantly related to the high total volatile solids proportion and the high crude protein content, which are synonymous with high extracellular polymeric substances.

Specific objective 3: Improvement of FS dewaterability

- Conditioning FS with 75 %TS dosage of sawdust and charcoal dust improved dewatering extent by 22.9 and 35.7 %, respectively, while dewatering rate improved by 14.3 and 15.8 %, respectively. The most dominant property contributing to improved dewatering extent of FS

from pit latrines is porosity/permeation. Therefore, focus should be on physical conditioners that are capable of improving porosity rather than the absorptive ones.

- FS conditioned with charcoal dust achieved better dewatering extent and had higher calorific value compared to that conditioned with sawdust. This is beneficial for local resource reuse, for instance, in promoting replacement of wood based charcoal with faecal sludge based fuel briquettes.

Specific objective 4: Optimisation of operation conditions for FS dewatering technology

- The per cent cake solids obtained in unconditioned FS at rotation of 920 rpm were obtained at no rotation and 160 rpm when sawdust and charcoal dust conditioners were used, respectively. Such reduced rotational speeds upon application of conditioners can be achieved by manual operation, thereby supporting implementation of low-cost dewatering centrifuges.

7.2 Recommendations

This study has provided insights into the differences in characteristics of FS from commonly used sanitation facilities in urban slums, the lined and unlined pit latrines. It has also provided a scientific basis for application of centrifugal dewatering in decentralised management of FS at a household or community level in an urban slum setting. The study of FS dewatering in a context of FSM service chain in a slum setting has generated lots of unanswered questions that are the basis for the following recommendations.

7.2.1 General recommendations

- There is a need to develop a low-cost local hand/cycle-powered pilot-scale centrifuge unit and its performance in terms of dewatering FS from pit latrines is determined. The improved dewatered cake properties need to be evaluated. Similarly, there is a need to fully characterise the leachate/centrate from the centrifugation with/without physical conditioners to ascertain the suitability for discharge to sewers or determine efficiency of pollutant removal when sand/crushed lava filters are used.
- Raw emptied FS contains high pathogen load, which poses health risks to the users of the centrifugation technology. Therefore, there is need for further investigations on the fate of

pathogens across centrifugal dewatering process in an urban slum setting. Subsequent disinfection of pathogens or treatment of water removed out of the solids during dewatering is required. Also, safe handling of solids prior to using them in energy is pertinent, to ensure that no disease causing pathogens are exposed to workers, users and customers at all stages of the FSM services chain.

7.2.2 Policy recommendations

- Decentralised management of FS may necessitate setting up of a number of transfer stations within the slums. However, the guidelines for locating transfer stations need to be followed. Optimisation of sawdust/charcoal dust sources in relation to these stations would help to minimise the costs incurred in FS management. These may necessitate a study to map the sawdust and charcoal dust sources in slums.
- Studied FS characteristics from pit latrines need to be preserved during emptying. This would imply promotion of non-vacuum emptying and transportation equipment, which do not require water addition during servicing. This would not only save scarce/expensive water in slums, but also influence designing of FS treatment plants by elimination/bypassing of the thickening stage.
- Non-vacuum emptying technologies are often operated by manual emptiers. Therefore, formalisation of the existing manual emptiers would avail more FS to be managed/dewatered at a decentralised scale, hence limiting indiscriminate disposal to the environment. However, stringent measures on usage of PPEs should be enforced to safeguard the manual emptiers.
- Preservation of FS quality for resource recovery and reduced FS emptying fees necessitates awareness raising on the impact of solid waste management and operation & maintenance of pit latrines in urban slums.

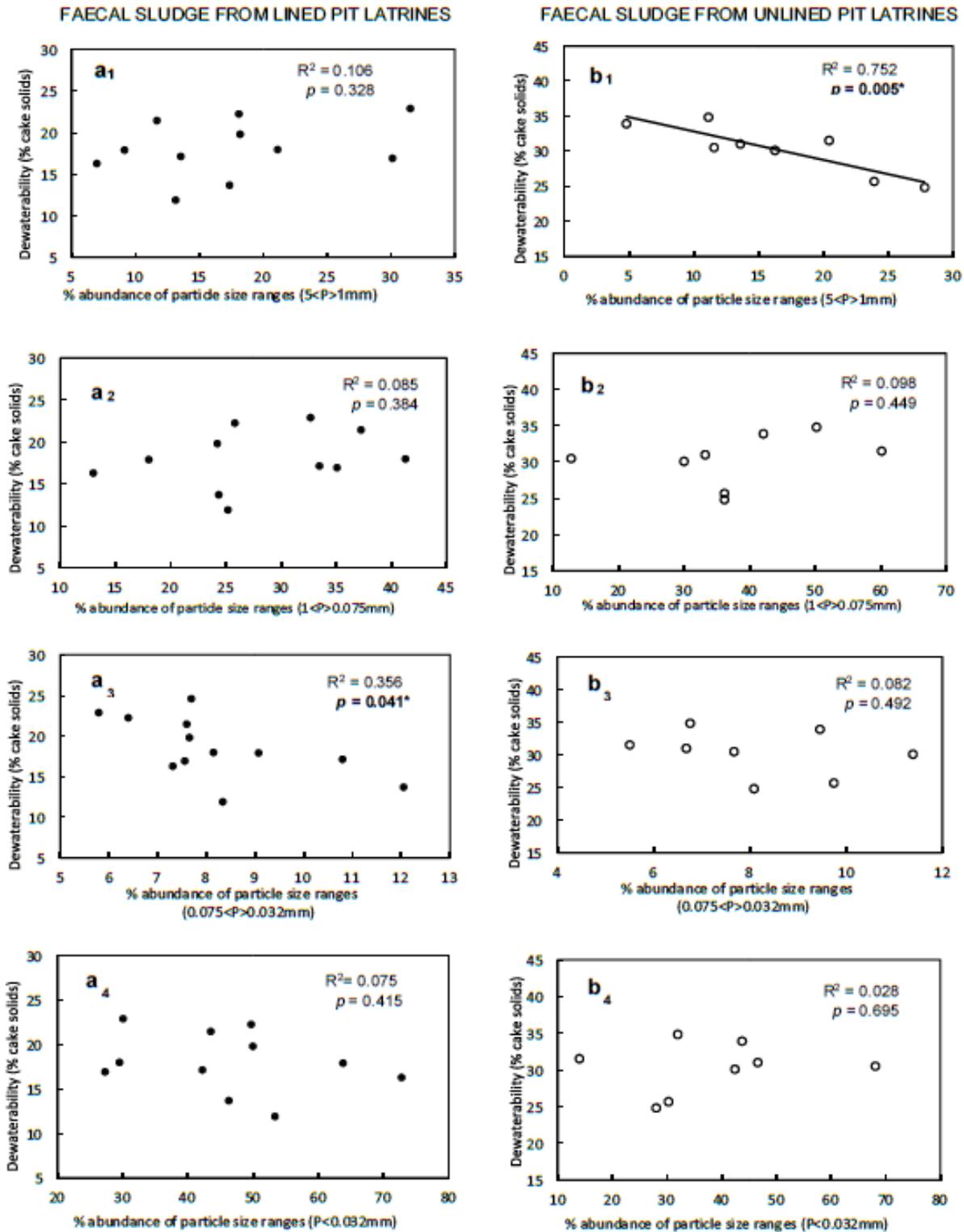
7.2.3 Recommendations for further research

- Work on development of compact dewatering technology was limited to optimisation of centrifuge conditions. Further studies on centrifuge design equations and design criteria are required. This would be followed by design of centrifuge for slums at field scale, costing the design and developing criteria for location in the slums.
- The study revealed that the particle sizes of FS from lined pits did not have an effect on dewatering extent. However, the study did not vary physical characteristics of conditioners such

as particle sizes, hence their contribution to dewatering extent could not be ascertained in this study, and hence future studies should be designed to investigate this. The method of using a mixture of sawdust/charcoal dust should, however be tested under field conditions. Future work is needed to include such measurements as surface area and pore sizes, in order to determine all the optimal operational variables for the usage of sawdust/charcoal dust characterised by the highest possible porosity.

- Physical conditioning of FS influences post-dewatering processes such as drying due to improved porosity. Therefore, the contribution of conditioners to the drying process and the design of appropriate drying technologies to handle FS from urban slums, at a decentralised level or modification of existing drying technologies at centralised FS treatment plants requires investigation.

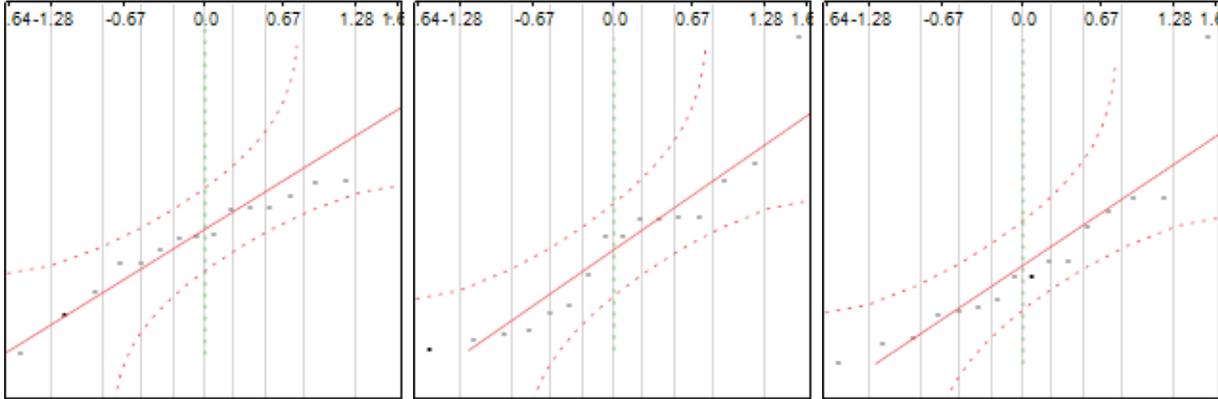
APPENDIX A



Pearson correlation between dewaterability extent and change in proportion of particles for different size ranges of FS from lined pit latrines (a₁ to a₄) and unlined pit latrines (b₁ to b₄). *statistically significant at $p = 0.05$.

APPENDIX B

Original FS

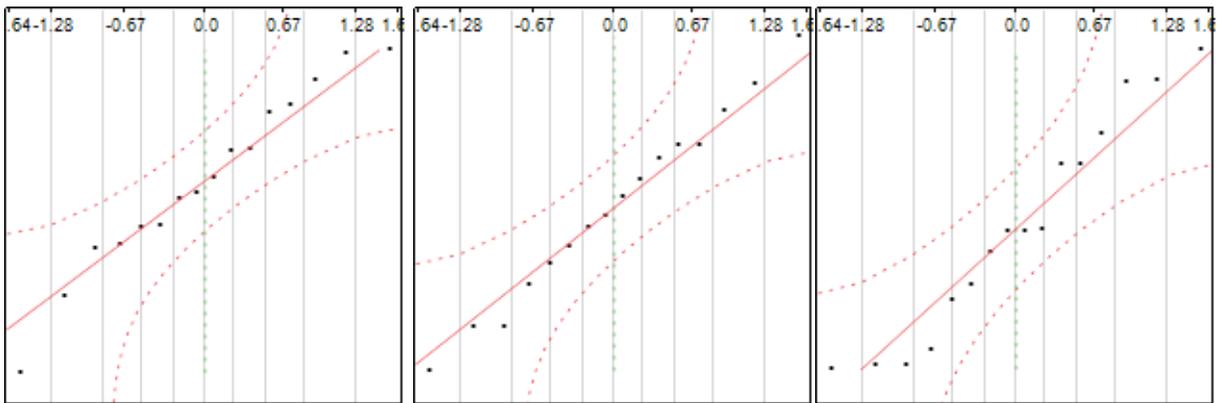


(a) Original residual distribution

(b) speed, speed*speed

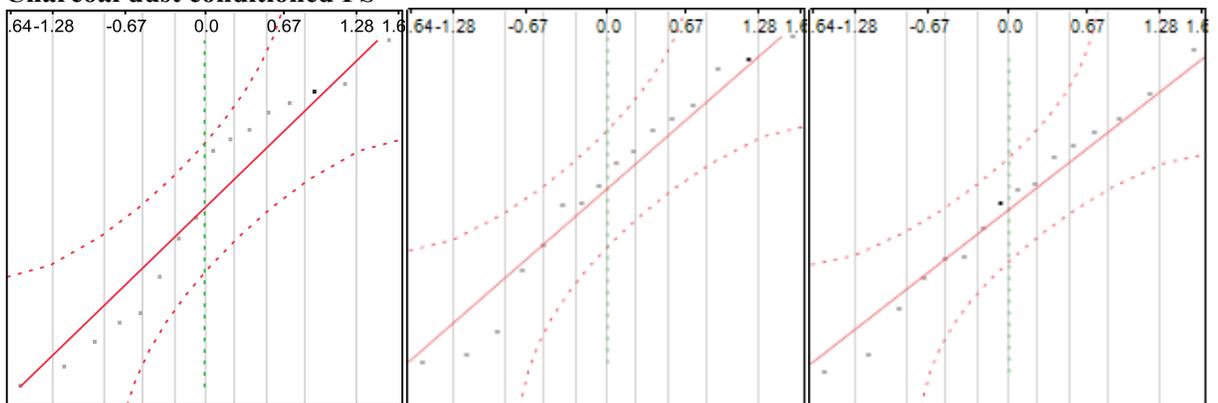
(c) only speed

Sawdust conditioned FS



(a) Original residual distribution (b) time, speed*time, speed², time² (c) only speed and quadratic of time

Charcoal dust conditioned FS



(a) Original residuals

(b) speed, speed*speed

(c) only speed

Normal quantile plots of the model residuals considering effect of (a) all factors, (b) significant factors and their interactions and (c) only significant terms.