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

Swaib Semiyaga*[a], Mackay A. E. Okure[b], Charles B. Niwagaba[a], Alex Y. Katukiza[a], Frank Kansiime[c]

[a]Department of Civil and Environmental Engineering,
College of Engineering, Design, Art and Technology; Makerere University
P.O. Box 7062, Kampala, Uganda

* Corresponding author. Email address: semiyaga@gmail.com Tel.: +256782317023.

[b]Department of Mechanical Engineering,
College of Engineering, Design, Art and Technology; Makerere University
P.O. Box 7062, Kampala, Uganda

[c]Department of Environmental Management,
College of Agricultural and Environmental Sciences; Makerere University
P.O. Box 7062, Kampala, Uganda

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 de-watered, 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 transport of FS from slums is costly due to lack of access, traffic congestion and long travel distances to treatment plants. Moreover, uncollected FS poses health risks and pollutes surface and/or ground water within slums. This review demonstrates that currently utilized technologies and practices fall short in various ways and discusses the possibility of minimizing FS management related costs, risks and pollution in urban slums by decentralized 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.

Key words: Decentralized, Faecal sludge management, Local context, Sanitation, Slums, Sub-Saharan Africa.

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 centers of low- and middle-income countries, less than 50% of the daily produced FS is collected (Koné and Strauss, 2004), of which about a half is properly treated (Blackett et al., 2014). The collected FS is either transported to centralized 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 (Murungi and van Dijk, 2014; Strauss et al., 1998). Poor disposal of FS is exacerbated by increased urbanization under limited infrastructure 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 and 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 also can 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 m^3 truck) per trip (Murungi and 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 centralized treatment locations, decentralized treatment and usage of FS products could be an option. In decentralized management systems, FS is emptied, treated and used or disposed 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. Decentralized FSM systems may include use of on-site systems and cluster systems designed to operate at small scale (Massoud et al., 2009). On-site decentralized systems treat FS of individual households, while cluster systems can treat FS from more than one household (Jones et al., 2001).

FS decentralized 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 centralized systems are reduced. Furthermore, harnessing the great resources contained in FS, not widely recognized 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 utilizable products could create an incentive that would ensure FSM bears its own cost, which is one of the great challenges in FSM. This paper reviews and analyzes technologies and practices suitable for decentralized 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. 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 diseases, 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 and 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 and 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 urbanized 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 urbanization 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 sewered 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 (Koottatep et al., 2002). 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 sewered sanitation. However, these problems have not been fully solved since sewered 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 decentralized 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.

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 and 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) (Niwagaba et al., 2014; Still and Foxon, 2012). 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 mechanized emptying exists, residual materials in FS have to be manually removed, which increases emptying charges (Murungi and 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 (Niwagaba et al., 2014; Still and Foxon, 2012). Consequently, available data on the characteristics of FS are variable (Table 1) and generalizations are difficult to make. Attempts to categorize 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) (Koottatep et al., 2002). The variation in FS characteristics (Table 1) within FS category of a particular origin may be attributed to the above mentioned factors (section 3).

Table 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 Kjedhal 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; [4]Koné 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 1) into the environment causes eutrophication and diseases.

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 stabilized 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 stabilization processes within the pit (Still and Foxon, 2012). Additionally, pathogen levels 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.

4. Current practices of faecal sludge management in urban slums

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 (Mikhael et al., 2014; Thye et al., 2011). Often, pit latrines in urban slums are designed and constructed without considering future emptying (Still et al., 2013). Furthermore, 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 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 and 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 and 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 minimize such indiscriminate practices of FS disposal. In addition, the interaction between emptying, transportation and treatment using decentralized technologies should be considered in order to verify whether emptying frequency, transportation length or treatment feasibility is most important.

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 stabilization ponds or treated using constructed wetlands (Koottatep et al., 2002; 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. Centralized 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 and 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 stabilization ponds often consists of an 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 and Pearson, 1986). It is not advisable to only treat the FS stream in stabilization 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 stabilization 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. Decentralized 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 and 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 required to get mature and stable compost (six weeks to three months) (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, though 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 (Koottatep 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 dewaterbility (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 presence of biodegradable organic constituents. Hence, the dewaterbility of FS can be improved by either including a stabilization stage in FS treatment or blending fresh FS with a stabilized 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 (Bennamoun, 2012; Niwagaba et al., 2006). This makes FS easier to handle, as utilization 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 in 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., 2014). 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^{o}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 and Monteith, 2008). Application of inorganic coagulants to improve sludge settleability increases the ash content further (Kalongo and 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.

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 and 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 minimize risks posed when untreated. If these farmers are sensitized on how to sanitize 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 minimizing 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 and 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 and 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 sanitization would necessitate large space requirement, which is not available in slums.

5. Resource recovery from faecal sludge

Utilization 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.

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 (UYDEL, 2006) could be contaminated. 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. Furthermore, the problem of heavy metal contamination exists as a result of using chemical phosphorous fertiliser. 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 (Heinonen-Tanski and van Wijk-Sijbesma, 2005; Wood and Cowie, 2004), while at the same time minimizing water pollution (Nyenje et al., 2010).

5.2 Vermicompost and animal protein from faecal sludge

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 and Buzie, 2013; Yadav and Garg, 2009). The worm biomass can be used as a protein source in poultry and fish feeds while the vermicompost used as a soil conditioner (Lalander et al., 2015; Ndegwa et al., 2000). 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/m^3 for the bulking agents in low- and middle-income countries (Diener et al., 2014) can increase FSM costs. Furthermore, the vermicompost stabilization and sanitization 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.

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 sanitization 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.

5.3 Faecal sludge as a construction material

Increasing urbanization 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 and 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 and Lo, 2013). Some of the construction materials include; artificial light weight aggregates, tiles, cement material and bricks (Tay and 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.

5.4 Faecal sludge as an energy source

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 meet 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 stabilized (Still and 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).

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 utilized. 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 carbonized 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 carbonized and non-carbonized 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.

5.5 Summary of pros and cons of FS products

A summary of the benefits and challenges in development and utilization of the discussed FS products by the urban slum dwellers in low- and middle-income countries of SSA is provided in Table 2.

Table 2: Summary of pros and cons of potential FS products in an urban slum context.

Potential FS product	Pros	Cons
Soil conditioner	• 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 minimizing 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.	• 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	• 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.	• Need to establish market for compost and worm biomass near the point of production to minimize on transportation charges. • Need to pre-compost FS to reduce intoxicating the worms with ammonia. • Reduced pollutants in vermicompost. • 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 decentralized plant in close proximity to urban slums. • Additional treatment needed for complete sanitization.
Animal protein	• 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.	• 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

Potential FS product	Pros	Cons
	• Does not require a big space for plant setup. Hence, multiple decentralized plants can be setup within the slums. • 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 *e.g.* 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.	and subsequent biomagnification in higher trophic levels like chicken and eventually humans. • Minimal dewatering of FS from some sources is required.
Construction material	• 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 motor due to cavities created after burning bricks. • Burning bricks completely eliminates the pathogens in FS. • Creation of jobs for the local population.	• 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	• 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.	• Low methane yield potential in stabilized 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 sanitization, 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	• FS has a calorific value comparable to other biofuels in use by slum dwellers. • Some slum dwellers are involved in energy briquette production through carbonization 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.	• 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. • Complete destruction of pathogens for easy briquette handling.

6. Acceptability of faecal sludge products and selection of technologies

Since urbanization resulted in the collapse of FS trade as manure (section 2), minimization of haulage distances through decentralized 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 of low- and middle-income countries. Processes for conversion of FS to energy include; aerobic fermentation to produce bio-diesel and methanol (Ting and Lee, 2006); pyrolysis, gasification and hydrothermal carbonization 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 decentralized systems, operation and maintenance has been reported to be challenging (Massoud et al., 2009). For on-site decentralized 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 decentralized 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 decentralized 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 decentralized 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 and Bassan, 2014).

FS management in slums should start at the generation unit (household). Once FS value is appreciated and realized 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 1).

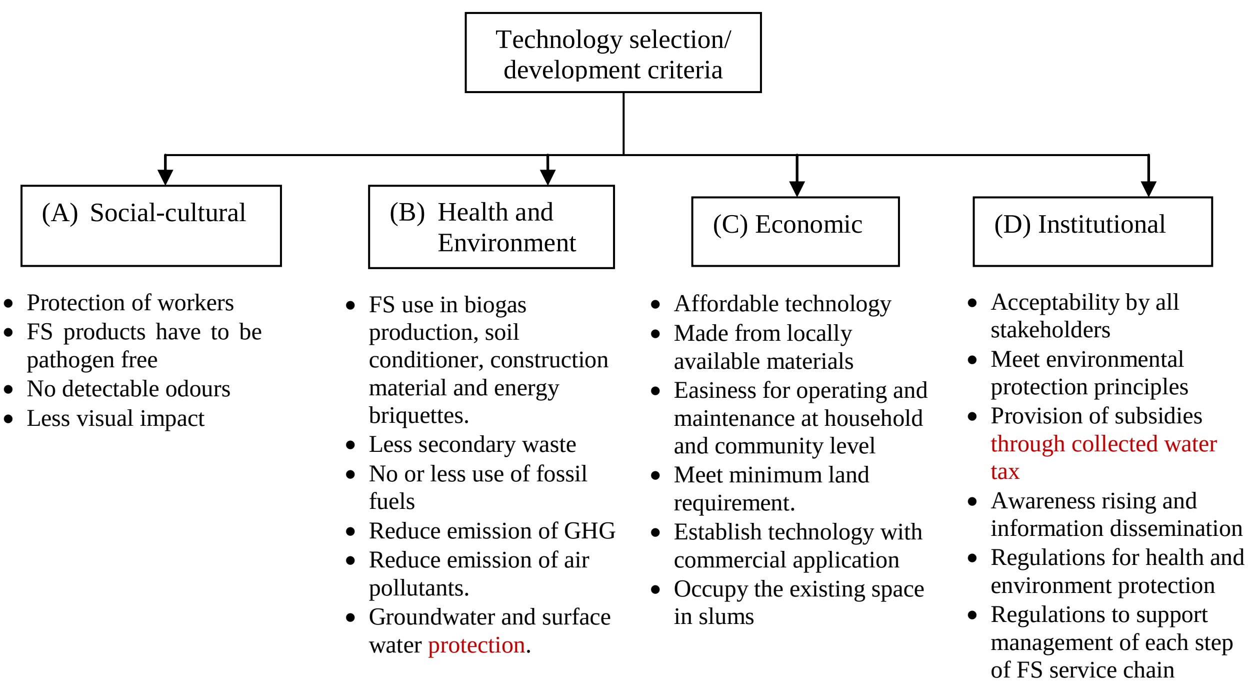

Figure 1: Social-cultural, economic, institutional, health and environmental criteria related to technology development for FS management. Adopted with modifications from (Kalongo and Monteith 2008; Tyagi and Lo 2013, Strande et al. 2014)

The decentralized 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-government organizations (NGOs), households or community. Their roles in FSM should be defined with respect to local context or site (Reymond and Bassan, 2014).

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 operable 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**). 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 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 characterization 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. 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 behavior 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 decentralized scale should be investigated. For production of biogas from FS, slurry results. However, the digester operation conditions are inadequate in production of sanitized slurry. Investigations into different ways of slurry sanitization 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.

8. Conclusions

The increasing rate of urbanization 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 decentralized management of the generated FS should be developed. Simple onsite 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 behavior 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.

Acknowledgements

The authors are grateful to the two anonymous reviewers whose comments and suggestions substantially helped to improve the quality of this paper. This review was carried out as part of the research project titled "Stimulating Local Innovation on Sanitation for the Urban Poor in Sub-Saharan Africa and South-East Asia", which is funded by the Bill and Melinda Gates Foundation, United States through UNESCO-IHE in partnership with Makerere University. Grant Number is OPP1029019.

REFRENCES

Alhajjar, B.J., Harkin, J.M., Chesters, G., 1989. Detergent formula and characteristics of wastewater in septic tanks. Water Pollut. Control Fed. 61, 605–613.

Alleman, J., Bryan, E., Stumm, T., Marlow, W., Hocevar, R., 1990. Sludge-amended brick production: applicability for metal-laden residues. Water Sci. Technol. 22, 309–317.

Bailis, R., Ezzati, M., Kammen, D., 2005. Mortality and Greenhouse Gas Impacts of Biomass and Petroleum Energy Futures in Africa. Science (80). 308, 98–103.

Banks, I.J., 2014. To assess the impact of black soldier fly (Hermetia illucens) larvae on faecal reduction in pit latrines. Doctoral Thesis, London School of Hygiene and Tropical Medicine.

Bassan, M., 2014. Institutional Frameworks for Faecal Sludge Management, in: Strande, L., Ronteltap, M., Brdjanovic, D. (Eds.), Faecal Sludge Management - Systems Approach Implementation and Operation. IWA Publishing, London, UK, pp. 255–272.

Baum, R., Luh, J., Bartram, J., 2013. Sanitation: A global estimate of sewerage connections without treatment and the resulting impact on MDG progress. Environ. Sci. Technol. 47, 1994–2000. doi:10.1021/es304284f

Bennamoun, L., 2012. Solar drying of wastewater sludge: A review. Renew. Sustain. Energy Rev. 16, 1061–1073. doi:10.1016/j.rser.2011.10.005

Blackett, I., Hawkins, P., Heymans, C., 2014. The Missing Link in Sanitation Service Delivery. A Review of Fecal Sludge Management in 12 Cities. Water Sanit. Progr. Res. Br. 1–8.

Bracken, P., Wachtler, A., Panesar, A.R., Lange, J., 2007. The road not taken: how traditional excreta and greywater management may point the way to a sustainable future. Water Sci. Technol. Water Supply 7, 219-227. doi:10.2166/ws.2007.025

Brown, A.D., 2003. Feed of feedback: Agriculture, Population Dynamics and the state of the Planet. International Books Utrecht, the Netherlands.

Cairncross, S., 2003. Sanitation in the developing world: current status and future solutions. Int. J. Environ. Health Res. 13, 123–131. doi:10.1080/0960312031000102886

Chen, G., Yue, P.L., Mujumdar, A.S., 2002. Sludge dewatering and drying. Dry. Technol. 20, 883–916. doi:10.1081/DRT-120003768

Chidumayo, E.N., Masialeti, I., Ntalasha, H., Kalumiana, O.S., 2002. Charcoal Potential for Southern Africa. Zambia Final Report. University of Zambia/European Union.

Cofie, O., Agbottah, S., Strauss, M., Esseku, H., Montangero, A., Awuah, E., Koné, D., 2006. Solid-liquid separation of faecal sludge using drying beds in Ghana: implications for nutrient recycling in urban agriculture. Water Res. 40, 75–82. doi:10.1016/j.watres.2005.10.023

Cofie, O., Koné, D., Rothenberger, S., Moser, D., Zurbrügg, C., 2009. Co-composting of faecal sludge and organic solid waste for agriculture: process dynamics. Water Res. 43, 4665–75. doi:10.1016/j.watres.2009.07.021

Cofie, O., Kranjac-Berisavljevic, G., Drechsel, P., 2007. The use of human waste for peri-urban agriculture in Northern Ghana. Renew. Agric. Food Syst. 20, 73–80. doi:10.1079/RAF200491

Correa, M.T., Grace, D., 2014. Slum Livestock Agriculture, in: Van Alfen, N.K. (Ed.), Encyclopedia of Agriculture and Food Systems. Elsevier Inc, San Diego, USA, pp. 113–121.

Diener, S., Semiyaga, S., Niwagaba, C.B., Muspratt, A.M., Gning, J.B., Mbéguéré, M., Ennin, J.E., Zurbrugg, C., Strande, L., 2014. A value proposition: Resource recovery from faecal sludge—Can it be the driver for improved sanitation? Resour. Conserv. Recycl. 88, 32–38. doi:10.1016/j.resconrec.2014.04.005

Diener, S., Studt Solano, N.M., Roa Gutiérrez, F., Zurbrügg, C., Tockner, K., 2011. Biological treatment of municipal organic waste using black soldier fly larvae. Waste and Biomass Valorization 2, 357–363. doi:10.1007/s12649-011-9079-1

Dodane, P.-H., Mbéguéré, M., Sow, O., Strande, L., 2012. Capital and operating costs of full-scale fecal sludge management and wastewater treatment systems in Dakar, Senegal. Environ. Sci. Technol. 46, 3705–11. doi:10.1021/es2045234

Elsaesser, T., Jaroslav, B., Houdkova, L., 2009. Dewatering of thermally disintegrated sewage sludge. Chem. Eng. Trans. 18, 983–988. doi:10.3303/CET0918161

Günther, I., Horst, A., Lüthi, C., Mosler, H.J., Niwagaba, C.B., Tumwebaze, K.I., 2011. Where do Kampala's poor "go"? Urban sanitation conditions in Kampala's low-income areas. Res. Policy 1.

Heinonen-Tanski, H., van Wijk-Sijbesma, C., 2005. Human excreta for plant production. Bioresour. Technol. 96, 403–11. doi:10.1016/j.biortech.2003.10.036

Heinss, U., Larmie, S.A., Strauss, M., 1998. Solids separation and pond systems for the treatment of septage and public toilet sludges in the Tropics – Lessons learnt and recommendations for preliminary design. EAWAG/SANDEC Report No. 05/98.

Hossain, T., Sarker, S.K., Basak, B.C., 2011. Utilization potential of rice husk ash as a construction material in rural areas. J. Civ. Eng. 39, 175–188.

IWMI, SANDEC, 2002. Co-composting of Faecal Sludge and Solid Waste. Swiss Federal Institute of Aquatic Science (EAWAG), Switzerland.

Jones, D., Bauer, J., Wise, R., Dunn, A., 2001. Small Community Wastewater Cluster Systems. Purdue University Cooperative Extension Services. Available https://www.extension.purdue.edu/extmedia/id/id-265.pdf Accessed: 30. 06. 15

Kalongo, Y., Monteith, H., 2008. State of Science Report : Energy and Resource Recovery from Sludge. Canada, USA.

Katukiza, A.Y., Ronteltap, M., Niwagaba, C.B., Foppen, J.W.A., Kansiime, F., Lens, P.N.L., 2012. Sustainable sanitation technology options for urban slums. Biotechnol. Adv. 30, 964–78. doi:10.1016/j.biotechadv.2012.02.007

Kengne, I.M., Akoa, A., Koné, D., 2009a. Recovery of biosolids from constructed wetlands used for faecal sludge dewatering in tropical regions. Environ. Sci. Technol. 43, 6816–21.

Kengne, I.M., Dodane, P., Akoa, A., Koné, D., 2009b. Vertical-flow constructed wetlands as sustainable sanitation approach for faecal sludge dewatering in developing countries. Desalination 248, 291–297. doi:10.1016/j.desal.2008.05.068

King, F.H., 1972. Farmers of Forty Centuries. Rodale Press, London.

Klingel, F., Montangero, A., Koné, D., Strauss, M., 2002. Fecal Sludge Management in Developing Countries. A planning manual. Duebendorf - Switzerland.

Koné, D., Strauss, M., 2004. Low-cost Options for Treating Faecal Sludges (FS) in Developing Countries – Challenges and Performance, in: 6th International IWA Specialist Group Conference on Waste Stabilisation Ponds. Avignon, France.

Koottatep, T., Polprasert, C., Thi, N., Oanh, K., Montangero, A., Strauss, M., Engineering, U.E., Laung, K., 2002. Constructed Wetlands for Septage Treatment – Towards Effective facal Sludge Management, in: IWA 8th Conference on Wetland Systems for Water Pollution Control, Arusha. Tanzania. Sept. 15-19. p. 17.

Kulabako, N., Nalubega, M., Wozei, E., Thunvik, R., 2010. Environmental health practices, constraints and possible interventions in peri-urban settlements in developing countries - a review of Kampala, Uganda. Int. J. Environ. Health Res. 20, 231–257.

Kung, K., Kamil, A., Ratti, C., McDonald, L., 2013. Low-Cost Production of Charcoal Briquettes from Organic Waste, mit.edu. Available at http://web.mit.edu/~kkung/Public/paper.pdf Accessed 05. 11. 14

Lalander, C., Diener, S., Magri, M.E., Zurbrügg, C., Lindström, A., Vinnerås, B., 2013. Faecal sludge management with the larvae of the black soldier fly (Hermetia illucens)--from a hygiene aspect. Sci. Total Environ. 458-460, 312–8. doi:10.1016/j.scitotenv.2013.04.033

Lalander, C.H., Fidjeland, J., Diener, S., Eriksson, S., Vinnerås, B., 2014. High waste-to-biomass conversion and efficient Salmonella spp. reduction using black soldier fly for waste recycling. Agron. Sustain. Dev. 35, 261–271. doi:10.1007/s13593-014-0235-4

Lalander, C.H., Komakech, A.J., Vinnerås, B., 2015. Vermicomposting as manure management strategy for urban small-holder animal farms – Kampala case study. Waste Manag. 39, 96–103.

Loehr, R.C., Neuhauser, E.F., Malecki, M.R., 1985. Factors affecting the vermistabilization process. Water Res. 19, 1311–1317. doi:10.1016/0043-1354(85)90187-3

Lüthi, C., Morel, A., Tilley, E., Ulrich, L., 2011. Community-Led Urban Environmental Sanitation Planning: CLUES. Complete Guidelines for Decision-Makers with 30 Tools. Duebendorf, Switzerland.

Mara, D., Pearson, H.W., 1986. Waste stabilisation ponds research: Experimental methods and data analysis, in: Regional research seminar on waste stabilization ponds, Gepis. Lima. 3-7 demarzo de 1986.

Massoud, M.A., Tarhini, A., Nasr, J.A., 2009. Decentralized approaches to wastewater treatment and management: applicability in developing countries. J. Environ. Manage. 90, 652–9. doi:10.1016/j.jenvman.2008.07.001

Melosi, M.U., 2008. The sanitary city: environmental services in urban America from colonial times to the present, 2nd ed. The Johns Hopkins University Press, United States of America.

Mikhael, G., Robbins, D.M., Ramsay, J.E., Mbéguéré, M., 2014. Methods and Means for Collection and Transport of Faecal Sludge, in: Strande, L., Ronteltap, M., Brdjanovic, D. (Eds.), Faecal Sludge Management - Systems Approach Implementation and Operation. IWA Publishing, London, UK, pp. 67–96.

Montangero, A., Koné, D., Strauss, M., 2002. Planning towards improved excreta management, in: 5th IWA Conference on Small Water and Wastewater Treatment Systems. Istanbul, Turkey, pp. 24–26.

Monte, M.C., Fuente, E., Blanco, A., Negro, C., 2009. Waste management from pulp and paper production in the European Union. Waste Manag. 29, 293–308. doi:10.1016/j.wasman.2008.02.002

Morella, E., Foster, V., Banerjee, G.S., 2008. Climbing the Ladder : The State of Sanitation in Sub- Saharan Africa. Africa Infrastructure Country Diagnostic (AICD) Background paper 13 (Phase 1). The World Bank, Washington DC, USA.

Murray, A., Cofie, O., Drechsel, P., 2011a. Efficiency indicators for waste-based business models: fostering private-sector participation in wastewater and faecal-sludge management. Water Int. 36, 505–521. doi:10.1080/02508060.2011.594983

Murray, A., Mekala, G.D., Chen, X., 2011b. Evolving policies and the roles of public and private stakeholders in wastewater and faecal-sludge management in India, China and Ghana. Water Int. 36, 491–504. doi:10.1080/02508060.2011.594868

Murray Muspratt, A., Nakato, T., Niwagaba, C., Dione, H., Kang, J., Stupin, L., Regulinski, J., Mbéguéré, M., Strande, L., 2014. Fuel potential of faecal sludge: calorific value results from Uganda, Ghana and Senegal. J. Water, Sanit. Hyg. Dev. 4, 223–230. doi:10.2166/washdev.2013.055

Murungi, C., van Dijk, M.P., 2014. Emptying , Transportation and Disposal of feacal sludge in informal settlements of Kampala Uganda : The economics of sanitation. Habitat Int. 42, 69–75. doi:10.1016/j.habitatint.2013.10.011

Ndegwa, P.M., Thompson, S.A., Das, K.C., 2000. Effects of stocking density and feeding rate on vermicomposting of biosolids. Bioresour. Technol. 71, 5–12. doi:10.1016/S0960-8524(99)00055-3

Nikiema, J., Cofie, O., Impraim, R., Adamtey, N., 2013. Processing of Fecal Sludge to Fertilizer Pellets Using a Low-Cost Technology in Ghana. Environ. Pollut. 2, 70–87. doi:10.5539/ep.v2n4p70

Niwagaba, C.B., Mbéguéré, M., Strande, L., 2014. Faecal Sludge Quantification , Characterisation and Treatment Objectives, in: Strande, L., Ronteltap, M., Brdjanovic, D. (Eds.), Faecal

Sludge Management - Systems Approach Implementation and Operation. IWA Publishing, London, UK, pp. 15–42.

Niwagaba, C.B., Nalubega, M., Vinnerås, B., Jönsson, H., 2006. Incineration of Faecal Matter for Treatment and Sanitation. IWA Publ. London, UK.

Njenga, M., Yonemitsu, A., Karanja, N., Iiyama, M., Kithinji, J., Dubbeling, M., Sundberg, C., 2013. Implications of Charcoal Briquette Produced by Local Communities on Livelihoods and Environment in Nairobi- Kenya. Int. J. Renew. Energy Dev. 2, 19–29.

Nwaneri, C.F., 2009. Physico-chemical characteristics and biodegradability of contents of ventilated improved pit latrines (VIPs) in eThekwini Municipality. University of KwaZulu-Natal, Durban - South Africa.

NWSC, 2008. Kampala Sanitation Program (KSP) - Feasibility study for sanitation master plan in Kampala, Uganda - Volume 1.

Nyenje, P.M., Foppen, J.W., Uhlenbrook, S., Kulabako, R., Muwanga, A., 2010. Eutrophication and nutrient release in urban areas of sub-Saharan Africa - a review. Sci. Total Environ. 408, 447–55. doi:10.1016/j.scitotenv.2009.10.020

Oonincx, D.G.A.B., van Huis, A., van Loon, J.J.A., 2015. Nutrient utilisation by black soldier flies fed with chicken, pig, or cow manure. J. Insects as Food Feed 1, 131–139.

Otterpohl, R., Buzie, C., 2013. Treatment of the solid fraction, in: Larsen, T.A., Udert, K., Lienert, J. (Eds.), Source Separation and Decentralization for Wastewater Management. IWA Publishing, London, UK, pp. 259–273.

Ouederni, A.R. El, Salah, M. Ben, Askri, F., Nasrallah, M. Ben, Aloui, F., 2009. Experimental study of a parabolic solar concentrator. J. Renew. Energy 12, 395–404.

Payá, J., Monzó, J., Borrachero, M. V., Amahjour, F., Girbés, I., Velázquez, S., Ordóñez, L.M., 2002. Advantages in the use of fly ashes in cements containing pozzolanic combustion residues: silica fume, sewage sludge ash, spent fluidized bed catalyst and rice husk ash. J. Chem. Technol. Biotechnol. 77, 331–335.

Reymond, P., Bassan, M., 2014. Stakeholder Engagement, in: Strande, L., Ronteltap, M., Brdjanovic, D. (Eds.), Faecal Sludge Management - Systems Approach Implementation and Operation. IWA Publishing, London, UK, pp. 341–362.

Rockefeller, A.A., 1998. Civilization and Sludge: Notes on the History of the Management of Human Excreta. Capital. Nat. Social. 9, 3–18. doi:10.1080/10455759809358806

Ronteltap, M., Dodane, P., Bassan, M., 2014. Overview of Treatment Technologies, in: Strande, L., Ronteltap, M., Brdjanovic, D. (Eds.), Faecal Sludge Management - Systems Approach Implementation and Operation. IWA Publishing, London, UK, pp. 97–122.

Seck, A., Gold, M., Niang, S., Mbéguéré, M., Diop, C., Strande, L., 2014. Faecal sludge drying beds: Increasing drying rates for fuel resource recovery in Sub-Saharan Africa. Water Sanit. Hyg. Dev. In press, 1–15.

Still, D., Foxon, K., 2012. Tackling the Challenges of Full pit latrines. Volume 1 : Understanding sludge accumulation in VIPs and strategies for emptying full pits. South Africa.

Still, D., Riordan, M.O., Mcbride, A., Louton, B., 2013. Adventures in search of the ideal portable pit-emptying machine. Waterlines 32, 187–199.

Still, D., Salisbury, H., Lorentz, S., Foxon, K.M., 2012. Beneficial Use of Faecal Sludge through deep row entrenchment. Sanit. Matters. Issue 4, March. 8-9.

Strande, L., 2014. The Global Situation, in: Strande, L., Ronteltap, M., Brdjanovic, D. (Eds.), Faecal Sludge Management - Systems Approach Implementation and Operation. IWA Publishing, London, UK, pp. 1–14.

Strande, L., Ronteltap, M., Brdjanovic, D., 2014. Faecal Sludge Management - systems approach implementation and operation. IWA Publishing, London, UK.

Strauss, M., Larmie, S.A., Heinss, U., Montangero, A., 1998. Treating Faecal Sludges in Ponds. Water Sci. Technol. 42, 283–290.

Tarr, J.A., Dupuy, G., 1988. Technology and the rise of the Networked City in Europe and America. Philadelphia: Temple University Press.

Tatsi, A.A., Zouboulis, A.I., Matis, K.A., Samaras, P., 2003. Coagulation – flocculation pretreatment of sanitary landfill leachates. Chemosphere 53, 737–744. doi:10.1016/S0045-6535(03)00513-7

Tay, J., Show, K., 1997. Resource recovery of sludge as a building and construction material — A future trend in sludge management. Water Sci. Technol. 36, 259–266.

Thye, Y.P., Templeton, M.R., Ali, M., 2011. A Critical Review of Technologies for Pit Latrine Emptying in Developing Countries. Crit. Rev. Environ. Sci. Technol. 41, 1793–1819. doi:10.1080/10643389.2010.481593

Ting, C.H., Lee, D.J., 2006. Production of hydrogen and methane from wastewater sludge using anaerobic fermentation. doi:10.1016/j.ijhydene.2006.06.063

Tumwesige, V., Fulford, D., Davidson, G.C., 2014. Biogas appliances in Sub-Sahara Africa. Biomass and Bioenergy In press, 1–11. doi:10.1016/j.biombioe.2014.02.017

Tyagi, V.K., Lo, S.-L., 2013. Sludge: A waste or renewable source for energy and resources recovery? Renew. Sustain. Energy Rev. 25, 708–728. doi:10.1016/j.rser.2013.05.029

Uganda Youth Development Link (UYDEL), 2006. Non-formal and livelihood skills for marginalised street and slum youth in Uganda. UNESCO Project report, Kampala, Uganda.

Van Vuuren, L., 2008. Back to basics: Research looks down the pit. The Water Wheel: Sanitation, Health, and Hygiene Supplement, 10–13.

Weng, C.-H., Lin, D.-F., Chiang, P.-C., 2003. Utilization of sludge as brick materials. Adv. Environ. Res. 7, 679–685.

WHO, 2006. WHO guidelines for the safe use of wastewater, excreta and greywater. Volume 1: Policy and regulatory aspects. France.

Wiszniowski, J., Robert, D., Surmacz-gorska, J., Miksch, J., Weber, V.., 2006. Landfill leachate treatment methods : A review. Env. Chem Lett 4, 51–61. doi:10.1007/s10311-005-0016-z

Wood, S., Cowie, A., 2004. A Review of Greenhouse Gas Emission Factors for Fertiliser Production. In IEA bioenergy task (Vol. 38, No. 1, pp. 1-20)

Yadav, A., Garg, V.K., 2009. Feasibility of nutrient recovery from industrial sludge by vermicomposting technology. J. Hazard. Mater. 168, 262–8. doi:10.1016/j.jhazmat.2009.02.035

Yadav, K.D., Tare, V., Ahammed, M.M., 2010. Vermicomposting of source-separated human faeces for nutrient recycling. Waste Manag. 30, 50–6. doi:10.1016/j.wasman.2009.09.034

Yadav, K.D., Tare, V., Ahammed, M.M., 2012. Integrated composting-vermicomposting process for stabilization of human faecal slurry. Ecol. Eng. 47, 24–29. doi:10.1016/j.ecoleng.2012.06.039