Sludge to Energy Enterprises in Kampala (SEEK) Project

Suitable Biowastes for Energy Recovery

June 2015

Aoife Byrne[1], Moritz Gold[1], Diana Turyasiima[2], Wim Getkate[3], Charles Niwagaba[2], Mohammed Babu[4], James Maiteki[4], Martin Orwiny[4], Linda Strande[1]

[1]Swiss Federal Institute of Aquatic Science and Technology (Eawag), Department of Water and Sanitation in Developing Countries (Sandec)
[2]Makerere University
[3]Centre for Research in Energy and Energy Conservation (CREEC)
[4]National Water and Sewerage Corporation (NWSC)

Project partners

Funding

SEEK (Sludge to Energy Enterprises in Kampala) Project

The goal of SEEK is to work towards making resource-recovery based solutions to waste management a reality, thereby providing new business opportunities, and increasing access to renewable energy and electricity while improving public and environmental health in urban areas through the provision of sustainable sanitation service chains. As part of the FaME project (Faecal Management Enterprises, www.sandec.ch/fame) Sandec and its research partners showed that dried faecal sludge (FS) has an energy content competitive to other solid biomass fuels and FS combustion in industries is technically feasible. In Uganda, electricity demand outstrips the electricity generation capacity and industries are in demand of solid fuels. In Kampala, Sandec and its research partners build on the results of the FaME project by investigating the viability of co-processing FS and other biowastes to produce fuel pellets and with these electricity through gasification. The SEEK project established a pilot-scale research facility at National Water and Sewerage Corporation (NWSC) Lubigi Wastewater and Faecal Sludge Treatment Plant and conducts market research to provide reliable data, working towards market implementation of technologies and endproducts. Visit www.sandec.ch/seek for more information.

Acknowledgements

The authors thank REPIC (www.repic.ch) and Symphasis (www.symphasis.ch) for funding the SEEK project. Thanks is given to all SEEK project partners including Dr. C. Niwagaba, Makerere University, Wim Getkate, Moses Kakooza and Smith Tukahirwa from the Centre for Research in Energy and Energy Conservation (CREEC), Martin Orwiny, James Maiteki, Mohammed Babu and Joseph Tweheyo from National Water and Sewerage Corporation (NWSC). The authors also thank staff at KCCA that provided valuable assistance, Dr. J. Semuwemba and Jude Zziwa, Josephine Kitaka and the associated Division Officers. Those that took the time to be interviewed and share their knowledge and experience including Prof. Elly Sabiiti, Prof. William Ekere and Dr. Alice Amoding, at the Department of Agriculture Makerere University, Dr. Noble Banadda at the Department of Agriculture and Biosystems Engineering Makerere University, Dr. Robinah Kulabako, Ritah and Joel Kinobe at the Department of Civil and Environmental Engineering Makerere University, Dr. Onesmus Semalulu and Joshua Karaire Atukuna at the National Agriculture Research Organisation, Freddie Leons from Crop to Cup Coffee Exporters, Jerome Nuwabaasa at Pamoja, Derrick Rubaramira, Kenlon Industries Ltd. and Abasi Musisi and Ronald Lukoda at Kampala Jellitone Suppliers Limited. The authors like to extend their thanks to Lars Schoebitz and Brian Sinnet at Eawag, and Timon Käser at Paul Scherrer Institut (PSI).

Abstract

Previous research in Sub-Saharan Africa determined that energy recovery from faecal sludge (FS) as solid fuel has a higher revenue potential compared to the use as soil conditioner in agriculture. Revenues from resource recovery of FS treatment endproducts can be used to offset FS treatment costs. However, currently the available quantities of treated FS are insufficient to meet demands of large-scale industries, which are the target market. Co-processing of FS with other biowastes could be a way to increase the quantity of a solid FS fuel, as well as reducing FS drying requirements and improving FS properties such as ash content and calorific value. In this study, Multi-Criteria Analysis (MCA) using criteria on biowaste availability-accessibility and physical-chemical properties was used to identify suitable biowastes for energy recovery in Kampala, Uganda (e.g. fuel pellets, gasification). In a preliminary assessment, 28 biowastes were identified to be available in Kampala and nine were selected for in-depth analysis. This included proximate and ultimate analysis of all biowastes. MCA identified sawdust, coffee husks, spent grain, market waste, malt/sorghum husks and maize cobs as the most suitable biowastes for energy recovery. Water treatment and wastewater treatment sludge have similar physical-chemical characteristics compared to FS and therefore they do not increase the fuel quality for energy recovery. Sufficient quantities of sawdust, coffee husks, spent grain, market waste, malt/sorghum husks and maize cobs are available for co-processing with FS with a contribution of biowaste of up to 80%. However, these biowastes already have a significant market value. Both, pelletizing and gasification experiments and financial modelling needs to investigate the technical and financial benefits of co-processing of FS with most suitable waste streams identified in this study. Proximate and ultimate analysis results of this study can be used to estimate the proximate and ultimate composition of FS co-processed in different ratios with biowastes.

1 Introduction

1.1 Faecal sludge management

Faecal sludge management (FSM) covers the storage, collection, transport, treatment and enduse or disposal of faecal sludge (FS) – sludge accumulating in onsite sanitation technologies such as pit latrines and septic tanks. FS properties and quantities vary spatially and temporally as a result of among others different onsite sanitation technology designs, geographic locations, user number and habits (Still and Foxon, 2012). Originally onsite sanitation technologies were more commonly implemented in rural areas (Strande, 2014). However, today, sanitation needs of 65 to 100% of the urban population in developing countries are met by such technologies. One reason is the lack of cities being able to keep up with the rate of urbanisation (Cairns-Smith et al., 2014). For developing countries, onsite sanitation technologies and FSM can be more appropriate compared to sewer-based solutions, however, collection, transport, treatment, enduse and disposal of FS are rarely implemented, resulting in untreated FS being discharged directly into the urban environment (Strande, 2014). High costs required by both households and the government is one of the main reasons of incomplete FSM. It is being recognised that giving a value to FS treatment endproducts, through resource recovery from FS and selling it for suitable enduse, can generate revenues to sustain and encourage appropriate FSM (Diener et al., 2014).

1.2 Resource Recovery from faecal sludge

Currently, treated FS is most commonly used as a soil conditioner in agriculture, but to a limited extent while large amounts are either landfilled, released indiscriminately into the environment or given away below value (Diener et al., 2014). In Sub-Saharan Africa, in addition to use as soil conditioner, untapped markets for resource recovery of FS treatment endproducts have been identified including the use of FS as a solid fuel, biogas generation from anaerobic digestion, protein feedstock from larvae used to treat FS and FS as building material (Diener et al., 2014) In general it appears that in urban Sub-Saharan Africa, large-scale energy production options for industries such as solid fuel and biogas production have the greatest revenue potential. The revenue potential varied greatly between cities depending on the local market environment. Hence, to capture maximum revenue from resource recovery, FS treatment technologies need to be designed in order to meet local market demands.

1.2.1 Solid fuel (fuel pellets)

In Kampala, industries are in demand for solid fuels. Alternative biomass fuels, for example coffee husks, sawdust, bagasse and briquettes produced from agricultural products are already in use and the cost of commonly used fuel such as firewood, charcoal and kerosene are continuously increasing (Diener et al., 2014, Gold et al., 2014, Rubaramira, personal communication, UBOS, 2006).

1.2.2 Electricity through gasification

In Uganda, only 14% of the population has access to electricity and only 4% in rural area (Rural Electrification Agency Uganda (REA), 2013a). In the last few years droughts reducing water levels in Lake Victoria and financial challenges to operate thermal power plants have resulted in significant rolling blackouts (or "load shedding") due to insufficient power generating capacity (Rural Electrification Agency Uganda (REA), 2013b). As illustrated in Figure 1, in Uganda rising electricity demand is expected to greatly outstrip generation in the coming years.

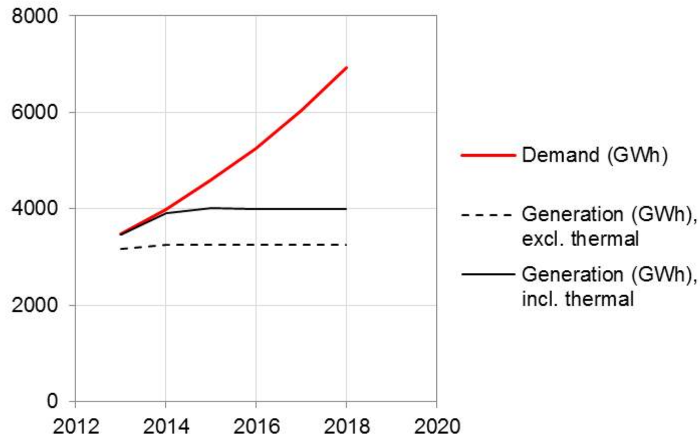

Figure 1: Electricity demand and generation capacity in Uganda (Rural Electrification Agency Uganda (REA), 2013b).

The Renewable Energy Policy for Uganda aims to increase the use of modern renewable energy from 4% in 2007 to 61% of the total energy consumption in 2017. The national government of Uganda plans for electrification are 40% national coverage and 25% rural in 2022, 80% national and 50% rural 2030, and 100% electrification in 2040 (Rural Electrification Agency Uganda (REA), 2013a). Producing electricity through biomass gasification can increase the electricity generation capacity and work towards achieving these national goals. Electricity could either be produced for own supply or fed into the grid through a Renewable Energy Feed-in Tariff scheme (REFIT) (Electricity Regulatory Authority (ERA), 2012). In general between 1-2 kg of biomass is required to produce 1 kWh of electricity.

1.2.3 Char through slow-pyrolysis (carbonization)

In Sub-Saharan Africa the majority of energy for cooking is provided by wood-based charcoal and it is also used in industrial boilers. Biomass including dried FS can be processed into char through slow-pyrolysis. Ward et al. (2014) obtained a char yield between 30-50% for excreta from source separation toilets. The char can be used a soil conditioner or briquetted and used as a substitute for wood-based charcoal as a cooking or industrial fuel.

1.3 Co-processing of faecal sludge with other urban biowastes

The calorific value of dried FS, a measure of a fuel`s energy potential, is on average 17.3 MJ/kg dry mass in Sub-Saharan Africa. This is competitive with other solid biofuels used in this region, such as sawdust or coffee husks. However, it was determined that three major challenges needed to be overcome in order to satisfy industry requirements and to work towards making FS to energy a financially viable resource recovery option. Firstly, FS treatment endproducts require 90 wt% dry mass to be used as a solid fuel in industries, although a minimum of 27 wt% dry mass can produce a net energy benefit (Muspratt et al., 2013, Gold et al., 2014). Hence, drying must be incorporated into the treatment process. Drying beds are commonly used in developing countries, however they require a large footprint to dry sludge to 90% wt% dry mass, which increases treatment cost (Gold et al., 2014). Innovative techniques can reduce the space requirements and increase the rate of drying, for example regularly mixing the sludge can increase treatment capacities by 20%. More research is needed to investigate further techniques to increasing FS drying rates and decrease the treatment footprint (Seck et al., in press). Secondly, the ash content of the FS fuel needs to be reduced. In general, high ash contents are undesired by industries as they increase disposal costs and affect the combustion process (Gold et al., 2014, Seck et al., in press). Thirdly, current FS treatment plants have insufficient capacity to provide significant FS fuel quantities of FS fuel to large-scale industries (e.g. Hima cement factory in Uganda). However the interest is there if the supply quantity and quality could be guaranteed (Gold et al., 2014, Bäuerl et al., 2014). Less than 50% of FS produced in onsite sanitation technologies in Kampala is collected and treated (Schoebitz et al., 2014). This is due to the high cost of collection and treatment services, as well as the inaccessibility of many onsite sanitation technologies.

Co-processing FS with other biowastes could potentially solve the challenges above, primarily increasing the quantity of solid fuel produced. Depending on the urban biowaste selected for co-processing, the ash content can be reduced and the wt% dry mass increased, reducing the need for drying which leads to a reduced production costs of FS treatment endproducts. In Kampala approximately 28,000 tons of municipal solid waste, which includes market waste, is landfilled monthly. This represents only 40% of the total waste generated in the city. This is due to the low coverage of waste collection and disposal services in the city and leads to illegal dumping in turn causing negative implications to both human health and the environment (Komakech et al., 2014). Uganda is an agricultural country. Primary processing of agricultural products is carried out at the farms before transporting the agricultural products to urban markets. Hence, agricultural waste is mostly generated at the farm level, in the rural parts of Uganda, and at the city level, as market waste (Sabiiti, personal communication). Often agricultural waste is burnt for disposal and the market waste is landfilled. However, the resource value of biowastes is being recognised and it is becoming common to recover its resources by selling it as a solid fuel, animal feedstock or soil conditioner (Sabiiti, 2011). For example, coffee husks, rice husks and sawdust are recovered for energy production, while sugar mills retain bagasse (by-product of sugarcane processing) to power their factories and animal dung from urban farming is recovered for fertiliser (Diener et al., 2014, Komakech et al., 2013, Rubaramira, personal communication). As mentioned, 60% of the municipal solid waste generated in Kampala is dumped illegally and agricultural waste in rural areas is commonly burnt for disposal (Musisi, personal communication, Komakech et al., 2014). Hence a large portion of these biowastes are not utilised in resource recovery. Recovering waste to produce solid fuel provides an environmentally acceptable way to dispose of it (Sabiiti, 2011) and co-processing it with FS can support both management of FS and other urban biowastes.

1.4 Scope of this study

At present there is no comprehensive study identifying the most suitable urban biowastes for energy recovery in Kampala. Studies conducted by Schoebitz et al. (2014), Kinobe et al. (2015) and Komakech et al. (2014) have provided some quantification and characterisation of different urban biowastes in Kampala, providing suggestions for resource recovery options but with insufficient information to select the most suitable biowastes for co-processing with FS. This study aims to identify the most suitable biowastes for energy recovery. The biowastes identified as part of this study will be co-processed with FS into fuel pellets using the Bioburn (www.bioburn.ch) pelletizing technology and gasified by a GEK Power Pallet to produce electricity.

2 Material and Methods

2.1 Study area

Kampala, Uganda, has a population of 1.7 million which is increasing rapidly at a rate of 3.2% (UBOS, 2012). Currently 74% of rural households and 84% of urban households have access to improved sanitation in Uganda. In Kampala, 6.4% of the people are served by a sewage network (Government of Uganda, 2014). Sanitation needs of the remaining population are met by onsite sanitation technologies. Wastewater collected by the sewage network is treated at the National Water and Sewerage Corporation (NWSC) Bugolobi Wastewater Treatment Plant and NWSC Lubigi Wastewater and Faecal Sludge Treatment Plant. FS is transported and treated at the latter plant. However, this represents only an estimated 44% of FS generated from onsite sanitation technologies. The remainder is dumped indiscriminately (Schoebitz et al., 2014). An estimated, 64% of onsite sanitation technologies in Kampala are unlined and hence the FS produced in these is commonly not collected because the pit could collapse during FS collection (Government of Uganda, 2014).

NWSC Lubigi has a treatment capacity of 400 m^3/d, however the capacity cannot keep up with the demand and FS is also discharged for treatment at NWSC Bugolobi which is not designed for FS treatment. NWSC Lubigi treats FS by screening and settling in sedimentation tanks. The two sedimentation tanks are batch operated. As per design, the tanks are alternated on a monthly basis; one tank receives FS while the other is allowing the solids to settle. The solids that settle can be categorised into two fractions; wet sludge that can be pumped directly to the drying beds and thicker sludge that must be removed by mechanical excavators as it is too dry to be pumped. The sedimentation tank is emptied after a period of approximately one month. Following settling, FS is dewatered for three to eight weeks with 19 covered drying beds until sufficient dryness is reached to remove the sludge from the beds, determined by visual inspection. Following dewatering, per design the sludge is stored in 18 covered storage units for six months before collection by farmers for enduse as soil conditioner in agriculture. Effluent of the sedimentation tank and drying beds is co-treated with wastewater in waste stabilization ponds at NWSC Lubigi (Orwiny, personal communication, Fichtner Water & Transportation, 2009).

2.2 Assessment approach

Multi-Criteria Analysis (MCA) was used to determine the most suitable biowastes for energy recovery with FS in Kampala. Primary and secondary data was collected for each biowaste. As many different biowastes are generated in Kampala and Uganda, the waste assessment was divided into pre-assessment and in-depth analysis.

In the pre-assessment, biowastes with the potential for energy recovery with FS were determined through secondary data collection. Secondary data was collected through the review of relevant literature and semi-structured interviews following stakeholder mapping according to the methodology described in Section 2.4.1. This followed an iterative approach. Literature and stakeholders were added during the process until no further resources could be identified. The list of biowastes identified during the pre-assessment was then narrowed down based on most relevant criteria for energy recovery (see section 2.4.3). Following pre-assessment, in-depth analysis was carried out on the preselected biowastes, to fill data gaps for a reliable MCA.

2.3 Multi-Criteria Analysis

2.3.1 Selection criteria

Suitable biowastes for energy recovery were selected based on criteria used by Lohri et al. (2015). The criteria were classified into two categories, waste availability and accessibility and physical-chemical waste properties. Legal regulations may affect access, transport, treatment or enduse of a biowaste, hence it is important for the suitability (e.g. costs) of biowastes and so was added to the list of selection criteria. Table 1 explains the significance of each criteria and how it is measured.

Table 1: Multi-Criteria Analysis criteria

Waste availability and accessibility	Physical-chemical waste properties
Quantity generated o Significance: This indicates if sufficient quantities of the biowaste are available for co-processing with FS. o Unit: tons dry mass/month.	Moisture content o Significance: Low moisture content is needed for pellet production and gasification. The moisture content of biowastes will dictate the degree of drying required before energy recovery. o Unit: wt% dry mass.
Cost (incl. transport costs) o Significance: This includes cost price estimates for the biowaste, transportation costs to NWSC Lubigi and costs for licenses (if applicable). These costs influence the financial feasibility of the biowaste for energy recovery. o Unit: USD/ton dry mass.	Ash content o Significance: Ash content indicates the incombustible material present. High ash contents reduce the calorific value and may cause operational problems (e.g. fouling). o Unit: wt% dry mass.
Competing uses o Significance: High demand and competition for biowastes will decrease its availability and increase costs. o Unit: % of total quantity used.	Fixed Carbon o Significance: Fixed carbon can be used to classify and compare biowaste characteristics and is an indicator for the char yield after pyrolysis. o Unit: wt% dry mass.
Degree of centralization o Significance: This considers the quantity of waste produced per location. Single bulk producers of a biowaste are favoured over multiple small-scale producers; it will take longer to collect a significant quantity of the biowaste from small-scale producers, increasing transportation costs. o Unit: Number of known locations for one biowaste. It is assumed a single or small number of locations indicates a bulk producer and a large number of locations indicates small quantities are being produced.	Calorific Value o Significance: Calorific value is metric of biowastes energy potential. o Unit: MJ/kg dry mass.
Seasonal variability o Significance: This indicates how consistent the supply of a biowaste is throughout the year, it impacts the supply of raw materials for pellet production and hence the product quality and product supply. o Unit: Number of months per year the material is available.	Bulk density o Significance: Bulk density affects transport and storage costs. o Unit: kg/m^3.
Legal regulations o Significance: Environmental regulations determine permit requirements for collection, transport and treatment of waste, this may	Particle size analysis o Significance: The pelletizer requires a particle size less than 2 cm. Hence, the particle size is assessed visually to determine if

affect the cost of a biowaste or if it can be used at all. o Unit: Y (yes) or N (no) indicates if a permits are required.	pre-processing is needed prior to pelletizing, for example shredding or cutting. o Unit: Degree of pre-processing required.
	Impurities o Significance: Impurities in the biowaste refer to the presence of non-organic material, for example plastics or metals. The concentration of impurities will determine if and to what extent pre-processing is required. . o Unit: wt% of impurity present.
	Heavy metals o Significance: Heavy metals concentrate in the ash during energy recovery influence emissions, corrosion and ash disposal. The most environmentally relevant heavy metals are arsenic, cadmium, chromium, copper, nickel, zinc, lead and mercury (European Environment Agency, 2013). o Unit: Y (yes) or N (no) represents whether heavy metals concentration are above limits for biosolids land application and operational limits (Obernberger et al., 2006).

2.3.2 Scoring

The data collected from the in-depth analysis, along with data from interviews and literature provided the basis to create a scoring system in order to identify the most suitable biowastes with the MCA. According to Lohri et al. (2015), each criteria listed in Table 1 was assigned a score of 1 to 5. Scores were assigned based on the range of values collected for each criteria using FS as a benchmark. A high score was assigned to desired values and low scores assigned to undesirable values. Additionally, criteria were given weights between one and five based on the importance of the criteria for energy recovery. As part of this study, quantity generated and costs were given a weight of five, moisture content, ash and calorific a weight of three and all other criteria a weight of one. This weighting also ensured that the availability-accessibility criteria and physical-chemical criteria contributed each 50% of the total score. In total, the highest score is 70 for each category and a total score of 170. The final score was expressed as percentage of total score.

2.4 Pre-assessment

2.4.1 Stakeholder mapping

An iterative approach was used to map relative stakeholders. A stakeholder list was developed, starting with principal stakeholders who were identified due to their role in waste generation or management in and around Kampala. The principal stakeholders were asked to advise additional stakeholders to be interviewed, as well as literature to be reviewed as often Master of PhD theses are not published or distributed. Recommended stakeholders were added to the list and interviewed, continuing the process until the list was exhausted.

2.4.2 Review of secondary data and stakeholder interviews

Relevant scientific papers, reports, MSc and PhD theses were reviewed for secondary data. Semi-structured interviews were conducted with stakeholders identified through the iterative stakeholder mapping. Open-ended questions were asked of the stakeholders and topics of interest that came up were discussed in more detail. In general, the interviews covered the following questions:

Waste management services, researchers and industries producing biowaste

- What type of biowaste is generated in Kampala/in your company/in your field of research?
- What quantity of biowaste is generated on a daily, weekly and/or monthly basis?
- How is the waste managed (collection, transport, treatment, enduse)?
    - Who is responsible for the collection and disposal of the biowaste?
    - Is the biowaste used or disposed?
    - Are there any cost or prices associated with the biowaste?
    - Who is the biowaste sold to (if applicable)?
    - How does the customer use the biowaste (if applicable)?

Users of urban biowastes

- What product is sold?
- What types of biowaste are used?
- From where is the biowaste obtained?
- What is the price for the biowaste?
- In what quantities is the biowaste used?
- What are the reasons for selecting the biowaste used?
- Is the biowaste obtained from a single bulk producer or multiple smaller producers?
- Who are competitors for the biowaste?

2.4.3 Pre-selection of biowastes for in-depth analysis

28 biowastes were identified in Kampala, however not all are suitable for energy recovery. Furthermore, secondary data and stakeholder interviews identified many data gaps, hence in-depth analysis was required to provide data for a reliable MCA. A matrix was developed to visualize existing data and data gaps for the MCA criteria. Based on most relevant criteria for energy recovery including average quantity generated, cost, competing uses, degree of centralisation, seasonal variability, moisture content, ash, calorific value and heavy metals a simplified version of the MCA was devised to rule out biowastes that appear to have low potential for energy recovery and hence do not need further investigation. A colour-coded system of green, orange and red was assigned values to identify high, medium and low suitability (see Table 2).

Table 2: Colour coded simplified score key for biowaste pre-assessment.

Colour code					
Suitability	Unit	High	Moderate	Low	No data
Cost	USD/ton	<100	100-150	>150	
Quantity available	ton/month	>1000	100-1000	<100	
Seasonal variation	-	consistent		inconsistent	
Degree of centralization	-	one bulk source	multiple sources within	source outside of Kampala	

Competing uses	-	no demand	Kampala Moderate demand	High demand
Moisture content	wt%	<20	20-40	>40
Ash content	wt% dry mass	<5	5-10	>10
Calorific value	MJ/kg dry mass	>18	14-18	>14

2.5 In-depth analysis

In-depth analysis was applied to the biowastes selected in the pre-assessment to provide reliable data to implement the MCA. This included primary data collection (i.e. biowaste characterisation and quantification) and stakeholder interviews to provide information for all selection criteria described in Section 2.3.1. Reliable secondary data was directly used in the MCA and not determined through in-depth analysis.

2.5.1 Waste availability and accessibility

Waste availability and accessibility included estimating the average quantity of biowaste generated, the seasonal variability, competing uses, the degree of centralisation, biowaste cost and legal regulations. This was based on literature data, stakeholder interviews (e.g. KCCA division officers) and qualitative field observation.

2.5.2 Physical-chemical waste properties

2.5.2.1.1 Waste sampling

Biowastes selected for in-depth analysis vary in composition, location and storage method. Hence, sampling methods for characterisation and quantification of the biowastes were tailored to each biowaste.

At NWSC Lubigi, dewatered FS was sampled for characterisation from drying beds and storage units. Drying beds were divided into six equal sections. A sample of equal volume was taken from the centre of each section and thoroughly mixed together to produce a composite sample. This was repeated for drying beds. At the time of sample collection, dewatered FS was stored in three storage units. For each storage unit, samples were collected from three locations within the storage unit – front, back and middle – and at two layers from each sampling point. Hence, a total of six samples were collected and mixed together thoroughly to produce one composite sample from each storage unit.

At NWSC Bugolobi, dewatered wastewater treatment sludge was sampled from the drying beds. The anaerobic and facultative ponds at NWSC Lubigi have not yet been emptied so no sludge was available on drying beds during the time of this study. At NWSC Bugolobi, dewatered wastewater treatment sludge was collected from drying beds for sludge characterisation. The beds were divided into nine equal sections and a sample of equal volume taken from each section. The samples were then thoroughly mixed together to produce one composite sample. Wastewater treatment sludge was not sampled for quantification of sludge production because records are kept of the quantities of sludge collected from the drying beds and sold to farmers as soil conditioner. These records were deemed more accurate and used to estimate the quantities of WWTS produced at Bugolobi. The amount of wastewater treatments sludge produced at Lubigi was estimated based on the plant design (Fichtner Water & Transportation, 2009).

Water treatment sludge at Gaba III was sampled for both characterisation and quantification. For characterisation, two samples were collected from drying beds and two samples collected from dewatered sludge stockpiled next to the drying bed. The drying beds were divided into six equal sections and a sample of equal volume taken from each section. The samples were mixed thoroughly to produce one composite sample. Samples from the stockpile were collected from two separate locations. Gaba III has four clarification tanks in which sludge is produced. Sludge is discharged alternately from clarification tanks. For each clarification tank, sludge is discharge from 36 pipes to the drying beds. Effluent pipes are grouped into three groups, which consist of three subgroups of four pipes. One group and one pipe of each subgroup discharge at one time. The discharge cycle from one clarification tank continues until sludge was discharged through all pipes of one clarification tank. This discharge is continuously for 24 hours. Length of discharge from each clarifier and discharge was estimated using a 30 litre bucket and a stopwatch. A sample of 100 ml was collected every ten minutes for one hour from the pipe discharging WTS from different clarifiers and one composite sample was produced. This was repeated at two separate days. In addition to this continuous discharge of sludge, sludge is collected during regular cleaning of the clarification tank. The quantity of sludge produced during cleaning of clarification tanks could not be estimated in this study.

The agricultural wastes, such was banana peels, banana leaves, bean husks were grab sampled at markets in Kampala. Coffee husks were sampled at the hulling factory. Samples for the agro-industrial waste such as brewery waste was sampled at Uganda Breweries Ltd. in Port Bell, Kampala and sawdust and woodshavings were sampled from a furniture workshop in Kampala. All samples were stored in plastic containers in a cooler box until they were transported to the fridge in the laboratory.

2.5.2.2 Waste analysis

If there is no current, reliable data available in the literature, each biowaste sampled was analysed for the properties listed in Table 3.

Table 3: Analysis methods used for biowaste characterisation and quantification

Properties	Method
Total solids (TS)/moisture content/wt% dry mass	Measured gravimetrically at 105°C according to Standard Methods APHA (2012) American Public Health Association (AWA) et al. (2012), ASTM 1756 (ASTM, 2008) and ASTM E871 (ASTM, 2013b).
Total suspended solids (TSS)	Total suspended solids were used to estimate sludge production at Lubigi and Gaba. TSS was analysed based on American Public Health Association (AWA) et al. (2012)
Bulk density	Measured by determining the weight of material that fill a box of known volume according to standard methods ASTM E873 (ASTM, 2013a).
Particle size analysis	Samples are inspected visually to determine if the cross-section of waste particles is greater or less than 2 cm.
Proximate Analysis	Measures the total volatile solids (TVS), ash content and fixed carbon of a 100% dry sample. TVS is measured gravimetrically at 950°C for seven minutes in a covered crucible according to ASTM E872-82 (ASTM, 2013c). Ash is determined gravimetrically at 575°C for three

	hours according to ASTM E1755 (ASTM, 2007). Fixed carbon is calculated by subtracting the sum of TVS and ash from 100%.
Ultimate Analysis	Ultimate analysis measures the C, S, N, P, Cl and heavy metal content of a 100 % dry sample. This was done with X-Fluorescence (Spectro Xepos) at Eawag.
Calorific value	Measured according to European Standard (2011) using the IKA C1 Calorimeter at Paul Scherrer Institute (PSI).

2.5.3 Multi-Criteria Analysis score key

The key for availability and accessibility and physical-chemical properties is shown in Table 4 and

Table 5. Co-processing of biowastes with FS aims to improve the fuel characteristics of FS. Therefore, FS characteristics determined in this study were used to set Score 1 for quantity generated (score 1 at least 50% of FS quaintly), ash content, fixed carbon, calorific value and bulk density (below). The highest score for ash content was set as the lowest range of ash content, with appropriate intervals made for the remaining scores. For fixed carbon and calorific value the best score was based on the range of values determined in the in-depth assessment, the maximum value measured was set as Score 5. Particle size is given scores based on the degree of pre-processing required, no pre-processing receives the best Score 5, the score decreases the more difficult the biowaste is to pre-process. The scores for impurities indicate anything with more than 10% impurities would not be considered.

Table 4: Availability and accessibility

Criteria	Unit	Score 1	Score 2	Score 3	Score 4	Score 5	Criteria Weight
Quantity Generated	tons dry mass/month	≤50	50-65	65-80	80-95	>95	**5**
Cost	USD/ton dry mass	>100	50-100	25-50	25-10	≤10	**5**
Competing Uses	% of waste reused	100	75-100	50-75	25-50	<25	**1**
Degree of Centralisation	Number of locations	≥10	7-9	4-6	2-3	1	**1**
Seasonal Variability	No. mon/year available	≤3	4-5	6-8	9-11	≥12	**1**
Legal Regulations	Permit required (Y/N)	Y	-	-	-	N	**1**

Table 5: Physical-chemical properties

Criteria	Unit	Score 1	Score 2	Score 3	Score 4	Score 5	Weight
Moisture Content	wt%	≥40	30-40	20-30	10-20	<10	**3**
Ash Content	wt% dry mass	≥45	30-45	20-30	10-20	<10	**3**
Fixed Carbon	wt% dry mass	≤10	10-11	12-13	14-15	≥16	**1**
Calorific Value	MJ/kg dry mass	≤12	13-14	15-16	17-18	≥19	**3**
Bulk Density	kg/m^3	≤300	300-450	450-600	600-750	>750	**1**
Heavy Metals	Cause for concern (Y/N)	Y	-	-	-	N	**1**

Particle Size	Degree of pre-processing needed	Size reduction of a variety of materials.	Size reduction required of large, soft material.	Size reduction of small, hard material.	Size reduction required of small, soft material.	No size reduction required.	**1**
Impurities	% of impurities	10	-	5	-	0	**1**

3 Results and Discussion

3.1 Pre-selection of biowastes

Pre-assessment identified 28 different biowastes in Kampala and Uganda. The results of the pre-assessment are summarized in Table 6. Based on the assessment of quantity available, estimated cost, moisture content, ash content and calorific value, next to FS, the following biowastes waste streams were identified for in-depth analysis. Water treatment sludge and wastewater treatment sludge were included despite their low potential for energy recovery as they remain currently unused or are sold below value.

- Market waste
- Water treatment sludge
- Wastewater treatment sludge
- Brewery waste
- Maize cobs
- Coffee husks
- Sawdust
- Banana peelings
- Banana leaves

The other identified waste streams were ruled out due to their low potential for energy recovery with FS. The following biowastes were identified in Kampala but ruled out for in-depth analysis:

- Uganda is a large-scale producer of sugar. Bagasse is a by-product of sugar production and has a calorific value of approximately 18 MJ/kg dry mass. However, energy recovery of bagasse with FS was ruled out due to the high competitive uses of bagasse for large-scale power production within the sugar industry or as solid fuel in industries (Rubaramira, personal communication, Miles et al., 1995, Jorapur and Rajvanshi, 1997).
- Large quantities of rice husks are being produced in Uganda and have a high calorific value of 13.2–15.3 MJ/kg dry mass (Mhilu, 2014, cited by Basu, 2013). However, energy recovery of rice rusks with FS was ruled out due to its high market value in Kampala of 300 USD/ton and its high ash content of 15.5-26.2 wt% dry mass (cited by Basu, 2013, Vera, personal communication, Mhilu, 2014).
- Large quantities of groundnut husks could not be identified in Kampala. Therefore, groundnut husks were ruled out for further analysis. Groundnut husks have an ash content of 3-7 wt% dry mass and a caloric value of 17-21 MJ/kg dry mass (cited by Werther et al., 2006, Gover, 1989).
- Limited data exists for both the availability and physical-chemical properties of wheat bran. Wheat bran was ruled out for energy recovery with FS due to its high cost estimated at 190 USD/ton and a moisture content of 20 wt% (Lukoda, personal communication, Rutaisire, 2007).
- Limited data exists for the availability and physical-chemical properties of wheat husk. Wheat husks were ruled out for energy recovery with FS due to its low available quantities of less than 4 tons/months which is too low to be of interest for industry-scale processing with FS (Musisi, 2002).

- Maize bran can cost up to 200 USD/ton and has high competition as it is used currently for animal feed because of its nutritional content (Vera, personal communication). Hence it was ruled out due to its high cost and competing use.
- Large quantities of millet husks could not be identified in Kampala and were therefore ruled out for further analysis. Moisture content for millet husks ranges from 4 to 9 wt% and ash of 3 to 9 wt% dry mass. The calorific value can reach 19 MJ/kg dry mass (Vassilev et al., 2010, AgroVäst and ÄFAB, 2006).
- Large quantities of ccoconut shells could not be identified in Kampala and were therefore ruled out for further analysis. Coconut shells have a moisture content ranging from 4 to 14 wt%, ash as low as 0.5 and up to 3 wt% dry mass and a calorific value of approximately 20 MJ/kg dry mass.
- Cotton stalk has a favourable calorific value of up to 19 MJ/kg dry mass and has a low ash content of approximately 3 wt% dry mass (Vassilev et al., 2010, Iyer et al., 1997) However, the ash can reach 17 wt% dry mass. Therefore, it was ruled out for further analysis.
- Sweet potato vines have a high moisture content of 80 wt% and an ash content over 12 wt% dry mass. Therefore, it was ruled out for energy recovery with FS (Katongole et al., 2008, Dung et al., 2002).
- No large quantities of bean husks could be identified in Kampala. Therefore, bean husks were ruled out for further analysis. Bean husks have a moisture content of 6 wt%, an ash content of 5 wt% dry mass and calorific value of 17.5 MJ/kg dry mass.
- Chicken litter and cow dung from poultry and cow farming, blood and bone meal from abattoirs, and fish waste from fish processing are available in Kampala. Chicken litter and cow dung were ruled out for energy recovery with FS due to its high moisture and ash content. Chicken litter has a moisture content of 16 to 40 wt%, ash content of 13 to 16 wt% dry mass and a calorific value between 14 to 19 MJ/kg dry mass. Cow dung has similar ranges, however moisture content can reach up to 80 wt% and ash up to 42 wt% dry mass. Blood and bone meal and fish waste were ruled out due to their high costs of 300 to 400 USD/ton for bone meal and 100 to 700 USD/ton for fish meal (Rutaisire, 2007).
- Paper waste was ruled out because the moisture content can reach up to 60 wt%, and the ash content ranges from 8 to 40 wt% dry mass. Further the calorific value can be as low as 10 MJ/kg dry mass (Sørum et al., 2001, Miles et al., 1995)

Table 6: Simplified Multi-Criteria Analysis to pre-select biowastes for in-depth analysis.

Waste Stream		Average Quantity	Seasonal Variability	Competing Uses	Degree of Centralization	Cost	Moisture Content	Ash Content	Calorific Value
Municipal Solid Waste									
Market Waste									
Water Treatment Sludge									
Wastewater Sludge									
Faecal Sludge									
Agricultural Waste	Bagasse								
	Coffee husks								
	Maize Cobs								
	Rice Husks								
	Groundnut husks								
	Banana peelings								
	Banana leaves								
	Wheat bran								
	Wheat husk								
	Maize bran								
	Millet husks								
	Coconut shells								
	Cotton stalks								
	Sweet potato vines								
	Bean husks								
Animal Waste	Poultry farms - chicken litter								
	Cattle farms - Cow dung								
	Abattoir - cow dung								
	Abattoir - blood and bone meal								
	Fish Processing								
Agro-Industrial Waste	Breweries								
	Sawdust								
	Paper								

3.2 Assessment of suitable biowastes for energy recovery

3.2.1 Status quo: Faecal sludge

Table 7 summarizes the quantities and characteristics of dewatered FS available for energy recovery in Kampala.

Table 7: FS quantity and characteristics analysed in this study.

Quantity	Ash Content (n=4)	Fixed carbon (n=4)	Calorific Value (n=4)	Bulk Density (n=5)
tons dry mass/month	wt% dry mass	wt% dry mass	MJ/kg dry mass	kg/m^3
19-250 **100 (average)**	44.4±9.7	10.8±4.6	11.1±4.6	306±115

The quantity of 100% dried FS varies between 19-250 tons per month depending on the calculation approach used. Based on operational data provided by NWSC, 19 tons dry mass were harvested per month within end of May and end of December 2014 (Orwiny, personal communication). This quantity does not include scum or sludge mechanically removed from the settling-thickening tank and therefore underestimates the total available FS quantity available for energy recovery.

The mass balance of NWSC Lubigi illustrated in Figure 2 appears to be a better estimate. The Figure demonstrates that the quantity of FS available for energy recovery is strongly influenced by the separation efficiency of the settling-thickening tanks and drying beds. The solids discharged at NWSC Lubigi by vacuum trucks gets reduced by solids discharged to the waste stabilization ponds and solids discharged through the filter layer of the drying beds. Based on discharge volumes at NWSC Lubigi (Orwiny, personal communication), concentration of TSS in FS in Kampala (Sandec, unpublished data) and the separation efficiency of the settling-thickening tank and drying beds (Orwiny, personal communication, Heinss et al., 1998) approximately 100 tons dry mass are produced per month at Lubigi. This includes scum and sludge removed mechanically from the settling-thickening tank. An estimated additional 30 tons dry mass/month would be produced at NWSC Lubigi in case all FS currently discharged at NWSC Bugolobi would be discharged at NWSC Lubigi. An increase in the separation efficiency, e.g. by more frequent emptying of the settling-thickening tank would increase the quantity of dried FS available for energy recovery.

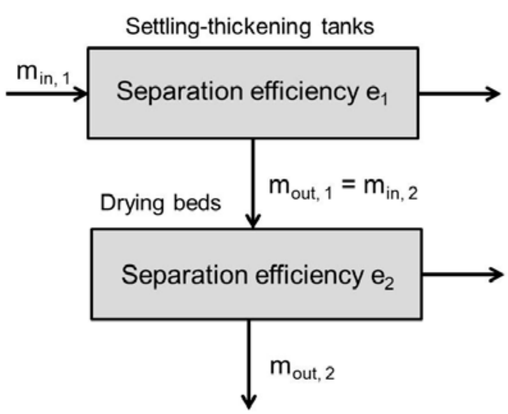

Figure 2: Mass balance of dried FS production at NWSC Lubigi.

The design of NWSC Lubigi is based on a production of 250 tons dry mass/month (Fichtner Water & Transportation, 2009). However, this calculation appears to overestimate the FS production as it assumes a higher separation efficiency in the settling-thickening tank and drying beds than currently achieved in operation. Further, it is based on TS rather TSS and therefore assumes that also dissolved solids contribute to the quantity of dried FS produced. FS production of 100 tons dry mass/month appears as the most accurate estimate for the currently discharged 380 m^3/month at NWSC Lubigi.

3.2.2 Availability and accessibility

Table 15 in the Appendix summarizes the values for the availability and accessibility criteria estimated in this study. The waste assessment revealed a huge variability in waste quantity and costs between different references and calculations for one biowaste. To account for this variability, a minimum, maximum and average value are being reported. The average quantity is the median of the minimum and maximum value.

Market waste includes fruit and vegetable waste – produce that is spoiled and can't be sold, off cuts, skins and peelings collected at markets in Kampala. It also contains paper, cardboard and plastic (packaging from the produce) and textiles from tailors working at the market. The average quantity of market waste produced in Kampala is estimated at 850 tons dry mass/month. Currently, market waste is disposed at the Kiteezi landfill. Therefore, the costs of market waste are equal to the transport costs from markets in Kampala to NWSC Lubigi (see Appendix, Table 11). Market waste can have a considerable amount of inorganic waste which needs to be removed before pelletizing and gasification. As shown in Table 8, the KCCA Division Officers in Kampala (Central, Nakawa, Rubaga, Makindye, Kawempe) qualitatively classified the markets according to their percentage of organics in market waste. The markets with the highest organic content such as Nakasero should be targeted for pelletizing and gasification with FS to reduce the need for pre-treatment.

Table 8: Organic content and quantity of waste per market

Division	Market	Organic Content	Quantity Collected
-	-	%	tons/day
Central	Nakasero	100	26
	Kamwokya	98	-
Rubaga	Kibuye	96	3
	Kasubi	90	5
	Nateete	95	5
Nakawa	Nakawa	90	9
	Bugolobi	85	4
	Bukoto	86	13
	Luzira	80	4.5
Makindye	Katwe	90	3
	Kasanga	85	3
	Kabalagala	80	3
	Munyonyo	85	5
	Gaba	75	3
Kawempe	Kalerwe	95	4
	Bwaise	85	4
	Kawempe	75	4

Collection, transport and treatment of market waste requires a licence from the National Environmental Management Authority (NEMA). Currently, market waste is mainly collected by the following private collection companies; Green Hope Uganda Ltd., Juakali Nakivubo, A&M Cleaning Services, Home Care General Enterprises Ltd. and Hill Top Enterprises Ltd.

Water treatment sludge is produced at NWSC Gaba I, Gaba II and Gaba III. Currently, sludge from water treatment is only collected for dewatering on drying beds at Gaba III. Based on field measurements in this study an estimated 30 tons dry mass water treatment sludge are generated per month at Gaba III. However, sludge often bypasses the drying beds for discharge into the adjacent wetland due to low dewatering efficiency of the drying beds (Tweheyo, personal communication). Further, sludge which is produced during cleaning of the clarification tank and mostly placed on drying beds could not be estimated and is not included in the above estimate. Dewatered wastewater sludge is currently stored next to drying beds at Gaba III without any reliable enduse. Therefore, the cost of water treatment sludge is equal to the transport costs from Gaba III to NWSC Lubigi (see Appendix, Table 11).

Wastewater treatment sludge is produced at NWSC Bugolobi and NWSC Lubigi from wastewater treatment. Currently, an estimated 100 tons dry mass wastewater sludge is produces per month at NWSC Bugolobi and sold to famers as soil conditioner in agriculture for 10,000 UGX/ton. This price should be seen as a rough estimate as the size of the truck is only estimated based on visual observations. At NWSC Lubigi, wastewater sludge is produced in anaerobic and facultative ponds. These ponds have not been emptied yet. Based on the design of NWSC Lubigi approximately 70 tons dry mass/month are produced.

Coffee husks are all residues produced during processing of coffee into coffee beans. Typically, coffee undergo processing close to their production before they are transported to the distributors and exporters in Kampala. Figure 3 shows regions of coffee farming in Uganda including the following: Mbarara, Ntungamo, Bushenyi. Hoima, Kasese, Mbale, Masaka, Kibale, Kisoro, Bududa, Kapchorwa, Mukono, Mubende, Luwerro, Mpigi, Rakai and Nakaseke (Semalulu, personal communication, Sabiiti et al., personal communication).

Coffee husks are produced as part of two different ways of processing; wet processing (washing) and dry processing. Wet processing ‘washes’ the coffee, separating the coffee cherry and the coffee bean. The wet cherry that is leftover from washing is referred to as pulp. Commonly, the pulp is directly used on the coffee farm as soil amendment. The coffee bean is dried and hulled, removing the outer shell, referred to as husk. This part can be used as an alternative fuel or soil amendment. In contrast, dry processing involves drying of the coffee cherry and coffee bean together. Following drying, the dried coffee cherry and coffee bean are hulled, removing the dried coffee cherry and outer shell of the coffee bean together. This outer shell is also referred to as husk and includes the dried coffee cherry and outer husk. When either of these methods are done at a primary pre-processing or hulling plant, the husks are either returned to the farm or sold (Leons, personal communication). Some husks remain on the beans which explains why small amounts of coffee husks are produced during further coffee processing of the coffee bean in Kampala, however, the majority of coffee husks are produced during pre-processing in the vicinity of coffee farms.

In Uganda, an estimated 7800 tons dry mass of coffee husks are produced per month. In Kampala, an estimated 100 tons dry mass/month are produced based on a survey of five coffee companies in Kampala. Coffee has a seasonal variability with larger quantities being available from June to September and November to January. The price for coffee husks showed a huge variability. Average costs for coffee husks were estimated at 140 USD/ton dry mass. The variability of prices can be explained by economies of scale (buying large quantities is cheaper, e.g. by brick companies) and lack of access to the market prices by small-scale farmers. The best way to obtain a reliable supply of coffee husks is directly from coffee processing in the vicinity of coffee farms. In Uganda, coffee husks have a high market demand by cement and clay companies. Hima cement reports to meet 45-60% of its energy demand by coffee husks.

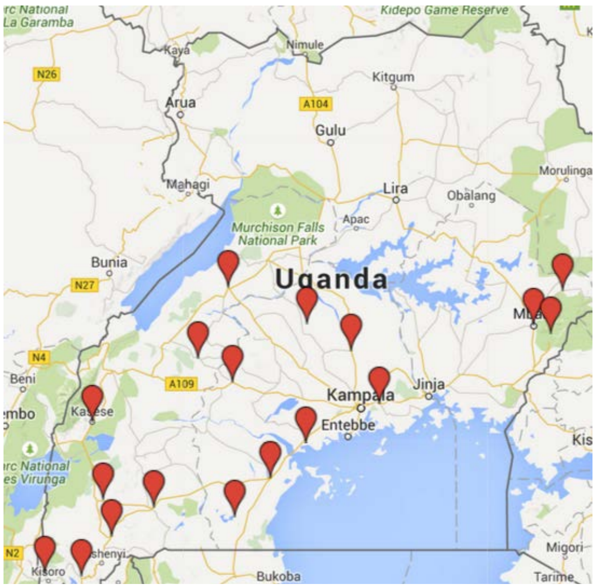

Figure 3: Regions of coffee farming identified as part of this study in Uganda

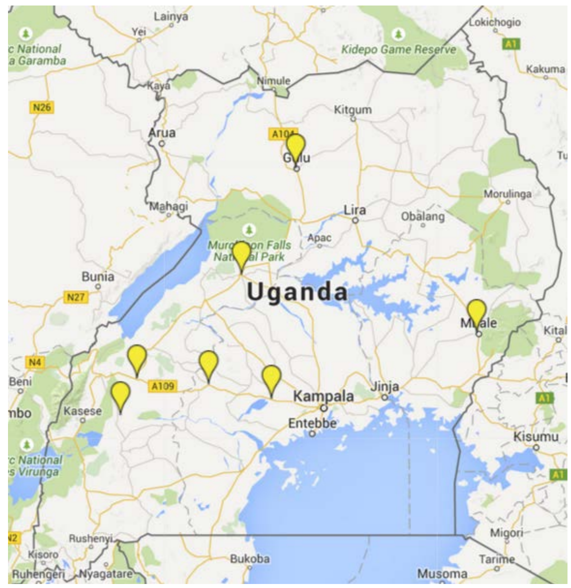

Figure 4: Regions of maize farming regions identified as part of this study in Uganda.

Maize cobs remain from production of maize products such as maize flour and maize bran. Similar to coffee husks, maize cobs are only produced in small quantities in Kampala whereas large quantities are produced in the vicinity of farms. Figure 4 shows regions of maize farming in Uganda including the following: Mubende., Masindi, Kamwenge, Kyenjojo, Mityana, Gulu and Mbale.

As part of this study, in the vicinity of Kampala, an estimated 40 tons dry/month maize cobs are produced. The quantity produced in Uganda is expected to be several magnitudes higher. Maize is grown and harvested all year around. Highest quantities are available from December to April (Kyongo et al., personal communication). Competition for maize cobs is low because it has a low nutritional content and hence is not widely used for animal feed (Nuwabaasa, personal communication). As part of this study, average costs for maize cobs were estimated at 80 USD/ton dry mass. Producers of maize products in Kampala stated that maize cobs are currently left behind during pre-processing because of its low market value in Kampala. Producers of maize products would be the best way to access larger quantities of maize cobs.

Banana peelings are produced at markets when they are either sold raw or cooked. At Nakawa and Kalerwe market, an estimated 10 tons dry mass/month banana peelings are being produced. Therefore, for all markets in Kampala, quantities of banana peelings being produced are expected to be above 100 tons dry mass/month. Banana peelings are available year round however larger quantities are available from May to September (Bikuuta et al., personal communication). Banana peelings have a high market value with an average price estimated at

250 USD/ton dry mass. The peelings are mostly recovered for animal feed, mainly for cattle, goats and pigs. The best way to access a reliable supply of banana peelings are market vendors.

Banana leaves are produced at markets in Kampala. They are used as packing material when transporting bananas from farms to the markets in Kampala. At Nakawa, Bwaise and Kalerwe market, an estimated 60 tons dry mass/month banana leaves are being produced. Banana leaves are available year round, however larger quantities are available May to September (Mubiiru et al., personal communication, Zziwa, personal communication, Sabiiti, personal communication).The average market price for banana leaves is around 750 USD/ton dry mass. Banana leaves are currently used for cooking matooke and posho, wrapped around or covering food and cooking pots to lock in flavour and keep food warm. Further, they are used in restaurants, canteens, at functions and parties, at barracks and are used domestically. They are reused several times before they are discarded.

Brewery waste is produced during brewing of beer at Uganda Breweries Limited (UBL) (owned by East African Breweries Limited), Nile Breweries Limited and Parambot Breweries Limited. UBL and Parambot Breweries are both located in Kampala, Port Bell and Kitetika respectively. Nile Breweries has a brewery in Jinja and Mbarara. Two types biowastes are produced in breweries: spent grain and malt/sorghum husks.

UBL (Port Bell), Nile Breweries (Mbarara) and Parambot Breweries (Kitetika) reported production of 620 tons dry mass/month spent grain. UBL (Port Bell) reported production of 4 tons dry mass/month malt and sorghum husks. This estimate does not include all brewery locations (e.g. Nile Breweries is Jinja), therefore, total quantities produced are expected to be significantly larger. Breweries reported that the production is continuous throughout the year, however the production rate is higher from October to December due to increased availability of the raw materials. Production is also impacted by intermittent power supply to the factory, storage capacity of raw materials and machinery breakdown (Cherukut, personal communication, Mugabi, personal communication, Oyo, personal communication). Spent grain and sorghum/malt husk are currently sold for an estimated 170 USD/tons dry mass and 50 USD/tons dry mass to poultry, pig and cattle farms as animal feed or for animal bedding.

Sawdust is produced in Kampala at carpentries and furniture workshops. In Kampala, an estimated 100 tons dry mass/month sawdust are produced. Sawdust production is very decentralized. Nine carpentry and furniture workshops surveyed within Kampala had a production of 4-27 tons dry mass/month. Decentralization suggest that only a fraction of carpenters and workshops were identified and total sawdust quantities produced in Kampala are significantly larger. The supply of sawdust is not expected to vary seasonally. The average price for sawdust is estimated at 100 USD/ton dry mass. Currently, sawdust is sold for use as animal bedding and to industries as a fuel (e.g. Uganda Clays Ltd, Kajjansi Brick, Tile Works Ltd).

3.2.3 Physical-chemical properties

Results of the physical-chemical characterization are included in the Appendix in Table 12, Table 13, Table 14 and Table 16. To highlight the physical-chemical properties biowastes analysed in this study can be classified within the most relevant parameters for energy recovery. Moisture content: Market waste, banana peelings and banana leaves and spent grain have a high moisture content of 70-85%. The moisture content of water treatment sludge, FS and wastewater sludge is also high with 44-60%, however, this can effectively reduce by longer drying times at NWSC Gaba, Lubigi and Bugolobi. High moisture contents not only requires pre-processing of the biowaste before pelletizing, but also increase transport costs per dry mass (see Appendix, Table 11). Coffee husks, maize cobs, sorghum/malt husks and sawdust have low moisture contents of 10-12%. This means co-processing with FS can reduce the need for drying of FS.

Ash content: Wastewater treatment sludge, wastewater treatment sludge and FS have high ash contents of 40-50% and market waste of 15%. In contrast, all other biowastes have ash contents of 1-9%. This means co-processing with these waste streams can efficiently reduce ash contents for energy recovery.

Calorific value: The calorific value is related to the ash content. All biowastes with low ash contents had a calorific value of 17-20 MJ/kg dry mass. In contrast, in this study, the calorific value of water treatment sludge, wastewater treatment sludge and FS was 8, 13 and 11 MJ/kg dry mass respectively.

Heavy metals: In this study, wastewater treatment sludge and FS had the highest concentrations in heavy metals. These values were below guiding values for combustion of biomass, the limits of land application of biosolids (US and Germany) and limits by cement industries (Gold et al., in preparation). However, elevated concentration in heavy metals need to be considered during selection of a gasification technology and for ash disposal. Most heavy metal will concentrate in the ash/char remaining from gasification.

3.2.4 Multi-Criteria Analysis

Figure 5 shows results of MCA of pre-assessed biowastes analysed in this study. Sawdust, coffee husks, spent grain, market waste, malt/sorghum husks and maize cobs received similar total scores above 80% of the total possible score. FS, wastewater treatment sludge, banana leaves and peels and water treatment sludge had the lowest scores.

In general, the results from MCA can be classified in two groups:

FS, water treatment sludge and wastewater treatment sludge: High availability-accessibility scores, low physical-chemical characterises scores.

All other biowastes: Low availability-accessibility scores, high physical-chemical characterises scores.

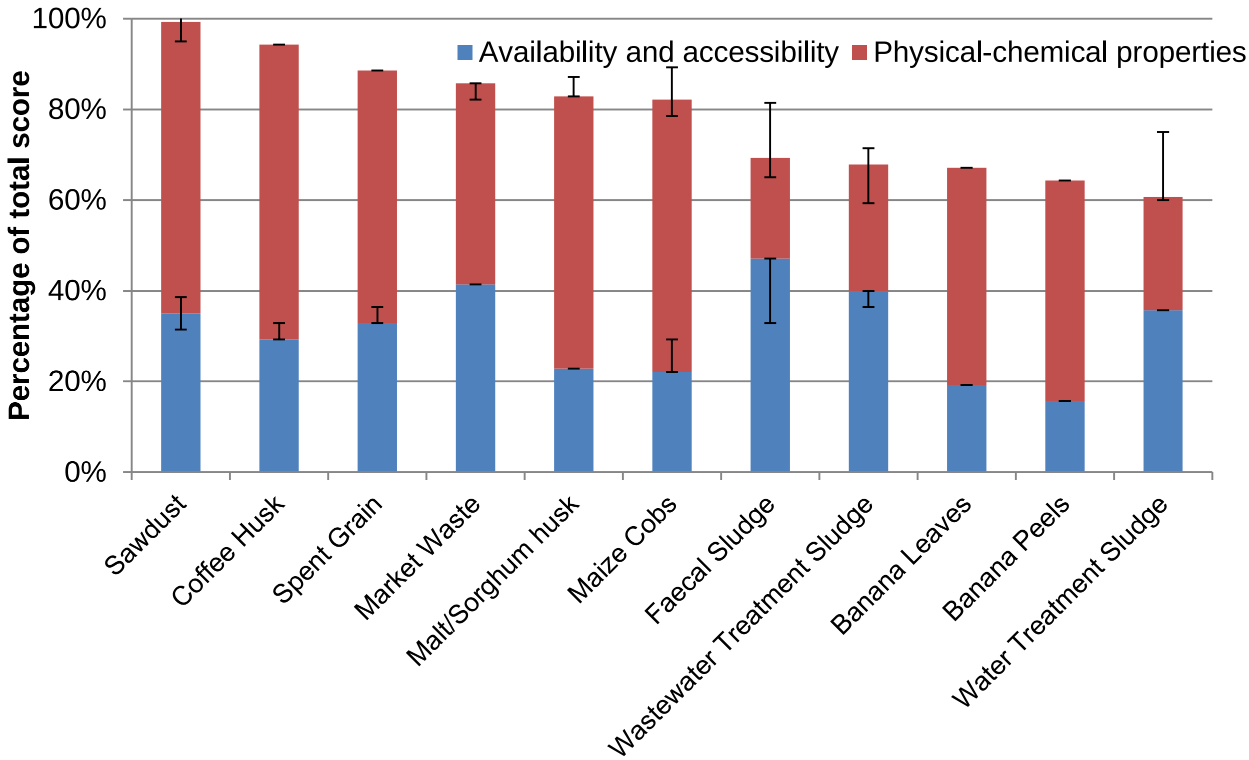

Figure 5: Results of MCA for pre-assessed biowastes (in percentage of total score).

Sawdust, coffee husks, spent grain, market waste, malt/sorghum husks, maize cobs and banana leaves and banana peels have good physical-chemical characteristics for energy and a high potential to increase the fuel quality of FS for energy recovery. However, these favourable characteristics come with high costs. All of these waste streams except for market waste already have a high market value. For wet biowastes such as spent grain, market waste, and banana leaves the market value per ton dry mass is significantly larger than the price for wet biowaste as a lot of the product is water which needs to be transported. Table 11 in the Appendix summarizes the transport costs per ton dry mass for each waste stream.

3.2.5 Feedstock analysis

Biowaste logistics: Table 11 shows transport costs for different biowaste streams in Kampala and from other parts of Uganda to Kampala. In Kampala and Uganda transport costs range from 6-43 USD/ton dry mass and 20-132 USD/ton dry mass respectively. According to Wade (personal communication) and Nyeko (personal communication) a realistic sales price for FS as a solid fuel is 60 USD/ton. This suggest that transport of biowastes from outside of Kampala for solid fuel production in Kampala is not financially feasible as transport costs may be higher than the sales price of a FS fuel.

FS fuel logistics: The bulk density of FS pellets at around 90% dry mass is around 650 kg/m^3 which is higher compared to crushed FS at the same dry mass of around 420 kg/m^3 (Sandec, unpublished information). This is much higher compared to the bulk densities of biowastes with a similar dry mass, e.g. 273 kg/m^3 for sawdust/woodshavings, 260 kg/m^3 for coffee husks and 276 kg/m^3 for maize cobs (see Table 11 and Table 12). Using the information provided in Table 9 and Table 10, this translate into transport costs for pellets of 4 USD/ton in Kampala and 14 USD/ton to places outside of Kampala and 6-7 USD/ton and 21 USD/ton for crushed FS.

4 Conclusions

This study demonstrated that biowaste streams with suitable physical-chemical for co-processing with FS for energy recovery are available in Kampala. Co-processing with these waste streams can overcome challenges of energy recovery with FS such as a low fuel quantity, high moisture and ash content and low calorific value. Key findings include:

- Sawdust, coffee husks, spent grain, market waste, malt/sorghum husks, maize cobs and banana leaves and banana peels have good physical-chemical characteristics for energy recovery. Co-pelletizing experiments of these waste streams with FS and subsequent gasification should be conducted in order to identify the benefits and challenges of co-processing.
- Sufficient quantities of the most suitable waste streams (i.e. sawdust, coffee husks, spent grain, market waste) are available for co-processing up to a ratio of 80%. However, these waste streams already have a significant market value, or need to be pre-processed which increases costs (e.g. for market waste). Therefore, financial modelling needs to identify at which ratio other biowastes can be financially viable co-processed with FS.
- FS, wastewater sludge and water treatment sludge are available in Kampala at no or low costs, however, they have poor physical-chemical characteristics for energy recovery. Technologies should be investigated to increase sludge characteristics for energy recovery.
- Transport biowastes from outside of Kampala for fuel production in Kampala appears not be financially viable. FS fuel pellets have lower transport costs compared to a crushed FS fuel. FS fuel transport costs are significant (4-21 USD/ton) compared to the sales price of a FS fuel (60 USD&/ton).

5 References

AGROVÄST & ÄFAB 2006. Tillverkning av agropellets i små- ock lokala tillverkningsenheter.

AMERICAN PUBLIC HEALTH ASSOCIATION (AWA), AMERICAN WATER WORK ASSOCIATION (AWWA) & WATER ENVIRONMENTAL FEDERATION (WEF) 2012. *Standard methods for the examination of water and wastewater,* Washington DC, American Water Work Association (AWWA).

AMODING, A. 2007. *Supply potential and agronomic value of urban market crop waste.* Makerere University.

ANVAL. 2015. *Bulk density chart: http://www.anval.net/Downloads/Bulk%20Density%20Chart.pdf* [Online]. [Accessed 6 April 2015].

ASTM 2007. Standard Test Method for Ash in Biomass. *E1755-01.* ASTM International.

ASTM 2008. Standard Test Method for Determination of Total Solids in Biomass. *E1756-08.* ASTM International.

ASTM 2013a. Standard Test Method for Bulk Density of Densified Particulate Biomass Fuels. *E873-82.* ASTM International.

ASTM 2013b. Standard Test Method for Moisture Analysis of Particulate Wood Fuels. *E871--82.* ASTM International.

ASTM 2013c. Standard Test Method for Volatile Matter in the Analysis of Particulate Wood Fuels. *E872-82.* ASTM International.

AUSTRIAN FEDERAL MINISTRY OF AGRICULTURE, F., ENVIRONMENT AND WATER MANAGEMENT, 2015. Compost ordinance. Vienna, Austria.

BASU, P. 2013. *Biomass Gasification, Pyrolysis and Torrefaction: Practical Design and Theory*, Academic Press.

BÄUERL, M., EDTHOFER, M., PRAT, M. A., TRÉMOLET, S. & MANDFRED, W. 2014. Financing Sanitation: Resource Recovery from Faecal Sludge in Sub-Saharan Africa. *Sustainable Sanitation Practice,* 21**,** 12-19.

BIKUUTA, N., MULOKOLE, A. & NAKALEMBE, J. 03/02/15 & 20/02/15 personal communication. *RE: Market Vendors - Banana peelings.*

BOWAN, P. A. & TIEROBAAR, M. T. 2014. Characteristics and Management of Solid Waste in Ghanaian Markets - A Study of WA Municipality. *Civil and Environmental Research,* 6**,** 114-119.

CAIRNS-SMITH, S., HILL, H. & NAZARENKO, E. 2014. Working Paper Urban Sanitation: Why a portfolio of solutions is needed. The Boston Consulting Group.

CHERUKUT, A. 2015 personal communication. *RE: Environmental Engineer, Nile Breweries Ltd.*

DAISY, A. 2011. The Impact and Treatment of Night Soil in Anaerobic Digester: A Review. *Journal of microbial & biochemical technology,* 3**,** 43-50.

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? *Resources, Conservation & Recycling,* 88**,** 32-38.

DUNG, N. N. X., MANH, L. H. & P., U. 2002. Tropical fibre sources for pigs--digestibility, digesta retention and estimation of fibre digestibility in vitro. . *Animal Feed Science and Technology,* 102**,** 109-124.

ELECTRICITY REGULATORY AUTHORITY (ERA) 2012. Uganda Renewable Energy Feed-in Tariff (REFIT) Phase 2 - Guidelines.

EUROPEAN ENVIRONMENT AGENCY, E. 2013. *Heavy metal (HM) emissions (APE 005)* [Online]. [Accessed 02/01/15 2015].

EUROPEAN STANDARD 2011. Solid recovered fuels - Determination of calorific value. *DIN EN 15400:2011-05.* Brussels: CEN.

FEDERAL MINISTRY FOR THE ENVIRONMENT, N. C., BUILDING AND NUCLEAR SAFETY (BMUB), 1992. Klärschlammverordnung (AbfKlärV). Bonn, Germany.

FICHTNER WATER & TRANSPORTATION 2009. Design Calculation of Lubigi Treatment Plant. *Final Report: Lake Victoria Protection I (LVP I).*

GOLD, M., DDIBA, D., SECK, A., SEKIGONGO, P., DIENE, A., DIAW, S., NIANG, S., NIWAGABA, C. B. & STRANDE, L. in preparation. Faecal sludge as a solid industrial fuel.

GOLD, M., NIANG, S., NIWAGABA, C. B., EDER, G., MURRAY MUSPRATT, A., DIOP, P. S. & STRANDE, L. 2014. Results from FaME (Faecal Management Enterprised) - can dried faecal sludge fuel the sanitation service chain? *37th WEDC International Conferecnce.* Hanoi, Vietnam.

GOVER, P. D. 1989. *Thermochemical characteristics of biomass residues for gasification,* Delhi, Indian Institute of Technology.

GOVERNMENT OF UGANDA 2014. Water and Environment Sector Performance Report 2014. *In:* ENVIRONMENT, M. O. W. A. (ed.). Kampala: Government of Uganda.

GROVER, P. D. 1989. *Thermochemical characteristics of biomass residues for gasification,* Delhi, India, Indian Institute of Technology.

HAPMAN. 2015. *Bulk material density guide: http://www.hapman.com/resources/bulk-material-density-guide* [Online]. [Accessed 6 April 2015].

HEINSS, U., LARMIE, S. A. & STRAUSS, M. 1998. Solids separation and pond systems for the treatment of faecal sludges in the tropics: lessons learned and recommendations for preliminary design. Dübendorf, Switzerland: Eawag.

HELENA LOPES, M., ABELHA, P., LAPA, N., OLIVEIRA, J. S., CABRITA, I. & GULYURTLU, I. 2003. The behaviour of ashes and heavy metals during the co-combustion of sewage sludges in a fluidised bed. *Waste Management,* 23**,** 859-870.

IYER, P. V. R., RAO, T. R., GROVER, P. D. & SINGH, N. P. 1997. *Biomass Thermo-chemical Characterization,* Delhi, Indian Institute of Technology.

JORAPUR, R. & RAJVANSHI, A. K. 1997. Sugarcane leaf-bagasse gasifiers for industrial heating purposes. *Biomass and Bioenergy***,** 141-146.

KAMPALA CITY CAPITAL AUTHORITY (KCCA) 2013. Quantities of Municipal Solid Waste delivered to Kiteezi Landfill May to December 2012. Kampala, Uganda.

KATONGOLE, C. B., BAREEBA, F. B., SABIITI, E. N. & LEDIN, I. 2008. Nutritional characterization of some tropical urban market crop wastes. *Animal Feed Science and Technology,* 142**,** 275-291.

KINOBE, J. R., GEBRESENBET, G., VINNERAS, B., NIWAGABA, C. B. & KOMAKECH, A. 2015. Mapping out the current waste collection system in Kampala City. *Journal of the Air & Waste Management Association,* 65**,** 197-205.

KITANI, O. & HALL, C. W. 1989. *Biomass Handbook,* New York, Gordon and Breach Science Publishers.

KOMAKECH, A. J., BANADDA, N. E., GEBRESENBET, G. & VINNERÅS, B. 2013. Maps of animal urban agriculture in Kampala City. *Agronomy for Sustainable Development*.

KOMAKECH, A. J., BANADDA, N. E., KINOBE, J. R., KASISIRA, L., SUNBERG, C., GEBRESENBET, G. & VINNERÅS, B. 2014. Characterisation of municipal waste in Kampala, Uganda. *Journal of the Air &Waste Management Association,* 3**,** 340-348.

KYONGO, H. A. M., ASHABA, E. & MUTEBI, H. 30/01/15 personal communication. *RE: Maize millers.*

LEONS, F. 24.02.15 personal communication. *RE: Crop to Cup Coffee Importers.*

LOHRI, C. R., FARAJI, A., EPHATA, E., RAJABU, H. M. & ZURBRÜGG, C. 2015. Urban biowaste for solid fuel production: Waste suitability assessment and experimental carbonization in Dar es Salaam, Tanzania. *Waste Management & Research,* 33**,** 175-182.

LU, Y. J., GUO, L. J., JI, C. M., ZHANG, X. M., HAO, X. H. & YAN, Q. H. 2006. Hydrogen production by biomass gasification in supercritical water: a parametric study. *International Journal of Hydrogen Energy,* 31**,** 822-831.

LUKODA, R. 28/11/14 personal communication. *RE: Kampala Jellitone Suppliers Limited.*

LUTS, D. 2000. Co-incineration of dried sewage sludge in coal-fired power plants: A case study. *Water science and technology,* 42**,** 259-268.

MERTENANT, A. 2014. *Master thesis: Assessment of organic waste availability and suitability for the co-digestion of faecal sludge in Vietnam.* EFPL.

MHILU, C. 2014. Analysis of Energy Characteristics of Rice and Coffee Husks Blends. *ISRN Chemical Engineering,* 2014**,** 1-6.

MILES, T. R., BAXTER, J. L., BRYERS, R. W., JENKINS, B. M. & ODEN, L. L. 1995. Alkali deposits found in biomass power plants. A preliminary investigation of their extend and nature. *NREL/TP-433-8142***,** 82.

MUBIIRU, J. S., MATOVU, G., WANDERA, C., NAKAYIWA, M., NDIRISA & LUGEMWA, S. 26/01/15 & 16/02/15 personal communication. *RE: Market Vendors - Banana leaves.*

MUGABI, H. 10/02/15 personal communication. *RE: Environmental Manager, Uganda Breweries Ltd.*

MUSISI, A. 2002. Feasibility Study for Kampala Jellitone Suppliers Ltd. and ABC Hansen A/S for non-carbonised Biomass Fuel Briqeuttes.

MUSISI, A. 17/11/14 personal communication. *RE: MD, Jelltione Suppliers Ltd.*

MUSPRATT, A., NAKATO, T., NIWAGABA, C. B., DIONE, H., KANG, J., STUPIN, L., REGULINSKI, J., MNÉGUÉRÉ, M. & STRANDE, L. 2013. Fuel potential of faecal sludge: calorific value results from Uganda, Ghana and Senegal. *Journal of Water, Sanitation and Hygiene for Developement,* 4**,** 223-230.

NKANDU, J. personal communication. Executive Director, National Union of Coffee Agribusiness and Farm Enterprises (Nucafe).

NUWABAASA, J. 13/11/14 personal communication. *RE: Director Technical Services, Pamoja Energy Ltd.*

NYEKO, P. personal communication. Managing Director & Co-Founder of Mandulis Energy.

OBERNBERGER, I., BRUNNER, T. & BÄRNTHALER, G. 2006. Chemical properties of solid biofuels-significance and impact. *Biomass and Bioenergy,* 30**,** 973-982.

OFUNGI, H. L. 18/02/15 personal communication. *RE: Cashier, NWSC Bugolobi WWTP.*

ORWINY, M. personal communication. Plant Engineer NWSC Lubgi Wastewater and Faecal Sludge Treatment Plant.

OYO, S. 09/02/15 personal communication. *RE: Environmental Manager, Parambot Breweries Ltd.*

RUBARAMIRA, D. 20/12/14 personal communication. *RE: Managing Director, Kenlon Industries Ltd.*

RURAL ELECTRIFICATION AGENCY UGANDA (REA). Implementation of the Rural Electrification Master Plan. Parliamentary Stakeholder Symposium, 19-20 July 2013, 2013a.

RURAL ELECTRIFICATION AGENCY UGANDA (REA). Overview of the performance of Uganda's electricity sector. Parliamentary Stakeholder Symposium, 19-20 July 2013, 2013b.

RUTAISIRE, J. 2007. Analysis of feeds and fertilizers for sustainable aquaculture development in Uganda. *In:* HASAN, M. R., HECHT, T., DE SILVA, S. S. & TACON, A. G. J. (eds.) *Study and analysis of feeds and fertlizers for sustainable development FAO Fisheries Technical Paper.* Rome: FAO.

SABIITI, B., KARUHANGA, H., BARRY, D., KAILASH, N. & LUBEGA, A. 15/01/15 personal communication. *RE: Managing Directors of various Coffee Exporters.*

SABIITI, E. 08/12/14 personal communication. *RE: Professor in the School of Agricultural Sciences, Makerere University Kampala.*

SABIITI, E. N. 2011. Utilising agricultural waste to enhance food secruity and conserve the environment. *African Journal of Food, Agriculture and Development,* 11**,** 1-9.

SCHOEBITZ, L., NIWAGABA, C. B. & STRANDE, L. 2014. RRR-Project From Research to Implementation, Component 1 - Waste Supply and Availability Report - Kampala. Zurich: Eawag; Makerere University Kampala.

SCHOUW, N. L., DANTERAVANICH, S., MOSBAEK, H. & TJELL, J. C. 2002. Composition of human excreta — a case study from Southern Thailand. *Science of The Total Environment,* 286**,** 155-166.

SECK, A., GOLD, M., NIANG, S., MNÉGUÉRÉ, M., DIOP, C. & STRANDE, L. in press. Faecal sludge drying beds: increasing drying rates for fuel resource recovery in Sub-Saharan Africa. *Journal of Water, Sanitation and Hygiene for Developement*.

SELLIN, N., DE OLIVEIRAA, B. G., MARANGONIA, C., SOUZAA, O., DE OLIVEIRAB, A. P. N. & DE OLIVEIRAA, T. M. N. 2013. Use of banana culture waste to produce briquettes. *Chemical Engineering* 32.

SEMALULU, O. 18/02/15 personal communication. *RE: National Agriculture Research Organisation.*

SINGH, A., SINGH, D., MUKHOPADHYAY, J., SARKAR, S. & DUTTA 2014. Studies on Effect of Plastic on Biodegradation of Vegetable Solid Market Waste Through Detailed Analysis of Leachate. *The Journal of solid waste technology and management,* 40**,** 266-284.

SØRUM, L., GRØNLI, M. G. & HUSTAD, J. E. 2001. Pyrolysis characteristics and kinetics of municipal solid wastes. . *Fuel***,** 1217-1227.

STILL, D. & FOXON, K. M. 2012. Tackling the Challenges of Full Pit Latrines. Volume 2: How fast do pit toilets fill up? A scientific understanding of sludge build up and accumulation in pit latrines. *In:* WRC (ed.) *Tackling the Challenges of Full Pit Latrines.* Pretoria: WRC.

STRANDE, L. 2014. The global situation. *In:* STRANDE, L., RONTELTAP, M. & BRDJANOVIC, D. (eds.) *Faecal sludge management: Systems approach for implementation and operation.* London: IWA Publishing.

SUAREZ, J. A. 2003. Physical Properties of Cuban Coffee Husk for Use as an Energy Source. *Energy Sources,* 25**,** 953-959.

TAKE, H., MTUI, G., KOBAYASHI, F. & NAKAMURA, Y. 2005. Additive Effect of Soybean Curd Residue, Okara, for Enhancement of Methane Production from Pretreated Woody Waste. *Journal of Food Technology,* 3**,** 535-537.

TAPCO INC. 2015. *Bulk material density table.* http://www.tapcoinc.com/content/product_data/Tapco_Catalog_09_p88-94.pdf [Online]. [Accessed 6 April 2015].

TWEHEYO, J. 09/12/14 personal communication. *RE: Reservoirs and Booters, NWSC.*

UBOS 2006. Uganda National Household Survey 2005/2006, Socio-economic Module. *In:* STATISTICS, U. B. O. (ed.). Kampala.

UBOS 2012. Statistical Abstract. *In:* STATISTICS, U. B. O. (ed.). Kampala.

UGANDA CLAYS LIMITED. 2012. http://www.ugandaclays.co.ug/ [Online].

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY (US EPA) 1999. Biosolids Generation, Use, and Disposal in the United States. Washingto DC, USA.

VAN LOOM, S. & JAAP, K. 2008. *Biomass combustion & co-firing,* London, UK, Earthscan.

VASSILEV, S. V., BAXTER, D., ANDERSEN, L. K. & VASSILEVA, C. G. 2010. An overview of th chemical composition of biomass. *Fuel***,** 913-933.

VERA. 28/11/14 personal communication. *RE: Public Relations, Ugachick.*

VINNERÅS, B., PALMQUIST, H., BALMÉR, P. & JÖNSSON, H. 2006. The characteristics of household wastewater and biodegradable solid waste—A proposal for new Swedish design values. *Urban Water Journal,* 3**,** 3-11.

WADE, T. personal communication. Chief Business Development Officer at Pivot Ltd.

WARD, B., WARD, T., YACOB, L. & MONTOYA 2014. Evaluation of Solid Fuel Char Briquettes from Human Waste. *Environmental science & technology,* 48**,** 9852-9858.

WERTHER, J., SAENGER, M., HARTGE, E. U., OGADA, T. & SIAGI, Z. 2006. Combustion of agricultural residues. *Prog.Energy Combust.Sci.,* 26**,** 1-27.

ZHANG, Y., GHALY, A. E. & LI, B. 2012. Physical Properties of Corn Residues. *American Journal of Biochemistry and Biotechnology,* 8**,** 44-53.

ZZIWA, J. 01.11.14 personal communication. *RE: Supervisor Water and Sanitation, KCCA.*

6 Appendix

Table 9: Transport costs of biowastes quoted by four waste collection companies in Kampala for different trucks size and transport distances.

	Destination	Distance (km)	Truck size	Truck volume	Transport costs	Transport costs
Units	-	km	tons	m^3	UGX	USD
Reedbuck Uganda	Mbale	230	35	63	1,700,000	595
	Mityana	65	35	63	1,000,000	350
	Port Bell	18	35	63	650,000	228
	Bugolobi	10	25	40	500,000	175
Real Food Maize Millers	Mbale	230	25	58	2,000,000	700
	Mubende	145	25	58	1,500,000	525
	Port Bell	18	25	58	300,000	105
	Bugolobi	10	25	58	300,000	105
	Jinja	84	25	58	1,000,000	350
Kibanyi & Sons	Kampala	10	8	22	300,000	105
	Mbale	230	8	22	200,000	70
	Port Bell	18	8	22	200,000	70
	Kampala	10	8	22	200,000	70
Green Hope Uganda	Mbale	230	20	32	710,000	249
	Mityana	65	20	32	600,000	210
	Mubende	145	20	32	1,100,000	385
	Port Bell	18	7	20	130,000	46
	Bugolobi	10	7	20	110,000	39
	Jinja	84	20	32	600,000	210

Table 10: Average transport cost for collection of biowaste in Kampala (small and large trucks) and within Uganda (large trucks only).

Destination	Truck size	Average cost	Average cost	Number of companies
Unit	m^3	$USD/100km*m^3$	USD/m^3	-
Kampala	20-22	20	3±1	2
	40-63	23	3±1	2
max. 85 km from Kampala	32-63	8	6	3
Uganda	32-63	7	9±3	3

Table 11: Average transport costs in dry mass for biowaste in Kampala and Uganda.

Biowaste	Bulk Density	Kampala Truck size: 40-63 m^3	Kampala Truck size: 20-22 m^3	Uganda Truck size: 32-63 m^3
Unit	kg/m^3	USD/ton dry mass	USD/ton dry mass	USD/ton dry mass
Wastewater Treatment Sludge	822	15	14	47
Water Treatment Sludge	795	7	6	20
Market Waste	468	21	19	64
Brewery waste - Spent Grain	880	13	12	41
Brewery Waste - Grain Husks	273	12	11	37
Sawdust & woodshavings	273	13	12	40
Coffee Husks	260	13	11	39
Maize Cobs	276	12	11	36
Banana Peelings/Banana Leaves	500	43	39	132

Table 12: Results from proximate analysis, calorific value, bulk density, sulphur, chlorine and phosphorus in biowastes analysed as part of this study. Literature results of wastewater sludge and faecal sludge are included for comparison.

	Number of samples	Moisture content	Volatile solids	Ash content	Fixed carbon	Calorific value	Bulk density	Sulphur	Chlorine	Phosphorus
Unit	-	wt%	wt% dry mass	wt% dry mass	wt% dry mass	MJ/kg TS	kg/m^3	wt% dry mass	wt% dry mass	wt% dry mass
Water treatment sludge	4	44.5	44.6	49.9	5.5	8.4	795	1.1	0.09	0.5
Wastewater treatment sludge	5	77.0	51.1	40.1	8.0	13.0	821	1.4	0.1	0.8
Wastewater treatment sludge[1]	-	6.6-26	51-53	41-44	-	13.1-14.4	-	1.0-1.2	0.07	3.1
Faecal sludge	4	59.6	44.4	44.8	9.1	11.1	306	1.2	0.4	2.2
Faecal sludge[2]	4	8.1	-	58.7	-	10.9	-	0.7	0.04	1.4
Faeces	1	-	76.6	8.3	15.0	20.7	-	0.5	0.4	1.2
Coffee husks	1	11.0	77.7	5.4	16.9	18.7	-	0.2	0.1	0.2
Banana peelings	1	84.7	80.5	6.0	13.5	-	-	-	-	-
Banana leaves	1	83.6	76.0	9.4	14.6	-	-	-	-	-
Spent grain	1	74.5	83.2	3.5	13.2	20.0	-	0.3	0.05	0.6
Sorghum husks	1	10.5	79.2	7.3	13.5	17.2	-	0.1	0.1	0.2
Malt husks	1	14.5	80.3	5.9	13.8	17.6	-	0.1	0.1	2.3
Sawdust	1	25.1	86.6	0.3	13.1	19.3	-	0.007	0.02	0.004
Woodshavings	1	12.0	83.9	1.1	15.0	19.2	-	0.02	0.009	0.009

[1]Helena Lopes et al. (2003), Luts (2000) [2]Gold et al. (in preparation)

Table 13: Concentrations of heavy metals in biowastes analysed as part of this study.

	Number of samples	Arsenic	Cadmium	Chromium	Copper	Mercury	Nickel	Lead	Zinc
	-	mg/kg dry mass	mg/kg dry mass	mg/kg dry mass	mg/kg dry mass	mg/kg dry mass	mg/kg dry mass	mg/kg dry mass	mg/kg dry mass
Water treatment sludge	4	0.5	<1.6	47	6	-	6	14	19
Wastewater treatment sludge	5	2.00	<2.0	161	151	-	28	78	960
Wastewater treatment sludge[1]	-	<0.3-14	4-10.1	190-530	5.3-400	2.1-5.4	40-45	220-365	1,132-4,900
Faecal sludge	4	0.8	<1.7	259	108	-	22	27	698
Faecal sludge[2]	4	0.6	<2.0	485	114	<0.9	24	28	646
Faeces[7]	1	0.5	0.5	18	29	-	7	4	241
Excreta/faeces[3]	-	-	0.3-0.4	0.6	22-31	2.1-5.4	40-46	0.6-1.4	1,132-4,900
Coffee husks	1	<0.5	<2.0	26.8	15.5	-	4.3	0.6	8.5
Spent grain	1	<0.5	0.3	21.7	11.4	-	4.2	1.1	60.1
Sorghum husks	1	<0.5	0.5	18.9	4.9	-	4.0	0.5	33.9
Malt husks	1	<0.5	<2.0	36.4	9.1	-	4.8	0.9	33.6
Sawdust	1	<0.5	<2.0	19.0	1.5	-	3.0	0.3	4.7
Woodshavings	1	<0.5	0.2	6.7	2.0	-	3.0	0.2	2.9
Operation limits[4]	-	-	<5	-	-	-	-	-	<800
Biosolids land application[5]	-	<41	<10-39	<900-1200	<800-1500	<8-17	<200-420	<300-900	<2500-2800
Compost limits[6]	-	-	<0.7-3.0	<70-250	<70-400	<0.3-3.0	<25-100	<45-200	100-1200

[1]Helena Lopes et al. (2003), Luts (2000) [2]Gold et al. (in preparation) [3]Schouw et al. (2002), Vinnerås et al. (2006) [4]Obernberger et al. (2006) [5]United States Environmental Protection Agency (US EPA) (1999), Federal Ministry for the Environment (1992) [6]Austrian Federal Ministry of Agriculture (2015) [7]Gold et al. (in preparation)

Table 14: Concentrations of ash forming elements in biowastes analysed as part of this study.

	Number of samples	Calcium	Potassium	Magnesium	Sodium	Phosphorus	Silicon
	-	wt% dry mass	wt% dry mass	wt% dry mass	wt% dry mass	wt% dry mass	wt% dry mass
Water treatment sludge	4	0.2	0.03	0.05	0.3	0.5	3.8
Wastewater treatment sludge	5	2.5	0.4	0.6	0.3	0.8	6.6
Wastewater treatment sludge[1]	-	5.3-8.5	0.5-0.7	0.35-0,5	0.2-0.4	3.11	5.1-9.2
Faecal sludge	4	3.0	0.6	1.8	0.8	2.2	9.3
Faecal sludge[2]	4	2.0	0.4	1.2	0.4	1.4	7.9
Faeces	1	1.0	1.7	0.8	0.1	1.2	0.2
Coffee husks	1	0.3	2.2	0.2	<0.010	0.2	0.3
Spent grain	1	0.3	0.4	0.3	0.2	0.6	0.2
Sorghum husks	1	0.02	0.7	0.1	<0.010	0.2	3.0
Malt husks	1	0.09	0.6	0.2	<0.010	2.3	2.1
Sawdust	1	0.08	0.02	<0.002	0.08	0.004	0.2
Woodshavings	1	0.5	0.06	0.05	0.07	0.001	0.01
Woodchips[3]	-	26.0-38.0	4.9-6.3	2.2-3.6	0.3-0.5	0.001-0.03	0.04-2.9
Limits operation[4]	-	15-35	<7.0	-	-	-	-

[1]Helena Lopes et al. (2003), Luts (2000) [2]Gold et al. (in preparation) [3]van Loom and Jaap (2008) [4]Obernberger et al. (2006)

Table 15: Average, minimum and maximum values for the availability and accessibility criteria.

Waste Stream		Quantity Generated (weight=5)			Cost (incl. transport) (weight=5)			Competing Uses (weight=1)	Degree of Centralization (weight=1)	Seasonal Variability (weight=1)	Ownership (weight=1)	Legal regulations (weight=1)
		Average	Min	Max	Average	Min	Max					
Unit		tons dry mass/month			USD/ton dry mass			% total quantity reused	no. of location	no. months/year available	benefit or hindrance	Permit Required? Y/N
Market Waste		853[1]	624[1]	1383[1]	20	20	20	0	8[1]	12	Hindrance	Y
Water Treatment Sludge		28[2]	18[2]	38[2]	6	5	7	0	1	12	Hindrance	N
Wastewater Treatment Sludge		167[3]	167[3]	167[3]	47[4]	33[4]	61[4]	100	1	12	Benefit	N
Faecal Sludge		100[5]	19[5]	250[5]	0[6]	0[6]	0[6]	100	1	12	Indifferent	N
Agricultural Waste	Coffee husks	7841[7]	106[7]	15576[7]	144[8]	54[8]	235[8]	100	50	7	Benefit	N
	Maize Cobs	40[9]	13[9]	66[9]	82[9]	63[9]	100[9]	0	10	12	Hindrance	N
	Banana peelings	10[10]	10[10]	10[10]	251[11]	143[11]	359[11]	100	3	5	Benefit	N
	Banana leaves	60[12]	60[12]	60[12]	749[12]	512[12]	987[12]	75	6	5	Indifferent	N
Agro-Industrial Waste	Spent Grain	622[13]	622[13]	622[13]	170[13]	53[13]	287[13]	75	3	12	Indifferent	N
	Sorghum & malt husks	4[14]	4[14]	4[14]	53[14]	53[14]	53[14]	75	1	12	Indifferent	N
	Sawdust & woodshavings	105[15]	100[15]	110[15]	97[15]	44[15]	270[15]	75	9	12	Benefit	N

[1]Amoding (2007), Kinobe et al. (2015), Kampala City Capital Authority (KCCA) (2013), degree of centralization: markets organic matter >90% [2]According to duplicate field measurements at NWSC Gaba III. [3]According to data provided by NWSC on sales of dewatered wastewater sludge at NWSC Bugolobi between August 2014 and January 2015 (101 ton dry mass/month). Quantities of wastewater sludge production at NWSC Lubigi based on treatment designed by Fichtner Water & Transportation (2009) (66 tons dry mass/month). [4]Diener et al. (2014), Ofungi (personal communication), Orwiny (personal communication) [5]Based on dewatered sludge removed from drying beds at NWSC Lubigi between end of May to end of December 2015 (19 tons dry mass/month; based on mass balance of NWSC Lubigi (100 tons dry mass/month); and based on Fichtner Water & Transportation (2009) (250 tons dry mass/month). [6]Faecal sludge is currently sold for farms for between 4-10 USD/ton. [7]Nkandu (personal communication), Musisi (2002), survey of five coffee companies in Kampala [8]Nkandu (personal communication), Uganda Clays Limited (2012), Rubaramira (personal communication) [9]Lukoda (personal communication), Nuwabaasa (personal communication), Musisi (2002) [10]Survey: three vendors in Nakawa and Kalerwe market [11]Sabiiti (personal communication), survey: three vendors Nakawa and Kalerwe market [12]survey: six vendors in Nakawa, Bwaise, Kalerwe market [13]Cherukut (personal communication), Oyo (personal communication), Mugabi (personal communication) [14]Mugabi (personal communication) [15]Musisi (2002), survey: 9 furniture workshops.

Table 16: Average, minimum and maximum values for the physical-chemical criteria.

Waste Stream		Moisture Content (weight=3)			Ash Content (weight=3)			Fixed carbon (weight=1)			Calorific Value (weight=3)			Bulk Density (weight=1)			Heavy Metals (weight=1)	Particle Size Distribution (weight=1)	Impurities (weight=1)
		Average	Min	Max	Average	Min	Max	Average	Min	Max	Average	Min	Max	Average	Min	Max			
Unit		wt%			wt% dry mass			wt% dry mass			MJ/kg dry mass			kg/m^3			Concern? Yes/No	degree of preprocessing required	wt%
Market Waste		70[1]	67[1]	77[1]	15[2]	25[2]	10[2]	20[3]	20[3]	20[3]	17[1]	16[1]	19[1]	468[4]	468[4]	468[4]	No[5]	Size reduction of a variety of materials[6]	2[5]
Water Treatment Sludge		44	19	96	50	39	66	5	4	7	8	6	10	795	722	898	Yes	Size reduction required of small, soft material[6]	0[6]
Wastewater Treatment Sludge		77	63	88	40	36	44	8	7	9	13	12	15	822	620	1024	No	Size reduction required of small, soft material[6]	5[6]
Faecal Sludge		60	21	95	44	37	68	11	6	15	11	9	13	306	191	421	Yes	Size reduction required of small, soft material[6]	5[6]
Agricultural Waste	Coffee husks	11	11	11	5	5	6	17	16	17	19	19	19	260[7]	260[7]	260[7]	No	No size reduction required[6]	0[6]
	Maize Cobs	10[8]	7[8]	13[8]	3[9]	1[9]	4[9]	18[9]	16[9]	19[9]	17[9]	16[9]	19[9]	276[10]	270[10]	282[10]	No	Size reduction of small, hard material[6]	0[6]
	Banana peelings	85	85	85	6	6	6	13	13	13	17[11]	17[11]	17[11]	500[12]	300[12]	300[12]	No	Size reduction required of small, soft material[6]	0[6]
	Banana leaves	84	84	84	9	9	9	15	15	15	17[14]	17[14]	17[14]	500[12]	300[12]	300[12]	No	Size reduction required of large material[6]	0[6]
Agro-Industrial Waste	Spent Grain	75	75	75	4	4	4	13	13	13	20	20	20	880[15]	880[15]	880[15]	No	No size reduction required[6]	0[6]
	Sorghum & malt husks	12	7	18	7	6	7	14	13	14	17	17	18	253[16]	250[16]	256[16]	No	No size reduction required[6]	0[6]
	Sawdust & woodshavings	19	9	28	1	0	1	14	13	15	19	19	19	273[17]	240[17]	290[17]	No	No size reduction required[6]	0[6]

[1]Komakech et al. (2014) [2]Take et al. (2005), Daisy (2011), Mertenant (2014) [3]Singh et al. (2014) [4]Bowan and Tierobaar (2014) [5]Amoding (2007) [6]visual observations [7](Suarez, 2003) [8]Musisi (2002), Lu et al. (2006) [9]Lu et al. (2006), Kitani and Hall (1989), Grover (1989) [10]Hapman (2015), Zhang et al. (2012) [11]assumption: similar to banana leaves. [12]no data was available. Banana peelings and banana leaves have very bulky but have a lot of water, therefore a moderate bulky density is assumed. [14]Sellin et al. (2013) [15]Tapco Inc. (2015) [16]Hapman (2015), Anval (2015) [17]van Loom and Jaap (2008), Hapman (2015)