MAKERERE UNIVERSITY

COLLEGE OF ENGINEERING, DESIGN, ART AND TECHNOLOGY (CEDAT)

SCHOOL OF ENGINEERING

DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING

CIV 4200: CIVIL ENGINEERING PROJECT II

ENERGY RECOVERY FROM SOLID WASTES IN PIT LATRINE FAECAL SLUDGE

BY

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Submitted in Partial Fulfilment of the Requirements for the Award of a Degree of Bachelor of Science in Civil Engineering

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FEBRUARY 2021

DECLARATION

We hereby declare that the work presented is original and has never been submitted for an award to any university or institution of higher learning. We can confirm that where we have done consultations either from published material or the works of others, it has been attributed in this report.

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DEDICATION

We would like to dedicate this report to our parents as there is no doubt in our minds that without their support and guidance we could not have completed this project. We also dedicate it to our lecturers at the School of Engineering who have in many ways enabled us to acquire this milestone of education**.**

ACKNOWLEDGEMENTS

First and foremost, we would like to thank the almighty God for keeping us in good health throughout the work of our project and everyone who contributed to the success of this project in whatever form.

We extend our sincere gratitude to our families for the great work they have done for us during this period and throughout our academic time.

We wish to acknowledge fellow students; Bamuhimbise Gilbert, Apio Sheilla Constance, Odongo Vincent and Nsubuga Emmanuel for helping us during the field work especially during the sorting and weighing of solid wastes.

We also extend special thanks to Mr. Musoke Michael and Mr. Nteziyaremye Ronald for aiding us during our experiments at the Department of Physics of Makerere University.

We wish to extend our sincere gratitude to Mr. Semukoteka Abubaker (Brilliant Sanitation Contractor) for aiding us during the pit emptying process.

We also thank the management of the Lubigi sewage treatment plant for allowing us to access their facility.

We also like to thank Mr. Otwane Dan Etiange for his support and aid during the execution of this project.

Special thanks to our supervisors; Dr. Alex Katukiza and Dr. Swaib Semiyaga for their guidance and assistance in the preparation of this report.

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LIST OF ABBREVIATIONS

APHA – American Public Health Association
AIT – Asian Institute of Technology
ABR – Anaerobic Baffled Reactors
CEDAT– College of Engineering, Design, Art and Technology
Chr – Chromium
COD – Chemical Oxygen Demand
CV – Calorific Value
Cu – Copper
DS – Dry solids
DW – Dry Weight
Fe – Iron
FS – Faecal Sludge
FSM – Faecal Sludge Management
HTC – Hydrothermal Carbonization
HV – Heat Capacity
KCCA – Kampala Capital City Authority
LaDePa – Latrine Dehydration and Pasteurization
MC – Moisture Content
MSW – Municipal Solid Waste
N/A – Not analyzed
Ni – Nickle
Pb – Lead
ppm - Parts per million
PHEE – Public Health and Environmental Engineering
SD – Standard deviation
SDW – Sterile distilled water
TVS – Total volatile solids
UDDT – Urine Diversion Dry Toilet
UGX – Uganda Shillings
USD – United States Dollar
VIP – Ventilated Improved Pit latrine
WHO – World Health Organisation
Zn – Zinc

ABSTRACT

Pit latrines in slums have faecal sludge mixed with solid waste. These solid wastes in pit latrines are incompatible with faecal sludge treatment as they can cause blockage at treatment plants, and neither can they be disposed off at landfills as they are hazardous and leachate from such waste can contaminate water sources. This creates a problem of limited options available to manage solid wastes from pit latrines, which results in a need to co-manage the faecal sludge together with the solid waste in pit latrines. This study was aimed at investigating the effect of solid wastes in pit latrines on the method of energy recovery from faecal sludge. Faecal sludge and solid wastes from pit latrines were considered for this study. The effect of solid waste on the method of energy recover was assessed by the determination of the solid waste composition and characteristics of faecal sludge mixed with the solid waste. The choice of incineration method was also determined with regard to the characteristics obtained. A total of 7 pit latrines were emptied and sampled. The waste from the 7 pit latrines was used to determine the solid waste composition and characteristics of the fresh faecal sludge.

The study revealed that the solid waste composition in pit latrines consisted of ; 5.1 ± 3.8% organics, 9.1 ± 7.5% polyethene, 11.2 ± 8.3% textile, 1.6 ± 0.4% plastic, 1.1 ± 1.6% glass, 9.2 ± 8% sanitary towels, 0.2 ± 0.2% rubber, 0.3 ± 0.4% metals, 15.9 ± 16.8% paper, 24.9 ± 25.8% rubble and 21.3 ± 21.3% others.The solid waste composition showed that the average percentage of total combustible solid waste was 52.3% of the total solid waste which indicated that about half of the solid waste from the pit latrines was combustible. The characteristics of the fresh faecal sludge were; 87.6 ± 3.2% Moisture Content, 35.7 ± 13.5%TS Ash Content, 64.3 ± 13.5 % TS Total Volatile Solids, 11508 ± 709 mg/L COD and 0.17 ± 0.04 COD/TVS ratio.The energy characteristics of dried faecal sludge alone and faecal sludge mixed with solid waste were determined based on samples from 3 pit latrines. The mean results were; 35.8% Moisture Content, 59.4 %TS Total Volatile Solids, 2720 J/KgoC Heat capacity and 15.0 MJ/Kg Calorific value for dried faecal sludge alone while for the mixture of solid waste and faecal sludge, the mean results were; 46.4% Moisture Content, 59.3% TS Total Volatile Solids, 4333 J/KgoC Heat capacity and 29.1 MJ/kg Calorific value.

There were correlations between the energy characteristics (calorific value and heat capacity) of the faecal sludge and the total mass of solid waste in the pit. The study showed that solid wastes from the pit latrine had an effect on the energy characteristics of the faecal sludge and hence influenced the choice of incineration option for the different mixtures of faecal sludge and solid waste.

CHAPTER 1: INTRODUCTION

1.1 Background and Justification

Globally, the great number of urban slum dwellers depend on on-site sanitation technologies such as pit latrines, which generate a mix of solid and liquid wastes referred to as “faecal sludge” (Blackett et al., 2014). As a consequence, there is a large amount of faecal sludge that remains uncollected due to the high costs of emptying and the high density of housing units which limit access to emptying facilities (Murungi & Meine, 2014). The majority of slums dwellers therefore turn to relatively cheap but unhygienic options such as manually emptying and burying faecal sludge within the living environment (Kulabako et al., 2010). Manual emptying of pits is therefore a common practice in urban slums where accessibility by vacuum trucks is not possible (Still & Lorentz, 2012). Faecal sludge management (FSM) represents a growing challenge in poor and rapidly expanding cities because it generates significant negative public health and environmental risks (Blackett et al., 2014). This can be seen in many cities where several private emptying service providers operate either legally or illegally, but with no legal discharge location leading to discharge of faecal sludge directly into the urban environment (Harada et al., 2016). For example, the initial results of a study carried out on FSM show that in; Dar es Salaam, Tanzania, where 90% of excreta is managed by on-site systems, but 23% of excreta is discharged to the environment without treatment (Brandes et al., 2015a) and in Danang, Vietnam, where 100% of excreta is managed by on-site systems, but 37% is discharged to the environment without treatment (Harada et al., 2015b). FSM can be made more economical and sustainable by developing a market for faecal sludge treatment end products because there is a high demand for affordable biomass fuels in many African cities (Diener et al., 2014).

In Uganda, specifically Kampala, a study carried out in 2014 showed that 90% of 1.5 million people in the city relied on on-site systems. The challenge is that without proper management, faecal sludge often accumulates in poorly designed pits and is discharged into storm drains, open water and unsanitary dumping sites (Blackett et al., 2014). There is therefore need for sustainable options in order to overcome the challenges associated with faecal sludge management (FSM) especially in slums.

For the sustainable implementation of FSM, there is a need for an integrated systems approach incorporating technology, management and planning (Blackett et al., 2014). In order to address the situation where most of the faecal sludge in slums cannot easily be transported to the centralized treatment locations, the usage of faecal sludge products is an option. A market exists for faecal sludge treatment end products such as biogas, solid fuels, soil conditioner, protein, fertilizer and compost (Diener et al., 2014). In sub-Saharan Africa, the energy-producing options have a higher revenue potential compared to other treatment end products (Diener et al., 2014). For example, a study in Kampala showed that faecal sludge used as a fuel in incineration can generate up to 32.3 USD/ton of dried solids compared to its use as a soil conditioner that can generate 16.3 USD/ton (Harada et al., 2016).

The few studies on faecal sludge (FS) as a fuel published to date have focused on characterizing its heating value, moisture, ash fraction, and heavy metals. However, other factors impacting fuel utility, such as solid wastes in the pits, have not been adequately quantified for faecal sludge and this limits the extent to which faecal sludge can be used as a fuel (Hafford et al., 2019).

1.2 Problem statement

Pit latrines in slums have faecal sludge mixed with solid waste (Zziwa, et al., 2016). These solid wastes in pit latrines are incompatible with faecal sludge treatment as they can cause blockage at treatment plants, and neither can they be disposed off at landfills as they are hazardous and leachate from such waste can contaminate water sources (Bras et al., 2017). The recycle and reuse of these solid wastes is also a challenge due to contamination by faecal matter. This creates a problem of limited options available to manage solid wastes from pit latrines, which results in a need to co-manage the faecal sludge together with the solid waste in pit latrines. This is because of the unique composition of solid wastes found in pit latrines, that are highly depended on in slums (Tembo et al., 2019). Co-management of faecal sludge and solid wastes in pit latrines can be achieved through incineration for energy recovery. However, there is limited information on the effect of solid wastes on energy recovery from faecal sludge. This information required so as to successfully co-manage faecal sludge with solid wastes from pit latrines through energy recovery.

1.3 Main Objective

To investigate the effect of solid wastes in pit latrines on the method of energy recovery from faecal sludge.

1.4 Specific objectives

- To determine the composition of solid wastes from pit latrine faecal sludge.
- To determine the energy characteristics of faecal sludge mixed with solid waste.
- To determine the correlation between the energy characteristics (calorific value and heat capacity) of the faecal sludge and the total mass of solid waste in the pit.
- To evaluate the different methods of energy recovery from faecal sludge mixed with solid waste.

1.5 Study Scope

The study involved investigation of the effect of solid wastes on the potential energy recovery from faecal sludge in two slums in Kampala; Kamwokya II Parish and Makerere III Parish in Kawempe Division which are under the jurisdiction of KCCA. The study focused on assessing the effect of the solid wastes on the calorific value of faecal sludge as well as the characteristics of faecal sludge that influence its calorific value such as ash content, moisture content and TVS. The research project also focused on assessing hydrothermal carbonization, pyrolysis, drying and pelletization as the potential energy recovery methods.

1.6 Expected Benefits

The study will provide valuable information on a direction to take when managing the different compositions of solid wastes mixed with faecal sludge through energy recovery. The study will also provide useful data for further innovation and research concerning energy recovery as a faecal sludge management approach.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Faecal sludge is the excreta and wastewater that accumulates in onsite-sanitation systems. It needs to be safely contained onsite. The accumulated faecal sludge then needs to safely emptied and transported to a treatment plant where it is treated and used for resource recovery or disposed of safely as shown in Figure 2-1. However, most of the faecal sludge is not properly managed due to lack of adequate and safe emptying, no treatment plants, and illegal dumping (Harada et al., 2016).

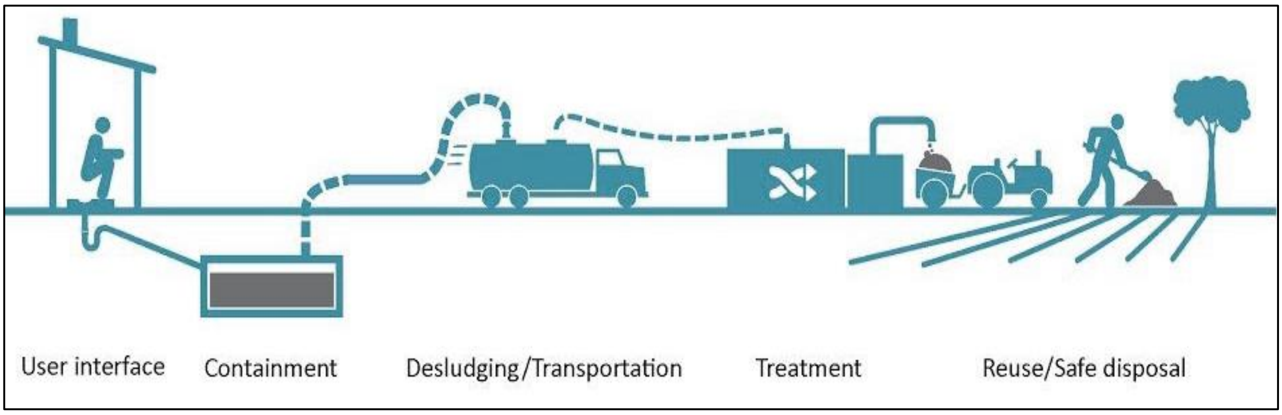


Figure 2-1 Faecal sludge management service chain (Environment & Public Health Organization, 2020)

2.2 Components of municipal solid wastes

Solid waste is any solid or semi-solid discarded from industrial, commercial, agricultural and community activities. Solid waste includes; garbage, construction debris, commercial refuse, hospital waste, sludge from water supply, waste treatment plants and other discarded materials. The composition of solid wastes varies significantly in each city and even in different seasons. This variation in the composition of solid waste is due to differences in the habits of the users, the demographics of the households as well as the type of cleansing materials used (Zuma et al., 2015). The solid wastes can be categorized into; organic (e.g. food scraps, leaves and wood), paper (e.g. new pepper, boxes and cardboard), plastic (e.g. containers, bags and cups), glass (e.g. bottles, bulbs and colored glass), metal (e.g. tins, cans and appliances) and others such as textile, rubber and ash (World Bank, 2012).

2.3 Energy characteristics of faecal sludge

Faecal sludge has several characteristics that affect its quality as a fuel, such as moisture content, ash content as described below:

2.3.1 Calorific value

The calorific value of faecal sludge is the amount of heat released during the combustion of a specified amount of it. Calorific value is an important fuel parameter during the process of energy recovery (Li et al., 2018). Previous studies on faecal sludge in Uganda, Tanzania and Ghana showed that the calorific value of faecal sludge ranges from 8.3 to 19.1 MJ/kg (Muspratt, et al., 2014 and Mwamlima, et al., 2017). The calorific value of faecal sludge depends on the characteristics of the faecal sludge such as its total volatile solids, ash content and moisture content. The calorific value of faecal sludge also decreases with increase in moisture content and ash content, while an increase in the TVS results in a higher calorific value (Makununika, 2016).

2.3.2 Heat capacity

Heat capacity is the ratio of the heat energy added to or removed from the faecal sludge to its corresponding temperature change. When faecal sludge is said to have a low heat capacity, a large temperature change will result from a relatively small heat input. The heat capacity of faecal sludge decreases as its moisture ratio decreases. The moisture ratio is the ratio of the moisture content of faecal sludge at a given time to its initial moisture content. The heat capacity of wet faecal sludge close to that of water according to previous studies (Makununika, 2016). Previous research on faecal sludge from South Africa also shows that the heat capacity of faecal sludge is between 1970 and 3430 J/kgK (Zuma et al., 2015).

2.3.3 Thermal conductivity

Thermal conductivity is the rate at which heat flows through faecal sludge. Wet faecal sludge has a thermal conductivity of 0.55 W/m.K which is close to that of pure water. On the other hand, dried faecal sludge has been found to have a low thermal conductivity with values as low as 0.044 W/mK according to previous studies. The thermal conductivity of faecal sludge decreases with decrease in its moisture content (Makununika, 2016).

2.3.4 Thermal diffusivity

Thermal diffusivity is the capacity of faecal sludge to conduct heat relative to its ability to store heat energy. According to previous research, the thermal diffusivity of faecal sludge is in the order of 10^{-7} m^2/s. The thermal diffusivity of dried faecal sludge is also higher that of wet faecal sludge. Therefore, dried faecal sludge heats faster compared to wet faecal sludge (Septien et al., 2020).

2.3.5 Ash content

The ash content of faecal sludge is considerably elevated compared with faeces and other fuel sources like coal. (Ward et al., 2017). Based on the results of research from India and the Czech Republic, it was found that a greater content of ash (from 20% to 32%) had a negative effect on the effective calorific value of fuel (Vankat et al., 2010). Other studies in Uganda, Tanzania and Senegal show that the ash content of faecal sludge ranges from 15.7 to 58.5% DW (Gold, et al., 2017, Andriessen, et al., 2019 and Hafford, et al., 2019). The ash content of faecal sludge also varies with the nature of the pit. According to a previous study reported by Semiyaga, et al., 2016, faecal sludge from unlined pit latrines had a higher ash content of 50.2 ± 26.5 % TS compared to that from lined pit latrines with 34.5 ± 20.4 %TS.

2.3.6 Moisture content

This is the percentage of moisture present in the faecal sludge. The moisture content of faecal sludge depends on the nature of the pit. A previous on faecal sludge from three slums in Kampala showed that lined pit latrines had faecal sludge with a higher moisture content of 92.4 ± 1.8% compared to unlined pit latrines whose faecal sludge had a moisture content of 83.4 ± 5.0% (Semiyaga et al., 2016). Moisture content has a negative effect on the calorific value of faecal sludge in such a way that the calorific value decreases with increase in moisture content (Szymajda & Łaska, 2019). This means that the presence of moisture reduces the energy value of the faecal sludge and makes it unsuitable for processes like incineration in its wet form.

2.3.7 Chemical Oxygen Demand

This is the amount of oxygen that is needed to completely oxidize all of the organic carbon to carbon dioxide and water (Gerba & Pepper, 2012). A study in Kampala showed that faecal sludge from unlined pit latrines had a higher COD of 132,326 ± 43,786 mg/L compared to that from lined pit latrines which had a COD of 65,521 ± 43,960 mg/L. This implies that the COD of faecal sludge is dependent on the nature of pit latrine. The study also revealed that the COD / TVS ratio is also important parameter as it indicates the retention time of the faecal sludge in the pit latrine since organic matter degrades with time (Semiyaga et al., 2016).

2.3.8 Total Volatile Solids (TVS)

The value of TVS has an impact on the calorific value of faecal sludge. From previous studies in Uganda, Rwanda and Kenya, the TVS of faecal sludge was found to be in a range of 41.5 to 84.3% DW (Andriessen, et al., 2019, Gold, et al., 2017 and Nyaanga, et al., 2018). The TVS of faecal sludge is also dependent on the nature of pit latrine. For example, a study on faecal sludge from three slums in Kampala revealed that faecal sludge from lined pit latrines had a higher TVS of 63.5%TS than that of unlined pit latrines with a TVS of 50.0% TS (Semiyaga et al., 2016). There is also a good correlation ($r = 0.909$, $R^2 = 82.6\%$) between the calorific value and the TVS which is given as $CV = 0.12TVS + 7.44$ (Ahmed et al., 2019). The calorific value of the faecal sludge therefore increases with its TVS.

2.3.9 Heavy metals

Heavy metals are of concern due to their toxicity and long-term negative effects on soils. This is true in the case of incineration where the ash produced could be used, for example as a cover material for urine diversion dry toilets or in construction, or it can be disposed of in landfill sites (Strande et al., 2014). The composition of the heavy metals, such as Cadmium, Chromium, Copper, Mercury, Nickel, Lead and Zinc, in faecal sludge is dependent on the source of the faecal sludge (Gold et al., 2017). From a previous study in Kampala, the composition of Chromium (485ppm), Copper(114ppm), Nickel (24ppm), Lead (28ppm) and Zinc (646 ppm) was found to be a high in faecal sludge compared to that from excreta faeces (Gold et al., 2017).

2.4 Energy characteristics of solid wastes

The energy content of solid wastes is influenced by different characteristics such as the calorific value, moisture content, total volatile solids and ash content as described below.

2.4.1 Calorific Value

The calorific value is the heat content from the solid waste and is influenced by the moisture, total volatile solids, ash content as well as the chemical composition of the solid waste. According to Amber et al., 2012, the calorific value of solid waste varies with the category of solid waste. The average calorific value of the solid waste is 17.23 MJ/kg. Polyethene has a high calorific value of 46.5 MJ/kg compared to other solid wastes while textile has a low calorific value of 9.27 MJ/kg (Amber et al., 2012).

2.4.2 Heat capacity

The heat capacity of solid waste is influenced by the chemical composition as well as moisture content. The higher the moisture, the higher the heat capacity of the solid waste. The heat capacity also varies with the category of solid waste. For example, a previous study on municipal solid waste showed that food waste had the highest heat capacity of 1715 J/kgK while the paper had the lowest heat capacity of 1260 J/kgK(Sliusar & Armisheva, 2013).

2.4.3 Moisture Content

The moisture content of solid wastes varies with the category of solid waste. The higher the moisture content of the solid waste, the lower the heat content will be (Amber et al., 2012). Previous studies on municipal solid waste in Kampala and India show that solid wastes have moisture content in a range of 48.08 to 70.2% (Khare & Mali, 2011 and Komakech, et al., 2014).

2.4.4 Ash Content

The ash content of solid wastes also varies with the category of solid waste. The higher the ash content, the lower the calorific value of the solid waste. The ash content of solid wastes also varies with the location of their source (World Bank, 1999). For example, previous studies in India and Nigeria show that the ash content of solid wastes is in a range of 29.88 to 45.80% DW (Khare & Mali, 2011 and Izionworu & Gunorubon, 2018).

2.4.5 Total Volatile Solids

According to previous research in India and Nigeria, solid wastes have a total volatile solid in a range of 54.69 to 70.53 %TS (Khare & Mali, 2011 and Izionworu & Gunorubon, 2018). Solid wastes like metals, glass and rubble, have a low amount of TVS compared to organics, plastics, textile, paper, wood and rubber that have a higher amount of TVS. Total volatile solids are important because an increase in the total volatile solids results into a lower ash content. Therefore, the more the volatile solids, the higher the calorific value of the solid waste. (World Bank, 1999).

2.5 Energy recovery technologies

The incineration of faecal sludge can be achieved through several options which are generally categorized in two; non-carbonized options and carbonized options (Andriessen et al., 2019).

2.5.1 Carbonized options

Carbonization is essential in the conversion of dried biomass into a fuel that is similar to coal. It can also improve the calorific value of the fuel. The carbonized options include; Hydrothermal Carbonization (HTC) and pyrolysis (Andriessen et al., 2019).

- **HTC**

HTC is the process of thermochemical conversion of wet faecal sludge at temperatures ranging from 180 to 250 ^{o}C for a retention time of 1 to 12 hours. Hydrothermal carbonization also operates under high pressure of more than 30 bars which creates a need for proper operation and maintenance to ensure safe operation. It is also necessary to treat the liquid by-products and this is also more likely to be feasible on a centralized scale (Andriessen et al., 2019). HTC also has high flexibility on the choice of feedstock. Any kind of biomass can be carbonized hydrothermally such as faecal sludge. (Funke & Ziegler, 2010). HTC has also been done on plastic and unsorted municipal solid waste (Berge et al., 2011). HTC is an optimal process when the sludge with 20% DS is used (Andriessen et al., 2019). The HTC process is dependent on temperature, residence time, pressure, pH and solid load (Robbiani, 2013). A typical HTC process is shown in Figure 2-2. HTC produces hydrochar from faecal sludge with a higher calorific value than dry sludge (Andriessen et al., 2019).

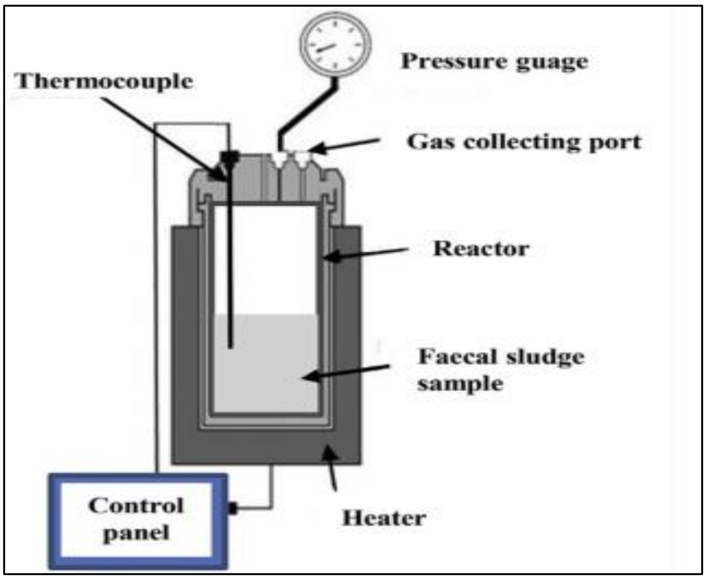


Figure 2-2 Schematic of HTC reactor

- **Pyrolysis**

Pyrolysis is the thermochemical treatment of biomass by heating to temperatures between 300 and 700 ^{o}C in the absence (or near absence) of oxygen. In order to produce solid fuel, slow-pyrolysis is applied because it has higher char yields than pyrolysis processes with higher heating rates. Slow-pyrolysis employs heating rates from 1 to 10 ^{o}C /min and residence times in the order of hours (Andriessen et al., 2019). Pyrolysis of wood and other cellulosic biomass usually produces higher energy chars with increasing pyrolysis temperatures (Ward et al., 2014). Through pyrolysis, faecal sludge can be used to generate fuel products such as bio-fuel. The ideal temperature ranges for the pyrolysis process using faecal sludge was found to be 150 to 400°C. However, in general, the pyrolysis of faecal sludge decreases its calorific value. Various pyrolysis reactors are available, but they vary in technical complexity. A simple reactor could consist of two oil drums with a chimney and a gas burner (Ankan et al., 2020). An example of a setup of a pyrolysis system for faecal sludge is shown in Figure 2-3.

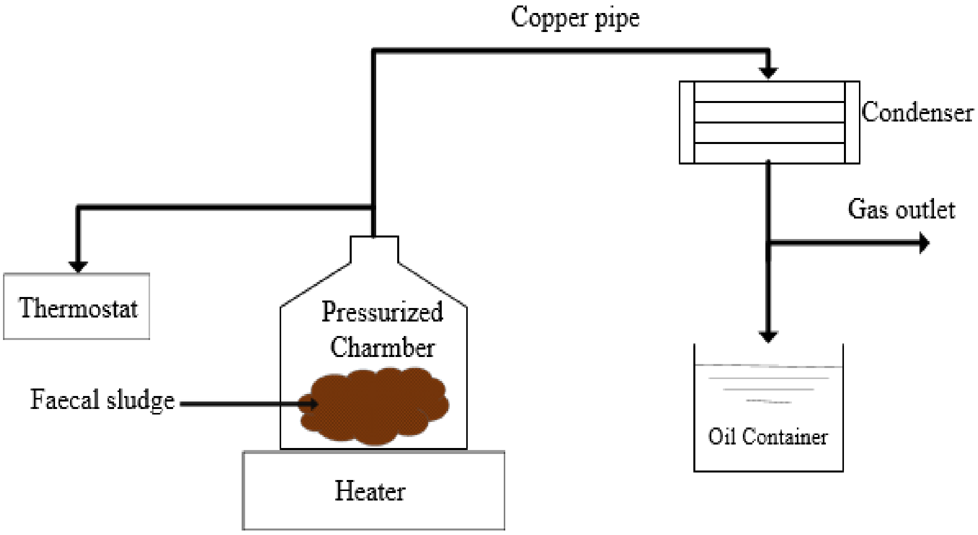


Figure 2-3 Flow diagram of pyrolysis setup (Ankan et al., 2020).

2.5.2 Non-Carbonized options

Non-carbonized faecal sludge has a higher calorific value and lower ash content compared to pyrolysed sludge, which makes it distinct from other biomass. A non-carbonized faecal sludge fuel is generally recommended unless a carbonized product is particularly needed by the combustion technology or end-user. Non–carbonized options include drying, conventional pelletization, bio-burn pelletizer and LaDePa process (Andriessen et al., 2019).

- **Drying technologies**

Drying of faecal sludge to more than 90% DS can be achieved either passively or actively. Passive drying depends on natural mechanisms of evaporation such as wind and the sun and does not involve the addition of energy. Active drying involves the application of external heat energy to enhance the evaporation process. Active drying is used where there is a need to accelerate the drying process and can increase processing capacity at treatment plants (Andriessen et al., 2019). The calorific value of faecal sludge from drying technologies is also dependent on the sanitation technology used to contain the faecal sludge. For example, faecal sludge from Anaerobic Baffled Reactors (ABR) has a higher calorific value compared to other technologies (Getahun, et al., 2020).

- **Pelletizing technologies**

Pelletization is the process that involves compressing biomass into pellets. Conventional pelletizing machines are compatible with the production of faecal sludge fuels as well as in animal feed and compost pellet production. The LaDePa pelletizer technology can be used to produce sanitized pellets from faecal sludge with 20 to 35% DS (Andriessen et al., 2019).

2.5.3 Preconditions for different energy recovery methods

For all the energy recovery methods, a precondition that is required in order to create solid fuel from faecal matter is that the calorific value of the dried sludge is high enough to make the solid fuel option technically and financially viable (Talyer, 2018). The following are the preconditions for the different energy recovery methods.

- **Thermal drying**

It is possible to use heat to evaporate water from sludge but the energy requirement increases with increased water content. For this reason, it will usually be advisable to reduce the water content of sludge before thermal drying (Talyer, 2018). Before thermal drying, the faecal sludge usually needs to undergo size reduction as well as screening and sorting (Lee & Shah, 2012).

- **Pyrolysis**

The energy requirements of pyrolysis increase with increased water content and hence reduction of the water content of sludge from drying beds is usually required (Talyer, 2018). The feed preparation and pretreatment for pyrolysis involves grinding and drying. Grinding improves the feed quality and subsequent heat transfer. Drying also improves the gas-solid contact, heat-mass transfer and reactions in the pyrolysis reactor (Lee & Shah, 2012).

- **Pelletization**

Before pellets can be made from the sludge, the sludge has to be prepared. The preparation usually consists of size reduction, screening, sorting, and in some cases drying to improve the handling characteristics and homogeneity of the waste material (Lee & Shah, 2012).

2.6 Evaluation of the Technologies

An evaluation is an independent and systematic investigation into how, why, and to what extent objectives are achieved by a particular technology (Twersky & Lindblom, 2012). There are several types of evaluation such as formative, summative and real-time evaluations. For projects are still under planning, for example where the selection of appropriate technologies is needed, a formative evaluation can be used (World Health Organisation, 2013).

The evaluation of the different technologies involves different steps such as scoping, developing criteria, data collection and analysis. Scoping involves defining the objective of the evaluation. An evaluation also requires the establishment of criteria to use such as efficiency, effectiveness and sustainability. The next step is data collection which can be done using different methods such as questionnaires, interviews and review of existing reports and documents. The collected data is then systematically analyzed by organizing, classifying and summarizing it so as to extract useful information that relates to the objectives of the evaluation (World Health Organisation, 2013). A summary of the literature review of different energy recovery methods is shown in Table 2-1.

Table 2-1 Summary of the literature review of the different energy recovery methods

Method	Preconditions	Operations	Input sludge requirements	Capability to enhance the output
Hydrothermal carbonization	-Shredding is required at feedstock (Robbiani, 2013).	-Thermal conversion of wet biomass by drying at temperatures of 180 to 250 ^oC in an HTC reactor (Robbiani, 2013).	-The feedstock is highly flexible and receives both faecal sludge and solid waste. - Input sludge is required to have 20% DS(Lee & Shah, 2012).	-60% to 90% of the gross calorific value of input material is available in the product (Lee & Shah, 2012). - Pathogens are also removed from the final product (Andriessen et al.,2019).
Pyrolysis	-Dewatering of faecal sludge is required as well as drying of wet material. -Grinding is also done to improve feed quality (Andriessen et al.,2019).	-Thermal decomposition of biomass in an inert atmosphere at high heating rates and temperatures of 300 to 750 ^oC (Andriessen et al.,2019).	-Input sludge is required to have 70% to 90% DS (Andriessen et al.,2019).	-Co-pyrolysis of faecal sludge with saw dust can be done to improve energy efficiency (Mwamlima et al., 2017). - Calorific value is generally reduced(Ankan et al., 2020). -There is pathogen removal in the final product (Andriessen et al.,2019).
Drying	-Size reduction, screening and sorting as well as dewatering of input material is required (Lee & Shah, 2012).	-Drying of input material to 90% DS by either natural mechanisms such as wind and sun or supply of external energy (Andriessen et al.,2019).	-Input sludge needs to be dewatered. -Input sludge also needs to have 20% DS (Andriessen et al.,2019).	

Method	Preconditions	Operations	Input sludge requirements	Capability to enhance the output
Pelletization	-Size reduction, screening, sorting, and in some cases drying to improve the handling characteristics and homogeneity of the input material (Lee & Shah, 2012).	-Compression of biomass into pellets up to around 70% DS for conventional pelletizing machines. -Pellets can further be dried to 90% DS in a Bioburn pelletizer (Andriessen et al.,2019). -In case of the LaDePa process, the sludge is treated with radiation to a temperature of 180 to 220 ^{o}C (Andriessen et al.,2019).	-Input sludge is required to have 70% DS for conventional pelletizers, 30% to 60% DS for Bioburn pelletizer and 20% to 30% DS for LaDePa process (Andriessen et al.,2019).	-Sanitized pellets can be produced via LaDePa Pelletizer technology. -Binders can be used to stick the biomass together (Andriessen et al.,2019).

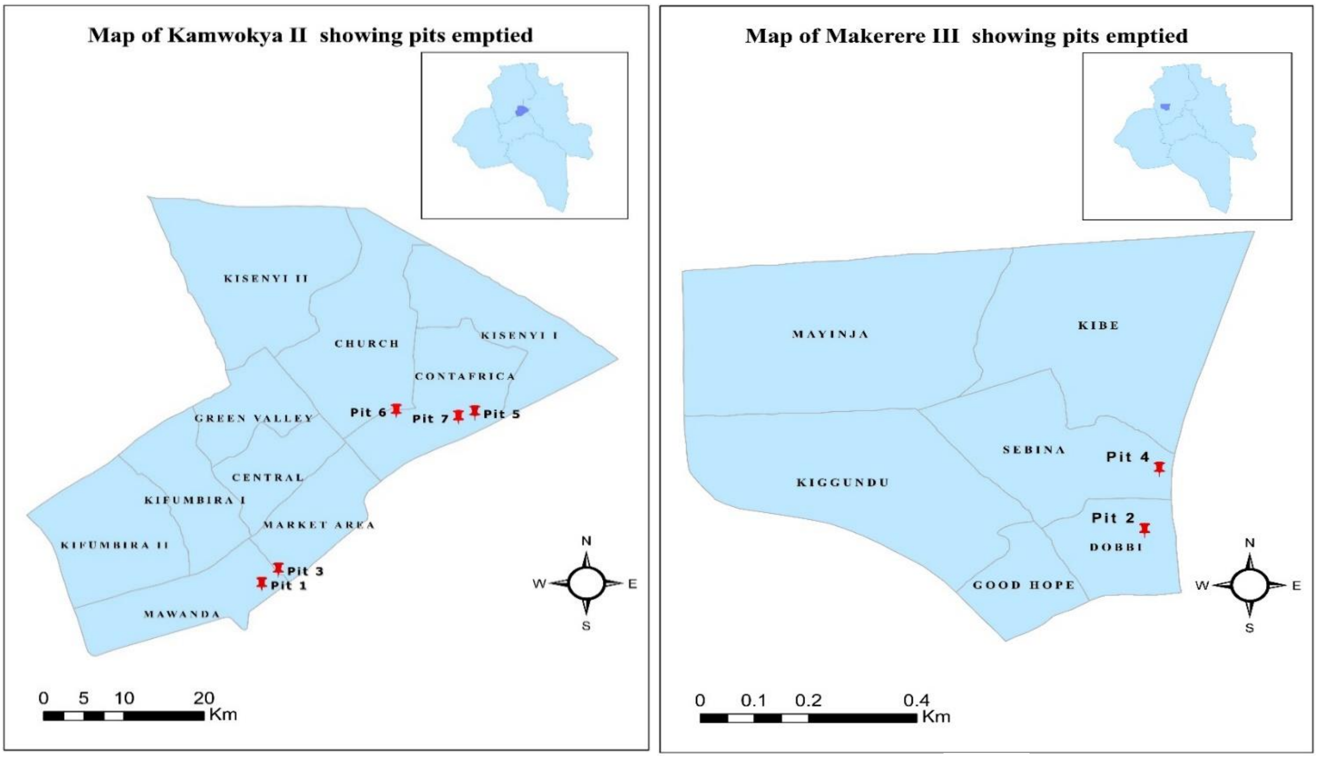
2.6.1 Selection of Technologies

The selection of the incineration technology depends on the intended use of the fuel (e.g. handling requirements, quantity needed and combustion technology) as well as the properties of the input faecal sludge such as ash content, and moisture content. The first step in the selection is to determine the characteristics of the input sludge. In case either quality or quantity of the input faecal sludge does not meet with user needs (for example, if either calorific value or quantity is too low), co-processing with other bio-wastes can be done to improve the faecal sludge fuel. Where land area for drying is limited, and operational safety can be ensured, either HTC or LaDePa can be a solution because both these technologies can handle faecal sludge with a high moisture content of 20% DS. In case the combustion technology cannot handle high-ash fuels, another biomass resource could be added to improve fuel quality and lower the ash fraction. In situations where the desired end product is to be compatible with coal or charcoal combustion systems and the receiving combustion technology can handle high-ash fuels, carbonization can be an option. Char also performs better than dried biomass for co-combustion with coal where very high-temperature combustion processes are required (Andriessen et al., 2019).

CHAPTER 3: MATERIALS AND METHODS

3.1 The study area

The study was conducted within Kampala which has five divisions; Nakawa Division, Kawempe Division, Makindye Division, Rugaba Division and Central Division. Kampala also has a population of 1.5 million people (Uganda Bureau of Statistics, 2017). Pit latrines in Kampala have also been found to have solid wastes present in the pit latrines (Zziwa et al., 2016). The research study was carried out on faecal sludge obtained from the pit latrines in slums of Kamwokya II and Makerere III which are shown by the maps in Figure 3-1 (a) and (b) respectively.



(a) (b)

Figure 3-1 Map of study areas in Kamwokya II and Makerere III

Before the research was conducted in study areas, permission was first sought from KCCA by means of a letter as shown in Appendix A. The following criteria was used for selecting the pit latrines in the study areas:

- **Faecal Sludge characteristics**

The characteristics of the faecal sludge from Kamwokya II and Makerere III differ significantly especially in terms of the solid waste composition present. This is because solid waste composition varies with location (Weinstein, 2006). The pit latrines in Kamwokya II and Makerere III therefore gave faecal sludge with significant variation in its energy characteristics and this facilitated the analysis of varying faecal sludge characteristics during the study.

- **User habits**

The people in slums; Kamwokya II and Makerere III, are found of dumping solid wastes in the pit latrines. This is favoured by the fact that there is more garbage generated yet councils in charge of the areas lack the capacity to dispose of it (United Nations Human Settlements Programme, 2007). This therefore made Kamwokya II and Makerere III suitable for the study.

- **Nature of the households and sanitation facilities**

Kamwokya II and Makerere III are also among the vulnerable urban areas in Kampala.There was also limited access to private toilets and this left most people in these slums to use shared toilets and communal toilets which had limited control in terms of usage. This therefore made Kamwokya II and Makerere III suitable for the research as these slums provided pit latrines with significant amounts of solid wastes.

3.2 Questionnaire

A questionnaire was used to obtain information about the quantity and quality of faecal sludge in the pit latrines. The questionnaire also provided information about; the emptying interval of the pits and solid wastes dumped in the pits if any. This information was then used to guide in the selection of pit latrines with solid waste and adequate quantity of waste for the study. The questionnaire that was used in the study is shown in Appendix B.

3.3 Determination of solid waste components in pit latrine faecal Sludge

All the waste from the pits was transported in drums to Lubigi sewage treatment plant for washing and sorting. The waste in the drums was poured through 50 mm, 25 mm and 5 mm sieves. The faecal sludge passed through sieves and drained into a containment tank at the Lubigi Gulpers' Dumping bay. The faecal sludge was then later removed by a vacuum truck. The solid waste that remained on the sieves was then washed using water from a hosepipe and then placed on a tarpaulin to dry as shown in Figure 3-2 (a). Once the solid wastes were dry, they were sorted and placed in polyethene bags as shown in Figure 3-2 (b).The polyethene bags were labelled with the solid waste category as described in Table 3-1. Each solid waste category was then weighed and its mass was recorded as shown in Table D - 1. The solid waste composition was determined by computing the percentage composition of each solid waste category as shown below (Zuma et al., 2015).

$$\text{Percentage composition of solid waste} = \frac{\text{Mass of solid waste category x 100}}{\text{Total mass of solid waste}}$$

(a) (b)

Figure 3-2 Drying and sorting of solid waste at Lubigi Sewage Treatment Plant

Table 3-1 Description of the different categories of solid waste

Waste category	Description
Organics	This included; mingling sticks, timber pieces and any wooden materials found.
Polyethene	This included; polyethene bags, polythene wrapping materials and any other polyethene material found.
Textile	This included; clothes, hair and other textile materials found in the pits.
Plastic	This included; plastic cups, bottles, tins, combs, straws, bottle caps and any other plastic material found with the exception of polyethene which had its category.
Glass	This included; soda bottles, glass plates and any other glass material found in the pits.
Sanitary towels	This included; sanitary pads and diapers.
Rubber	This included; condoms, rubber tyres and any other rubber material found in the pits.
Metals	This included metallic forks, cups, tins and any other metallic material identified.
Paper	This included all paper material found in the pit.
Rubble	This included; broken bricks and stones found in the pits.
Others	This included; soil and any very small and not easily unidentifiable materials found in the pits.

3.3.1 Determination of the combustible solid waste components

According to Jerie (2016) , combustible solid wastes include; paper, plastic, rubber and textiles. The combustible solid wastes have a significant calorific value that can support combustion while non-combustible solid wastes, such as metal, stones and glass, have a calorific value which is near zero in comparison to the combustible waste,and hence not suitable for combustion (Amber et al., 2012). The combustible solid waste categories that were considered for the study are:

- Organics
- Polyethene
- Textile
- Plastic
- Sanitary towels
- Rubber
- Paper

The percentage composition of combustible solid wastes was determined using the formula below. The computed percentage composition of combustible solid wastes is also shown in Table D - 2.

$$\text{Percentage composition of combustible solid waste} = \frac{\text{Mass of combustible solid waste x 100}}{\text{Total mass of combustible solid wastes}}$$

The percentage of the total combustible solid waste in the pits was also computed to determine the fraction of the total solid waste from the pits that was combustible as shown in the formula below. The computed percentage of the total combustible solid waste is shown in Table D - 3.

$$\text{Percentage of total combustible solid waste} = \frac{\text{Total mass of combustible solid waste x 100}}{\text{Total mass of solid waste}}$$

3.4 Sampling Strategy

3.4.1 Pit latrines emptied

The sampling strategy entailed manually emptying purposively selected pit latrines. The emptying was done by Brilliant Sanitation Contractor, a private contractor working together with KCCA to empty pits in the slums of Kamwokya II and Makerere III. The pits were emptied to full depth and where not possible, they were emptied close to the full depth. The waste removed from the pits was moved in jerry cans and placed into drums of 160 litres as shown in Figure 3-3 (a) and Figure 3-3 (b). The waste in each drum was then weighed using an digital weighing scale. During the weighing process, the weight of each empty drum was first measured, and then the weight of each drum filled with waste was measured. The mass of the waste in the drum was determined by subtracting the weight of drums from the combined weight of the waste and the drums. The drums containing the waste were then transported to Lubigi sewage treatment plant where the waste was washed and sorted.

(a) (b)

Figure 3-3 Pit emptying and transportation of waste from the pits in drums

3.4.2 Faecal sludge Sampling

Faecal sludge sampling was carried out manually by collecting sludge in a plastic container as the sludge was being removed from the pit. From this faecal sludge, samples were also collected in 60ml plastic containers and taken for laboratory analysis for the determination of the characteristics of the fresh faecal sludge shown in Section 4.2. A field sampling sheet was also used to record and track the samples to used for different laboratory tests as shown in Appendix A.

3.4.3 Sample preparation

After sorting and weighing all the solid waste, the combustible components were then selected. The different combustible solid wastes were then reduced in size to allow for testing using laboratory equipment, for example, the textile, plastics, rubber and polyethene were cut using scissors and the wood was crushed using a mortar as illustrated in Figure 3-4 (a) and Figure 3-4 (b). The faecal sludge from the corresponding pit was placed on a silver disposable plate and sun-dried in a greenhouse at Lubigi briquette plant for 5 to 6 days. The faecal sludge was then mixed with the solid waste sample which was crushed in a ratio of 1:1 with respective to mass. The samples were then taken for laboratory analysis for determination of energy characteristics such as; total volatile solids, ash content and calorific value.


(a) (b)

Figure 3-4 Crushing of solid waste and a sample of the crushed solid waste

3.5 Determination of energy characteristics of the faecal sludge mixed with solid waste

The energy characteristics of the waste from the different pits were determined using the following methods. Detailed procedures of these methods are included as Appendix C of this report.

3.5.1 Moisture content

The moisture content was determined following the standard method 2540G for solids and semi-solid samples (American Public Health Association, 2012). 30 ml of the sample were oven-dried at 105°C for 24 hours till a constant mass of the sample was obtained. The sample mass was measured before and after drying. The moisture content was then obtained as a percentage of the wet mass of the sample.

3.5.2 Total Volatile Solids (TVS)

TVS was also measured according to 2540 G for solids and semi-solid samples (American Public Health Association, 2012). The oven-dried sample was heated in a muffle furnace at 550 °C for 2 hours and the mass of residue was then measured and recorded. TVS was then obtained as the difference between the mass of the oven-dried sample and that of the residue after ignition at 550 °C expressed a percentage of the mass of the total solids obtained after drying at 105°C.

3.5.3 Ash content

Ash content was also determined following the standard method 2540G for solids and semi-solid samples (American Public Health Association, 2012). The Ash content was obtained as the mass of the residue obtained above after drying at 550 ^{o}C expressed as a percentage of the mass of the total solids after drying at 105^{o}C. The results obtained for the ash content of the different samples are shown in Table D - 4 and Table D - 8.

3.5.4 Chemical Oxygen Demand (COD)

The COD for the samples of fresh faecal sludge was determined using the titrimetric method according to 5220 C (American Public Health Association, 2012). The detailed results for the COD of fresh faecal sludge are shown in Table D - 10.

3.5.5 Heat capacity and Thermal conductivity

Thermal conductivity was measured using a thermal conductivity meter (QTM -500) at the Project's laboratory of the Department of Physics at Makerere University. An oven-dry sample was first moulded in a steel mould as shown in Figure 3-5 (a). The sample was compressed using a compression machine under a force of 150kN in a steel model at CEDAT Materials Laboratory as shown in Figure 3-5 (b). The moulded sample was then placed under the standard probe of QTM-500 Thermal Conductivity as shown in Figure 3-6 (a). The machine was then set to read to thermal conductivity parameter. After the sample was heated and tested for 60 seconds, the thermal conductivity in W/mK was displayed on the screen of the machine as shown in Figure 3-6 (b). The results obtained for thermal conductivity of the dried faecal sludge are shown in Table D - 5.

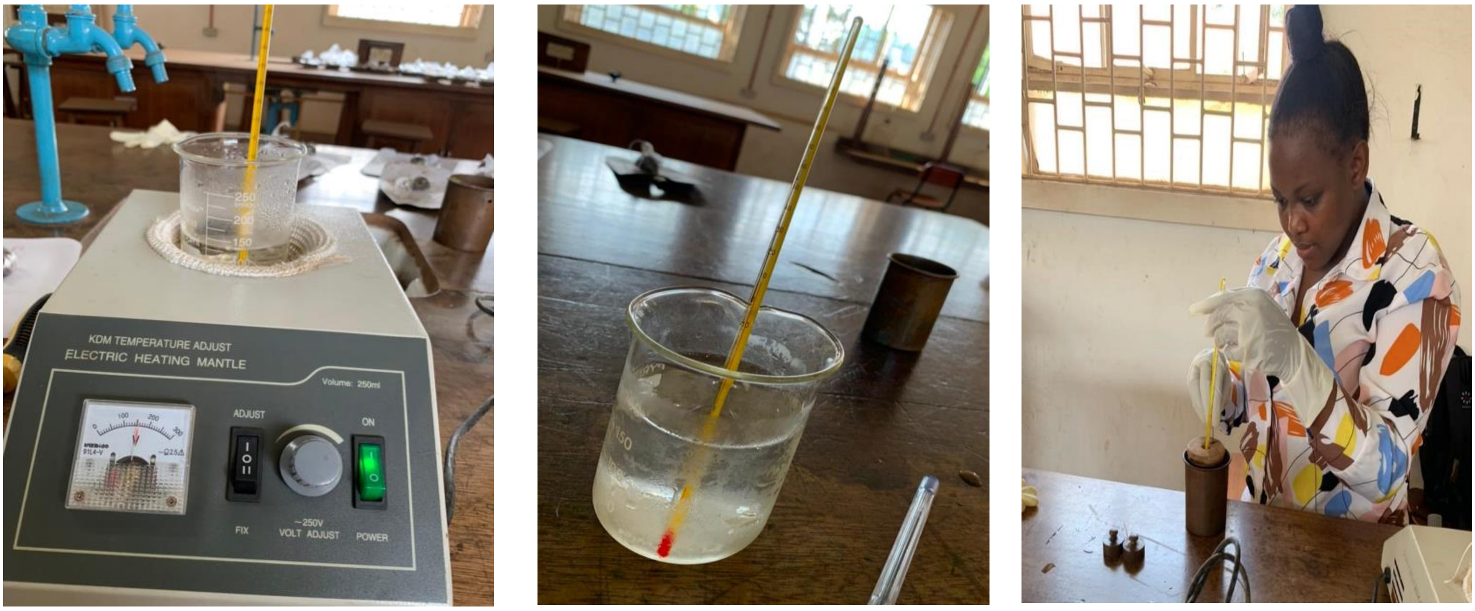
(a) (b)

Figure 3-5 Steel mould used to shape the samples and compression of the sample in the mould

(a) (b)

Figure 3-6 Testng of sample under QTM -500 probe and display of the thermal conductivity readings from the machine.

The heat capacity of the sample was determined by the method of mixtures using a calorimeter at the Department of Physics of Makerere University. The samples were placed in a thin light polyethene material to prevent them from dissolving in the water. The samples were then heated in a beaker of water at the boiling point of the water and the temperature was measured and recorded as shown in Figure 3-7 (a). Cool water was placed in a beaker and its temperature was measured and recorded as shown in Figure 3-7 (b). The cool water was then placed in the calorimeter and the solid sample was immediately immersed in it and gently stirred as shown in Figure 3-7 (c). After stirring the sample gently, the final equilibrium temperature was recorded and used to determine the heat capacity as shown in Table D - 6.



(a) (b) (c)

Figure 3-7 Heat capacity experiments conducted at the physics department of Makerere University

3.5.6 Thermal diffusivity

The thermal diffusivity of dried faecal sludge was determined as the ratio of its thermal conductivity to the product of its specific heat capacity and density as shown in Table D - 11.

3.5.7 Heavy metals

The heavy metals in the faecal sludge were determined using an atomic absorption spectrometer. The sample was first crushed and placed in block digester with 5ml of Nitric Acid and Hydrochloric Acid. The digest was then diluted and used with the atomic absorption spectrometer to determine the proportions of the heavy metals; Zn, Pb, Cd, Cu and Ni. The heavy metal proportions obtained for fresh faecal sludge are shown in Table D - 7.

3.5.8 Calorific value

The calorific value of the samples was determined using an oxygen bomb calorimeter in MJ/kg, and Benzoic acid was used as a standard in calibration (Water and Sanitation Program, 2016). Oven-dried samples were first crushed using a press and one gram of the samples was burnt in the bomb calorimeter to determine the calorific value. The detailed results obtained for the calorific value of the different samples are shown in Table D - 9.

3.6 Determination of the correlation between the energy characteristics of the faecal sludge and the total mass of solid waste in the pit

The correlations between the heat capacity and calorific value of faecal sludge and total mass of solid waste in the pits were determined by plotting graphs of the energy characteristics against the total mass of the solid waste. The coefficient of determination, R was then used to assess the significance of the correlations. The coefficient of determination is a measure of the extent to which the correlation fits the plotted data (Schober, et al., 2018).

3.7 Evaluation of the different methods of energy recovery from pit latrine faecal sludge

The evaluation of the different energy recovery methods was done using the formative evaluation method. The evaluation involved defining the scope, criteria as well as collecting data and analyzing the collected data.

3.7.1 Scope of the evaluation

The evaluation was limited to assessing hydrothermal carbonization, pyrolysis, drying and pelletization as the potential energy recovery methods. The goal of the evaluation was to determine the most appropriate method for energy recovery from faecal sludge mixed solid waste.

3.7.2 Criteria of the evaluation

The following criteria were used to evaluate the different technologies in order to develop a decision-making matrix for selecting a suitable energy recovery method.

- **Preconditions**

In the case of the preconditions such as screening and sorting, the most suitable energy recovery method was determined to be that which allows the solid waste components with a favourable effect on the energy value to remain. However, if the waste was found to be hazardous, methods that involve screening were considered suitable as screening is then a requirement by WHO guidelines (Talyer, 2018).

- **Input sludge requirements**

In terms of input sludge requirements, a review of the existing literature on the characteristics of faecal sludge required for use in a given method was done ,and this was used to determine if a given method is suitable for the mixed waste. The moisture requirements of the different methods were considered based on previous studies as shown in Table 2-1.

- **Heating requirement**

The energy requirement of the different methods was evaluated in terms of how much energy is needed to heat the input waste to the required temperatures in each method. For example, the case of pyrolysis, temperatures up to 700°C may be required and this results into a high amount of heat energy required to convert waste with a high capacity, and hence an increase in energy requirements. The heat energy required was determined as shown below (Irvine et al., 2010).

$$\text{Heat Energy} = \Delta T \times Cp$$

where ΔT is the required average temperature change required for a given method and Cp is the specific heat capacity of the input waste.

- **Capability to enhance the calorific value**

The efficiency of the methods was also assessed based on literature review and this helped to identify the methods that enhance faecal sludge to produce products with higher calorific value. For example, such methods were considered suitable for faecal sludge which has low calorific value.

- **Pathogen removal**

The technologies were also assessed in terms of the ability to sanitize the final fuel product. The desirable options were those that removed pathogens from the final product.

3.7.3 Data Collection and Analysis

The data collection was done through a review of existing literature on the different methods of energy recovery so as to obtain information on preconditions, input sludge requirements as well as operations involved in each method. The data collected from the literature review was analyzed together with the energy characteristics of waste that were determined.

3.7.4 Analysis

The analysis of the data was done using the multi-criteria analysis method in which the different energy recovery options were given scores based on the defined criteria (Department for Communities and Local Government, 2009). A performance matrix table was developed for the different technologies showing their scores under the different criteria as shown in Table D - 13.The score was awarded if the technology meets the condition under the given criteria with respect to a given waste category as an input. For example, a score of 1 was awarded under the pathogen removal criteria if the method removes pathogens from the final product, while a score of 0 was awarded if the method does not remove pathogens. The higher the score awarded, the more suitable the incineration option was for the given waste category. Table 3-2 below shows the scoring system used to score the different options.

Table 3-2 Scoring system for the different energy recovery options under evaluation

	Criteria	Score	Condition
A	Preconditions	1	If the preconditions favourably alter the characteristics of the input waste to make it suitable for the given option. For example, where drying is required as a precondition and the moisture of the input waste is high.
		0.5	If the preconditions do not affect the characteristics of the input waste for the given technology.

	Criteria	Score	Condition
		0	If the preconditions do not favourably alter the characteristics of the input waste.
B	Input sludge requirements	1	If input waste meets the moisture requirement for the given technology.
		0.5	If input waste partially meets the moisture requirement for the given technology. For example, if the moisture of the input waste is very close to the required range of moisture and its possible to dry the waste to required moisture content as a precondition.
		0	If input waste has a moisture content very far from the required range and drying is not possible as a precondition for the given technology.
C	Heating requirements	Between 1 to 4	A score of 4 was given to pelletization (conventional and bio burn pelletizer) because these methods require minimum heating energy. A score of 3.5 was given to drying technologies because this method requires less heating energy compared to HTC, pyrolysis and the LaDePa Process, but the heating energy required can exceed that of conventional and bio-burn pelletizers. HTC, Pyrolysis and LaDePa Process were given a score between 1 and 3 using a ranking based on the energy required to heat the input waste as shown in Table D - 12.
D	Capability to enhance the calorific value	1	If the technology can enhance the calorific value of the input waste especially where it has a low calorific value.
		0.5	If the technology cannot enhance the calorific value of the input waste but input waste already has a high calorific value.
		0	If the technology either reduces the calorific value or cannot enhance the calorific value where the input waste has a low calorific value.
E	Pathogen removal	1	If the technology removes pathogen from the final product.
		0	If the technology does not remove pathogens from the final product

3.8 Experimental Setup

All the extracted solid waste from the pits was used for the solid waste composition study. The mixed waste was then prepared and used to determine the energy characteristics of the waste from the different pits. The results from the solid waste composition study and the testing of faecal sludge samples were then used in the determination of the variability of the faecal sludge characteristics as well as in the evaluation of the methods of energy recovery such as pelletization, drying, pyrolysis and HTC. The experimental setup that was used during the study is shown in Figure 3-8.

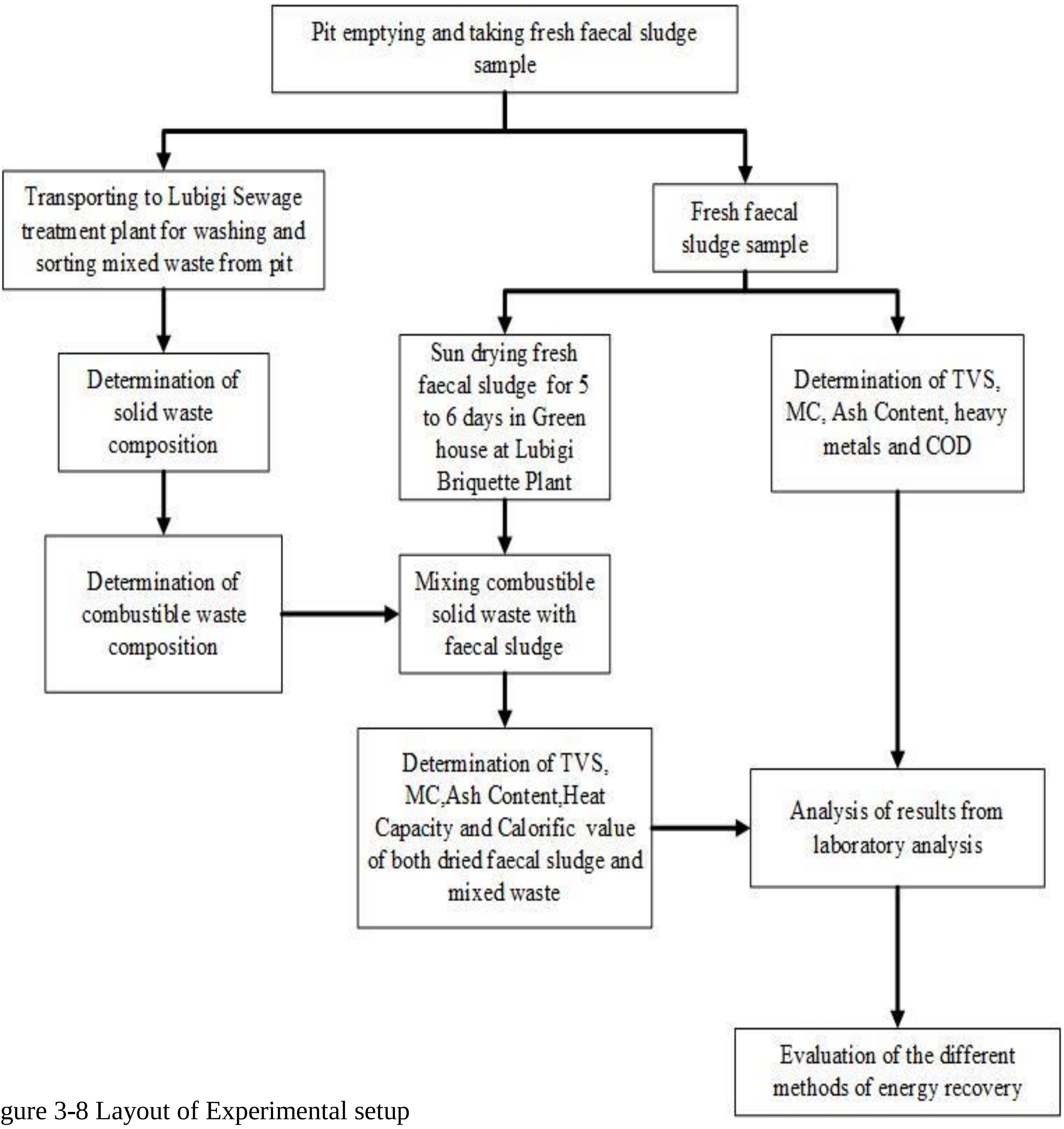


Figure 3-8 Layout of Experimental setup

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Solid waste composition in pit latrines

The study revealed that the solid waste composition in pit latrines consisted of; 5.1 ± 3.8% organics, 9.1 ± 7.5% polyethene, 11.2 ± 8.3% textile, 1.6 ± 0.4% plastic, 1.1 ± 1.6% glass, 9.2 ± 8% sanitary towels, 0.2 ± 0.2% rubber, 0.3 ± 0.4% metals, 15.9 ± 16.8% paper, 24.9 ± 25.8% rubble and 21.3 ± 21.3% others. The solid waste composition showed a high composition of rubble within the pits which indicated the collapse of the walls of the lined pits. According to Gudda et al. (2019), the presence of solid wastes in the pit latrines is likely due to the low level of sanitation awareness among households. The result also revealed that the solid wastes in the pits vary as shown in Figure 4-1. According to Zuma et al. (2015), this is due to differences in the habits of the users, demographics and type of cleansing material. A study on faecal sludge in Zambia showed the textiles had the highest composition of 54.4 ± 13.3% within pit latrines (Tembo, et al., 2019). However, that high composition of textiles can be explained by the fact that the textiles were considered to consist of both sanitary towels and clothes, while in this current study, textile consisted of only clothes. The results of the solid waste composition also showed that the pit latrines contained both combustible and non-combustible solid waste. The non-combustible solid wastes included; glass, metals and rubble. Previous studies have also shown that solid waste such as paper, polyethene, textile, plastic, organics, sanitary towels and rubber, are combustible (Amber et al., 2012).

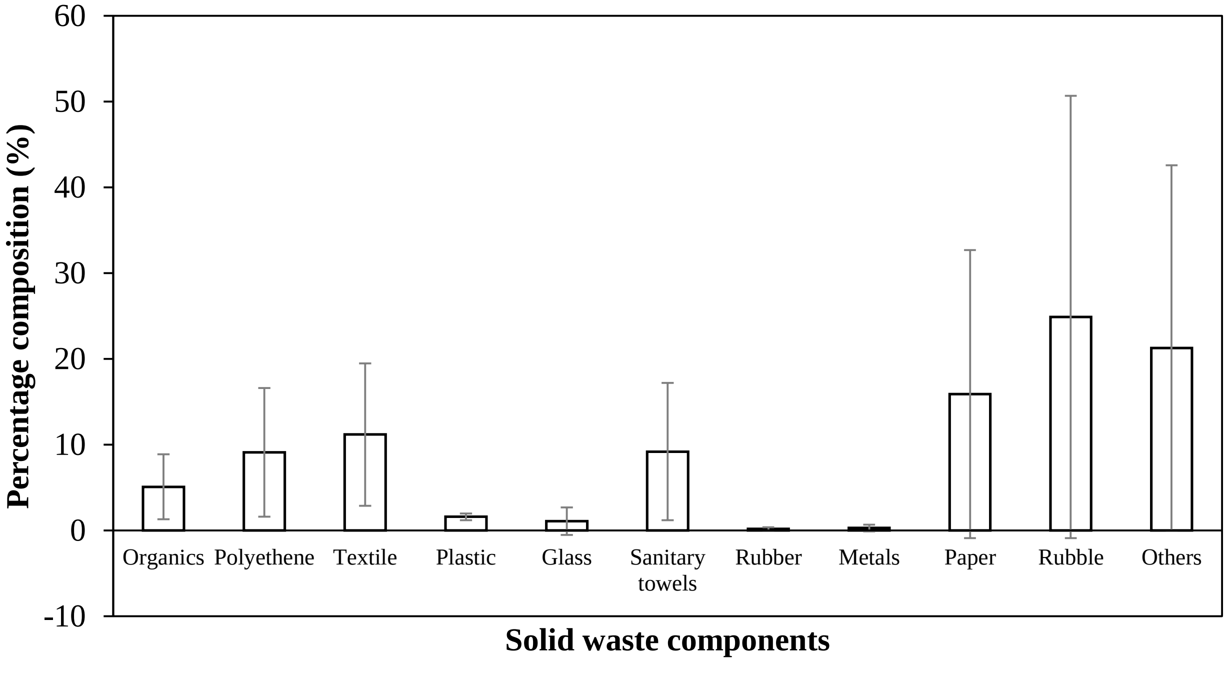


Figure 4-1 Percentage composition of solid waste in pit latrines

From the solid waste composition, the average percentage of total combustible solid waste was found to be 52.3% of the total solid waste which showed that about half of the solid waste from the pit latrines was combustible. The composition of combustible solid waste consisted of; 10.9 ± 7.2% organics, 18.2 ± 15% polyethene, 21.3 ± 12.4% textile, 4.2 ± 2.7% plastic, 15.8 ± 8.8% sanitary Towels, 0.5 ± 0.9% rubber and 29.1 ± 28.2% paper. From this composition, paper had the highest composition compared to other combustible solid wastes as shown Figure 4-2. This is because paper is used as a sanitary and anal cleansing material, and is often disposed of in pit latrines (Zuma et al., 2015). Polyethene, textile, sanitary towels and paper generally had a high composition in the pit. This is because users have a habit of disposing off such waste in pit latrines according to previous studies in Kampala, Kenya and South Africa (Zziwa et al., 2016, Gudda et al., 2019 and Still & Foxon, 2012).

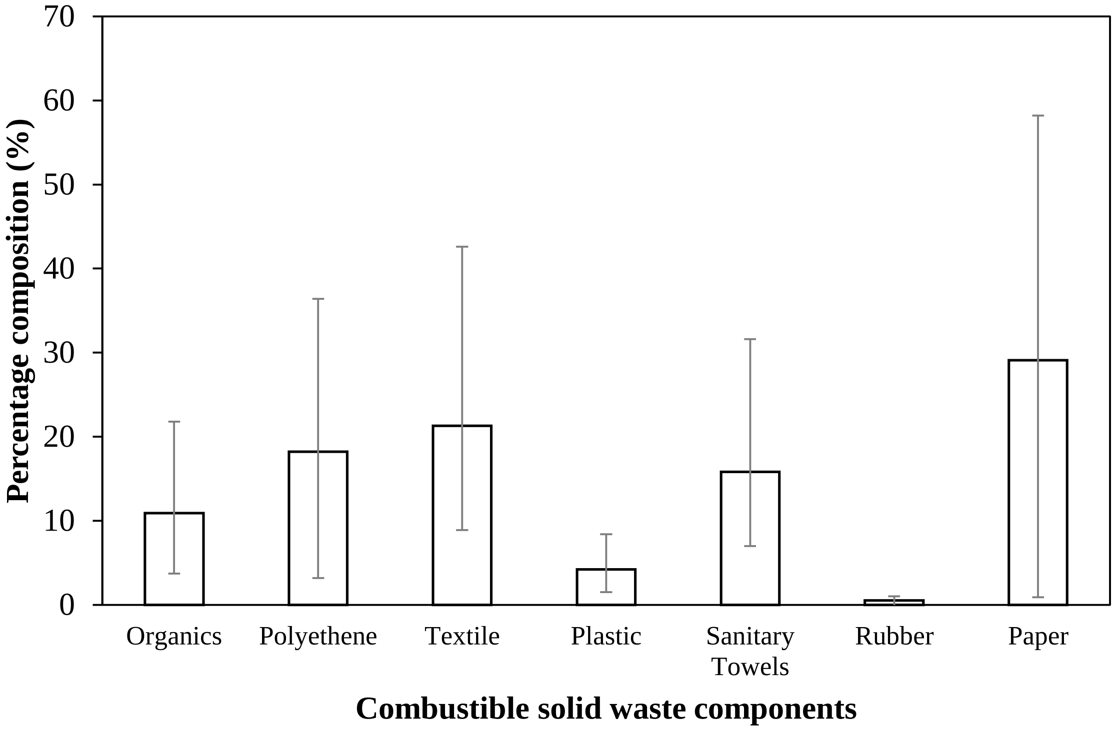


Figure 4-2 Percentage composition of combustible solid waste in pit latrines

4.2 Faecal sludge characteristics

Fresh faecal sludge was the faecal sludge that was obtained directly from the pit latrines and tested in the laboratory without first drying. The moisture content value of 87.6 ± 3.2 % for the fresh faecal sludge was within the range of 77.63 to 94.37 % reported by Zziwa et al. (2016). The main source of this moisture in the faecal sludge is urine and water used for anal cleansing as well as cleaning the pit latrines. The presence of a high-water table, which was evidenced by the fact the most of the pit latrines emptied were raised, also contributed to this moisture content.

The values of 64.3 ± 13.5% TS and 35.7 ± 13.5% TS for total volatile solids and ash content respectively of the fresh faecal sludge were within the range reported by previous studies (Andriessen et al., 2019 and Gold et al., 2017). The COD value of 11,508 ± 719 mg/l for the fresh faecal sludge was also within the range of 10,000 to 20,000 mg/l of COD from pit latrines reported by Schoebitz et al. (2016). Fresh faecal sludge with a COD/TVS ratio of 0.2 had a lower TVS of 61.3%TS compared to fresh sludge with a COD/TVS ratio of 0.13 which had higher TVS of 76.3%TS. This implied that the TVS of the fresh faecal sludge decreases with age because the higher values of COD / TVS ratio indicate a longer retention time in the pit latrine. This is likely to be a result of microbial degradation into carbon and ammonia leading to a higher ash content as reported by Semiyaga et al. (2016). Table 4-1 shows the characteristics of fresh faecal sludge obtained from the different pit during the emptying process.

Table 4-1 Characteristics of fresh faecal sludge

Parameter	Unit	Fresh FS from pit latrines Mean ± SD
Moisture Content	%	87.6 ± 3.2 (n = 7)
Ash Content	%TS	35.7 ± 13.5 (n = 7)
TVS	%TS	64.3 ± 13.5 (n = 7)
COD	mg/L	11508 ± 719 (n = 5)
COD / TVS ratio		0.17 ± 0.04 (n = 5)

The study showed that heavy metal composition of fresh faecal sludge consisted of; 1.1 ± 0.7 ppm Lead,7.3 ± 3.8 ppm Copper, 21.8 ± 8.9 ppm Zinc,1.4 ± 0.9 ppm Cadmium and 0 ± 0 ppm Nickle. The results showed a low concentration of all the heavy metals in comparison to previous studies. These heavy metals are important because they can be toxic to plants and people (Englund & Strande, 2019). The results were more comparable to the heavy metal composition of excreta faeces reported by Gold et al., 2017. The composition for Zinc was the highest compared to that other of metals as shown in Figure 4-3. This is comparable to previous studies that show Zinc to have the highest composition in faecal sludge (Gold et al., 2017). According to Effah et al. (2015), the high composition of zinc in faecal sludge can be explained by the leaching of zinc residue contained in waste, such as deodorants and cosmetics, which is disposed off at dump sites located close to the toilets.

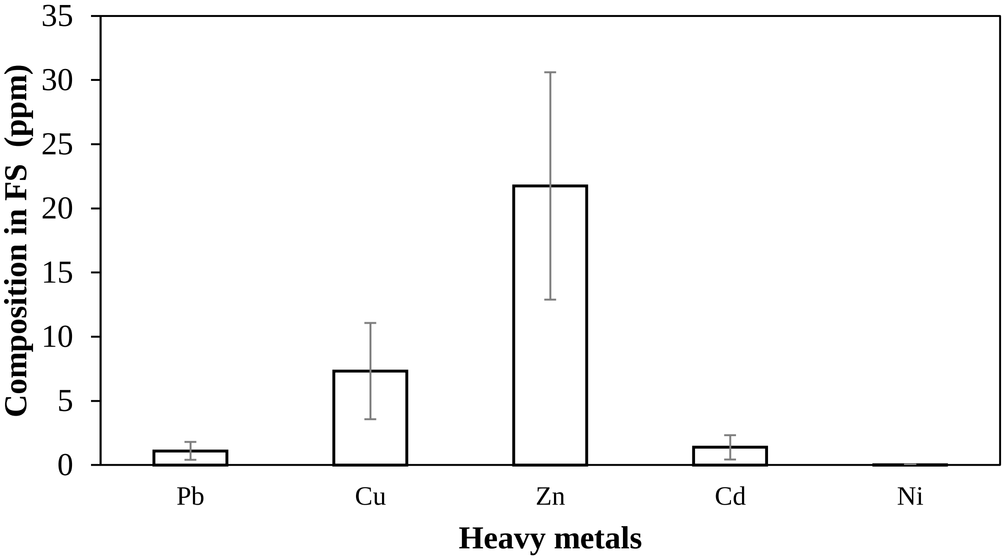


Figure 4-3 Heavy metal of faecal sludge from the pit latrines

Dried faecal sludge was the faecal sludge which was sun-dried for 5 to 6 days in a green house and then tested in the laboratory. The moisture content of 35.8 ± 6.3% for the dried faecal sludge showed a dryness value of 64.2 ± 6.3%, and this is within the range of previous studies that showed a dryness greater 20% beyond a drying period of 5 days in a greenhouse (Seck et al., 2015).

The total volatile solids of 59.6 ± 14.1% TS for the dried faecal sludge was lower than that of fresh faecal sludge due to loss of volatile components from the faecal sludge during the drying process in the green house (Seck et al., 2015).

The thermal conductivity of 0.32 ± 0.21 W/mK for the dried faecal sludge was in the range of 0.258 to 0.478 W/mK reported by Mugauri (2019). The heat capacity of 2720 ± 720 J/Kg^{O}C for the dried faecal sludge was also in the range of 1200 to 2900 J/Kg^{O}C reported by previous studies (Septien et al., 2020). The thermal diffusivity (1.63 x 10^{-7} m^2/s) of the dried faecal sludge was also in the order values reported by Septien et al. (2020). According to Septien et al. (2020), these values of thermal diffusivity are higher than those of wet faecal sludge, and therefore dried faecal sludge was expected heat faster than the wet faecal sludge.

The calorific value of 15.0 ± 2.7 MJ/kg for the dried faecal sludge was in the range reported by previous studies in Kampala and Ghana (Muspratt et al., 2014 and Gold et al., 2017). The characteristics of the sun-dried faecal sludge which was used for laboratory analysis are shown in. Table 4-2.

Table 4-2 - Energy characteristics of dried faecal sludge

Parameter	**Unit**	**Sun-dried FS (n=3)** **Mean ± SD**
Moisture Content	%	35.8 ± 6.3
Ash Content	%TS	40.6 ± 14.1
TVS	%TS	59.4 ± 14.1
Thermal conductivity	W/mK	0.32 ± 0.21
Heat Capacity	J/Kg^{O}C	2720 ± 720
Thermal diffusivity	m^2/s	1.63 x 10^{-7} ± 9.52 x 10^{-8}
Calorific Value	MJ/kg	15.0 ± 2.70

4.3 Solid waste characteristics

The study showed that the moisture content of the solid wastes was; 61.6 ± 18.2 % for plastics, 51.4 ± 15.7 % for textile, 45.6 ± 4.1 % for polyethene, 64.2 ± 5.5 % for paper, 43 ± 7.5 % for sanitary towels, 69.8 ± 25.1 % for organics and 50.2 % for rubber. In general, the average moisture content for the solid wastes was 55.1 ± 10.1 % which is within the range of previous studies (Khare & Mali, 2011 and Komakech et al., 2014). This value of moisture content also showed that the solid waste attains an average dryness of 44.9 ± 10.1 % after 5 days of solar drying. The moisture content of the solid wastes after drying also varies as shown in Figure 4-4, which indicates that the solid wastes dry at different rates. This is likely to be due to the differences in chemical nature and molecular structure of the different solid wastes which allows some solid wastes to trap and absorb more moisture than others.

The TVS of the solid wastes was; 62.5 ± 15.7 %TS for plastic,57.4 ± 7.5 %TS for textile,59.1 ± 21.1 %TS for polyethene, 64.2 ± 10.5 %TS for paper, 72.9 ± 6.6 %TS for sanitary towels, 73.5 ± 5.1 %TS for organics and 76.9 %TS for rubber, while the ash content was; 37.5 ± 15.7 %TS for plastic,42.6 ± 7.5 %TS for textile,40.9 ± 21.1 %TS for polyethene, 35.8 ± 10.5 %TS for paper, 27.1 ± 6.6 %TS for sanitary towels, 26.5 ± 5.1 %TS for organics and 23.1 %TS for rubber. On average, the solid wastes had TVS and ash content values of 66.6 ± 7.7% TS and

33.4 ± 7.7 % TS respectively which are within the range reported in previous studies (Khare & Mali, 2011 and Izionworu & Gunorubon, 2018). The results also showed that the TVS and ash content of the solid wastes vary with the solid waste category. From the study, rubber had a very high TVS compared to other solid wastes as shown in Figure 4-4. This is can be attributed to the fact that rubber consisted of highly flammable materials such as condoms.

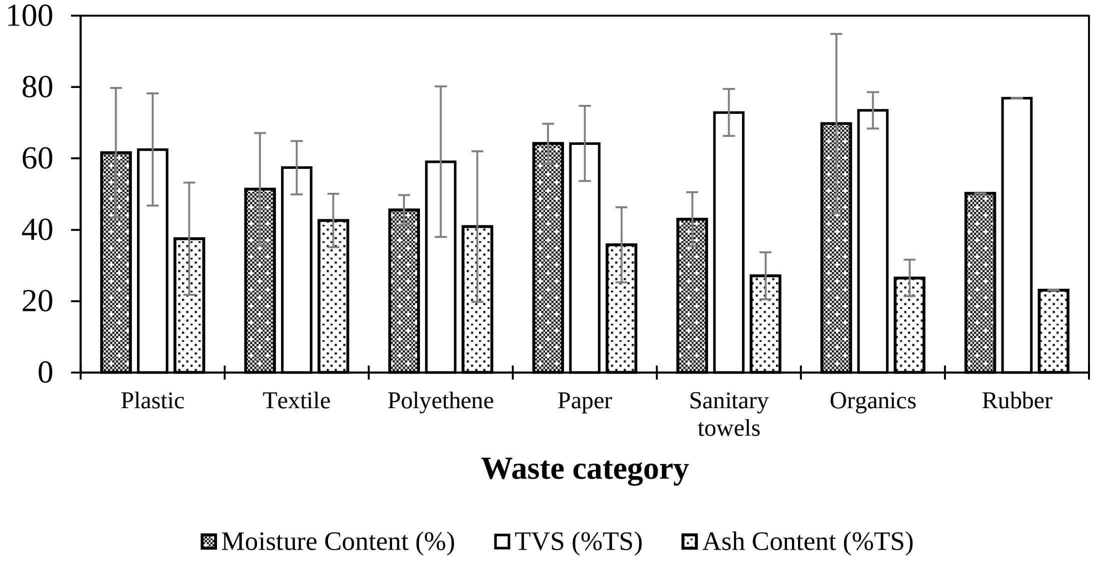


Figure 4-4 Moisture content, TVS and Ash content of solid wastes from pit latrines

The heat capacity of the solid wastes was found to be; 3811 ± 1956 J/Kg^{O}C for textile,4746 ± 1034 J/Kg^{O}C for polyethene,2579 ± 1374 J/Kg^{O}C for paper, 3799 ± 271 J/Kg^{O}C for sanitary towels and 3814 ± 1033 J/Kg^{O}C for organics. Generally, the average heat capacity of the solid wastes was 3750 ± 770 J/KgK. This value showed that the solid waste had high heat capacity compared to the previous study reported by Sliusar & Armisheva (2013). This was likely to be due to contamination of the solid waste streams with faecal sludge particles and other particulates from the pit. The heat capacities of the solid wastes also vary as shown in Figure 4-5. This variation is likely due to the differences in chemical composition and density for the different solid wastes.

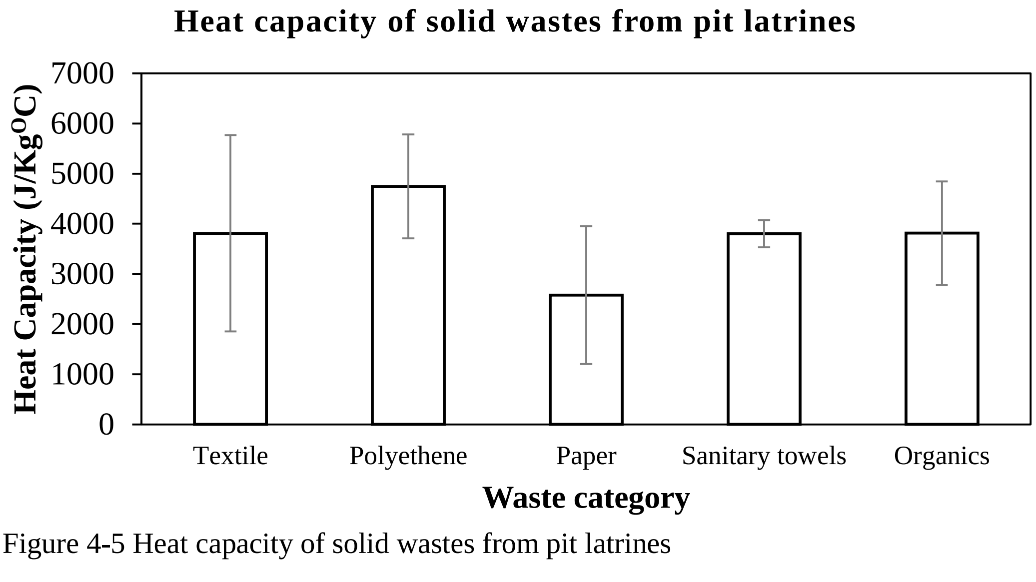


Figure 4-5 Heat capacity of solid wastes from pit latrines

The calorific values of the different solid wastes were found to be; 40.8 ± 1.9 MJ/kg for plastic,14 ± 1.8 MJ/kg for textile,43.3 ± 1.9 MJ/kg for polyethene,13.4 ± 2.2 MJ/kg for paper,19.9 ± 2.7 MJ/kg for sanitary towels, 21.2 ± 3.1 MJ/kg for organics and 64.3 MJ/kg for rubber. In general, the average calorific value of the solid wastes was 31.0 MJ/kg which is above the value of 17.23 MJ/kg reported by Amber et al. (2012). This high value of the calorific value was likely to be due to contamination of the solid waste with faecal matter. Polyethene had the highest average calorific value of 43.3 MJ/kg compared to other solid wastes as shown in Figure 4-6. This was comparable to the previous study that showed polyethene to have the highest calorific value of 46.5 MJ/kg (Amber et al., 2012).

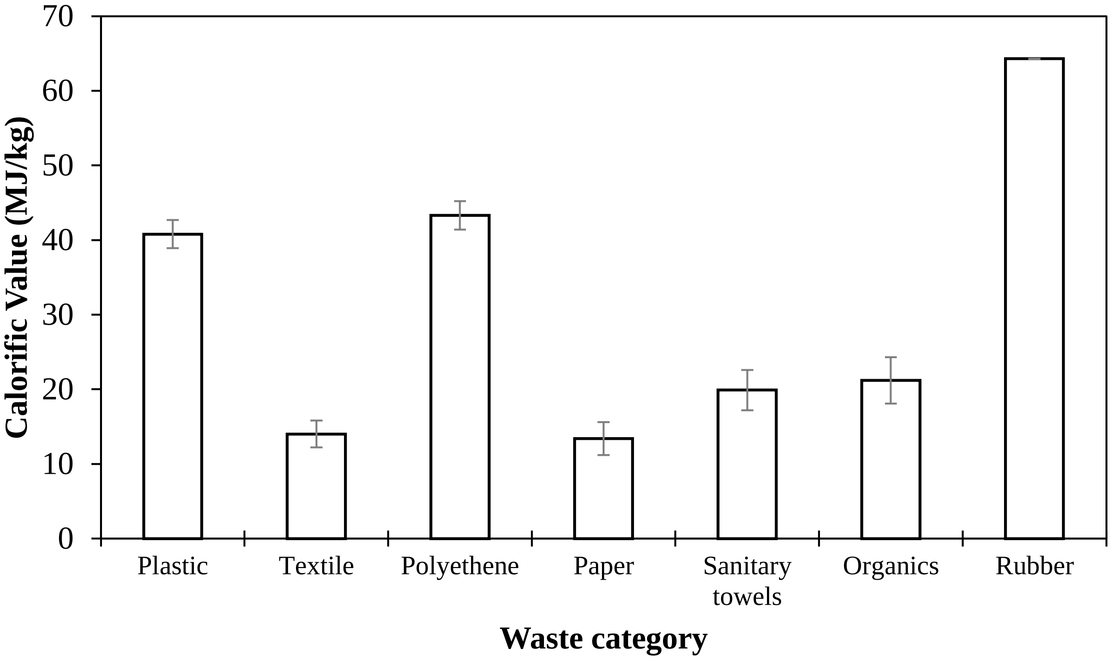


Figure 4-6 Calorific value of solid wastes from pit latrines

4.4 Characteristics of faecal sludge mixed with solid waste

The moisture content of the mixture of dried faecal sludge and solid wastes was found to be; 37.2 ± 6.1 % for FS and Textile, 43.9 ± 15.4% for FS and Polyethene, 46.2 ± 10.9% for FS and Paper, 51.7 ± 10% for FS and Sanitary towels, 47.8 ± 9.4% for FS and Organics, 40.7 ± 11% for FS and Plastic, 40.2% for FS and Rubber, and 54.5 ± 6.6% for FS and all solid waste. Mixtures of faecal sludge with all solid waste had the highest moisture compared to other mixtures as shown in Figure 4-7. This indicated mixing of faecal sludge with solid waste generally increases its moisture content.

The TVS of faecal sludge mixed with solid waste was found to be; 65.7 ± 4.1%TS for FS and Textile, 58 ± 1.7%TS for FS and Polyethene, 60.9 ± 7%TS for FS and Paper, 54.2 ± 7.9%TS for FS and Sanitary towels, 63.8 ± 5.7%TS for FS and Organics, 52.6 ± 15.3%TS for FS and Plastic, 61.4%TS for FS and Rubber, and 64.8 ± 7.1%TS for FS and all solid waste, while ash content was; 34.3 ± 4.1%TS for FS and Textile, 42 ± 1.7%TS for FS and Polyethene, 39.1 ± 7%TS for FS and Paper, 45.8 ± 7.9%TS for FS and Sanitary towels, 36.2 ± 5.7%TS for FS and Organics, 47.4 ± 15.3%TS for FS and Plastic, 38.6%TS for FS and Rubber, and 35.2 ± 7.1%TS for FS and all solid waste. In general, the average values of TVS and ash content for the mixtures of faecal sludge and solid waste were 59.4 ± 4.7% TS and 40.6 ± 4.7%TS respectively. These values showed that the TVS for the mixture of faecal sludge and solid waste was lower than that of fresh faecal sludge alone. This implies that mixing of solid waste with faecal sludge increases its ash content and hence reducing its total volatile solids. However, the TVS of the mixtures of faecal sludge and textile was higher compared to that of other mixes as shown in Figure 4-7. This implied that the textile adds more volatile components to faecal sludge when mixed with it compared to other solid wastes.

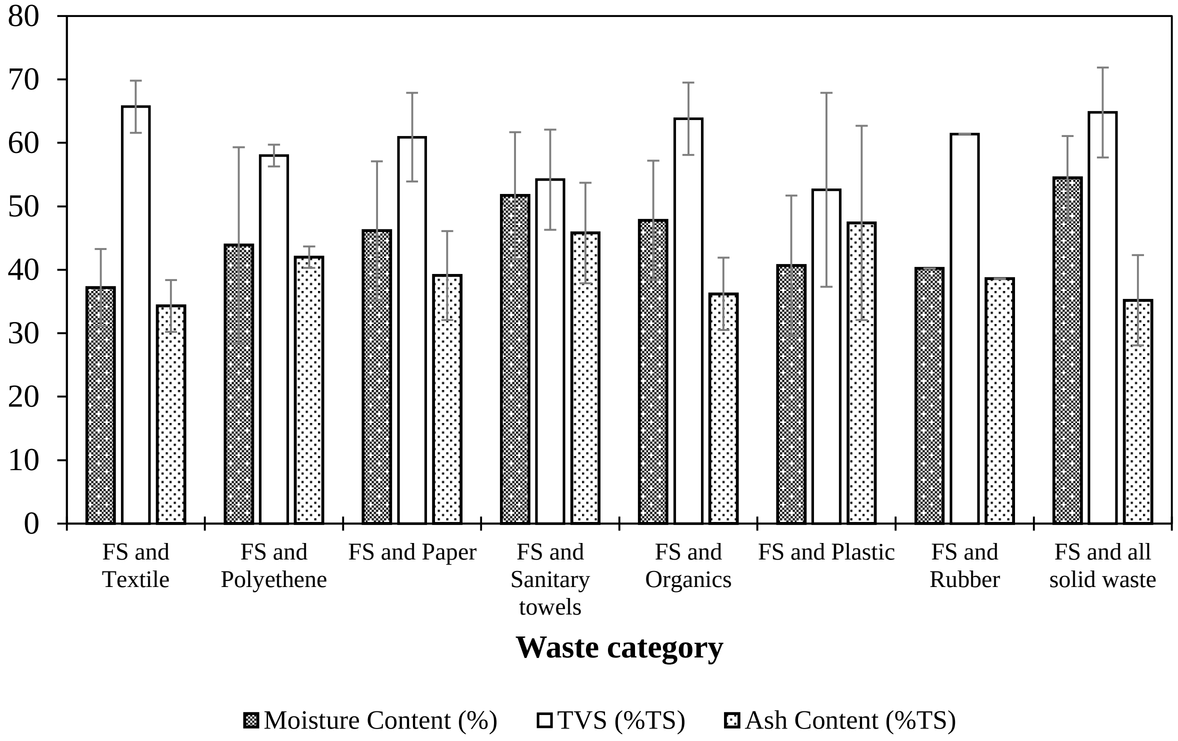


Figure 4-7 Moisture content, TVS and Ash content of faecal sludge mixed with solid waste

The study also showed that the heat capacity of faecal sludge mixed with solid waste was; 3043 ± 2143J/Kg^{O}C for FS and Textile, 4596 ± 964 J/Kg^{O}C for FS and Polyethene, 2848 ±1025 J/Kg^{O}C for FS and Paper, 4996 ±1151 J/Kg^{O}C for FS and Sanitary towels, 3131 ± 1322 J/Kg^{O}C for FS and Organics, 6709 J/Kg^{O}C for FS and Plastic, 5008 ± 253 J/Kg^{O}C for FS and all solid waste. Generally, the average heat capacity of faecal sludge mixed with solid waste was 4333 ± 1410 J/Kg^{O}C which was greater than that of faecal sludge alone. This indicated that solid wastes, when mixed faecal sludge, increased its heat capacity. Mixtures of faecal sludge and solid waste like sanitary towels, polyethene, plastic and organics had high heat capacities compared to the other mixes as shown in Figure 4-8. This is likely to be due to the unique chemical composition of these solid wastes compared to others.

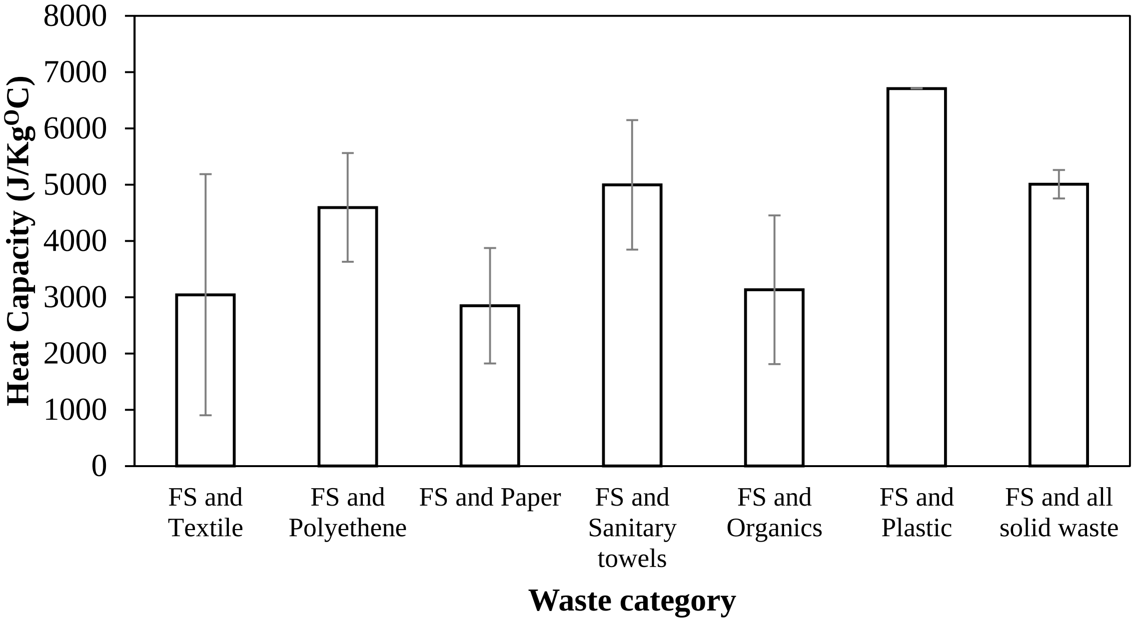


Figure 4-8 Heat capacity of faecal sludge mixed with solid waste

The calorific value of faecal sludge mixed with solid waste was found to be; 14.3 ± 1.4 MJ/Kg for FS and Textile, 38.9 ± 4.8 MJ/Kg for FS and Polyethene, 9.7 ± 3 MJ/Kg for FS and Paper, 14.7 ± 1.7 MJ/Kg for FS and Sanitary towels, 15.8 ± 1.0 MJ/Kg for FS and Organics, 33 ± 0.6 MJ/Kg for FS and Plastic, 52.6 MJ/Kg for FS and Rubber, and 39.2 ± 3.6 MJ/Kg for FS and all solid waste. In general, the average calorific value of faecal sludge mixed with solid waste was 29.1 ± 15.9 MJ/kg and this value was greater than that of faecal sludge alone. This showed that the calorific value of faecal sludge is higher when mixed with solid waste. Polyethene, plastic and rubber, when mixed with faecal sludge, resulted in high calorific values. This indicated that the addition of such solid wastes to faecal sludge increases its energy content highly. The mixture of faecal sludge and rubber had the highest calorific value compared to other mixes as shown in Figure 4-9. This is likely to be due to the high TVS of rubber that led to an increase in the calorific value.

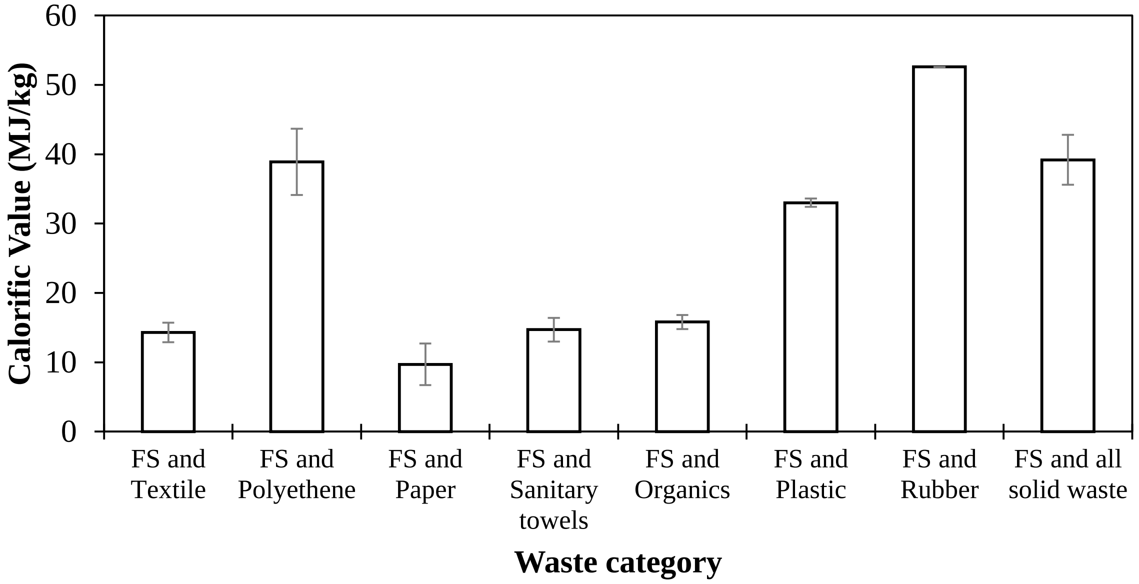


Figure 4-9 Calorific value of faecal sludge mixed with solid waste

4.5 Correlation between the energy characteristics of faecal sludge and total mass of all solid waste in the pit

There was a positive correlation ($R^2 = 81.1\%$) between the TVS of fresh faecal sludge and total mass of solid waste in the pit as shown in Figure 4-10. The study also showed a positive correlation ($R^2 = 99.8\%$) between TVS of the dried faecal sludge and the total mass of solid waste from the pit as shown in Figure 4-11. According to previous studies on correlations, these correlations are strong (Schober et al., 2018). These correlations indicate that an increase in the total mass of solid wastes in the pit increases the amount of total volatile solids of the faecal sludge.

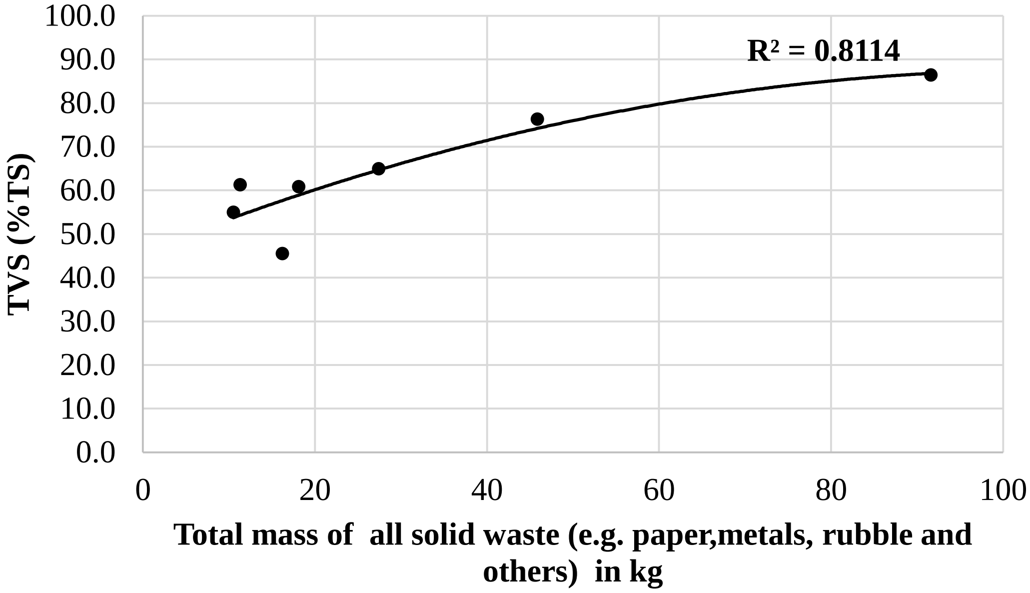


Figure 4-10 Correlation between TVS of fresh faecal sludge and total mass of solid waste in the pit

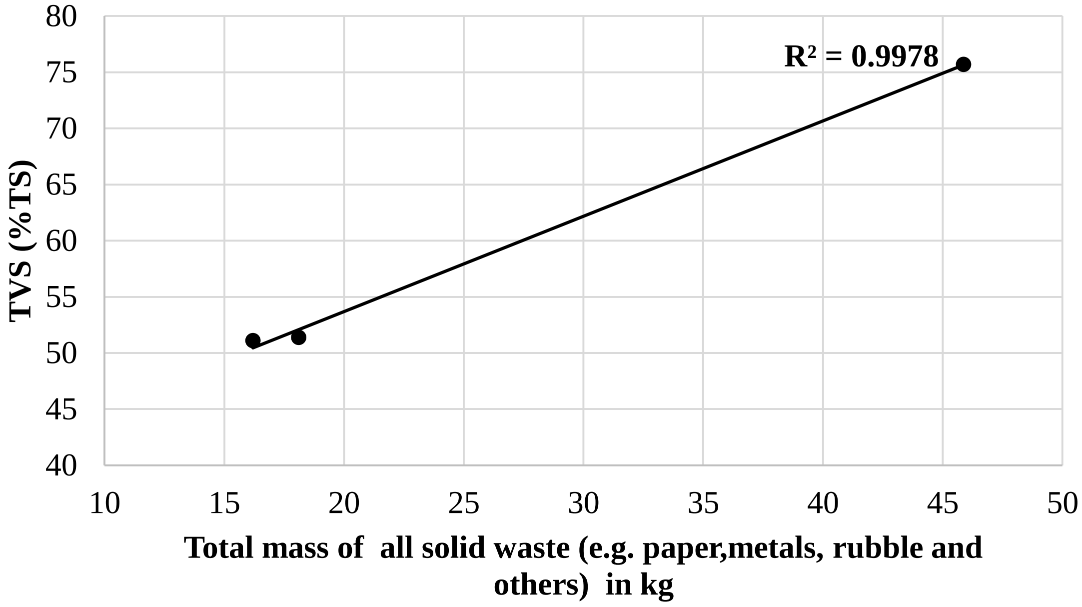


Figure 4-11 Correlation between TVS of dried faecal sludge and total mass of solid waste in the pit

There was also a positive correlation (R^2 = 92.1%) between the calorific value of dried faecal sludge and the total mass of combustible solid waste from the corresponding pit as shown in Figure 4-12. This was also a strong correlation and it showed that an increase in combustible solid waste in the pit latrine increases the energy content of faecal sludge when burnt.

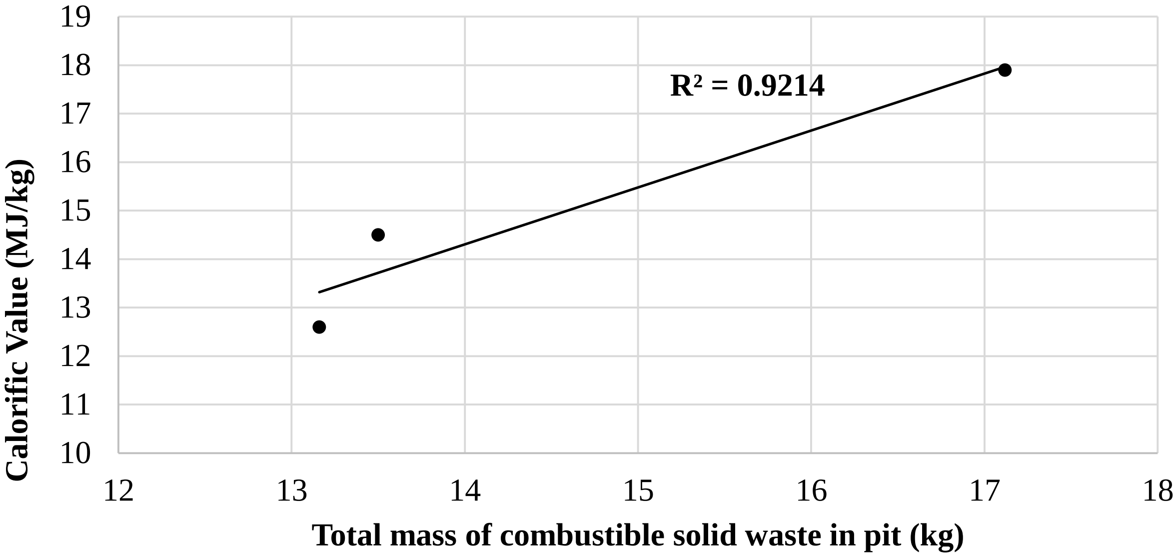


Figure 4-12 Correlation between calorific value of fresh faecal sludge and total mass of solid waste in the pit

4.6 Evaluation of Technologies

From multi-criteria analysis of the different incineration options, the average scores were; 4.9 for hydrothermal carbonization, 4.5 for pyrolysis, 5.2 for drying, 5.7 for pelletization (conventional pelletizer), 6.2 for the bio burn pelletizer and 6.2 for the LaDePa process. The results showed also that the choice of technology was dependent on the input waste category as shown in Table 4-3. The non-carbonized options performed better than the carbonized options due to a low heating requirement. A low heating requirement was important because the different waste streams had high heat capacities. Among the carbonized options, hydrothermal carbonization performed better than pyrolysis. This is because pyrolysis had a higher heating requirement than hydrothermal carbonization as shown in Table D - 12. Hydrothermal carbonization also enhances the calorific value of the final product while pyrolysis generally reduces the calorific value (Lee & Shah, 2012 and Ankan et al., 2020). Drying performed poorly compared to pelletization because drying has a higher heating requirement. A detailed performance matrix of the different technologies is shown in Table D - 13.

While the study showed that there are suitable methods of energy recovery from faecal sludge mixed with solid waste, it is important to consider the impacts of energy recovery from these solid wastes. These impacts include; global warming due to release of greenhouse gases (e.g. NO_x and CO_2), air pollution in form of smoke, cancer due to the release of micro pollutants, soil pollution by residue ash as well as possible water pollution by leachate from the residue ash (Rabl et al., 2008). Therefore, there is a need for proper disposal and treatment of residue from the energy recovery processes. Fuel from the mixtures of faecal sludge and solid wastes (such as rubber and plastics) that can release toxic residues and should be used in industries which have the capacity to treat the residues before discharge to the environment. For other uses like domestic, preconditions such as sorting and screening of any hazardous waste, can be implemented to ensure control on energy recovery from such waste so that adverse impacts on human life and the environment can be prevented.

Table 4-3 Decision matrix for selecting the different incineration options.

Waste Category	**Total Scores**					
	Carbonized options		**Non – carbonized options**			
	HTC	**Pyrolysis**	**Drying**	**Pelletization (Conventional Pelletizer)**	**Pelletization (Bio burn pelletizer)**	**Pelletization (LaDePa Process)**
FS and Textile	5.0	4.5	5.0	5.5	6.0	6.0
FS and Polyethene	5.0	4.5	5.5	6.0	6.5	6.5
FS and Paper	5.0	4.5	5.0	5.5	6.0	6.0
FS and Sanitary towels	5.0	4.5	5.0	5.5	6.0	6.0
FS and Organics	5.0	4.5	5.0	5.5	6.0	6.0
FS and Plastic	5.0	4.5	5.5	6.0	6.5	6.5
FS and Rubber	5.0	4.5	5.5	6.0	6.5	6.5
FS and all solid waste	5.0	4.5	5.5	6.0	6.5	6.5
Faecal sludge	4.5	4.5	5.0	5.5	6.0	6.0
Average Score	**4.9**	**4.5**	**5.2**	**5.7**	**6.2**	**6.2**

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

This chapter presents the conclusions drawn from the findings of the study and the recommendations with regard to the effect of solid wastes in pit latrines on the method of energy recovery from faecal sludge.

5.1 Conclusions

- The composition of solid wastes in pit latrines varies due to difference in habits of users, nature of households and location of the source. Paper has the highest average composition of 29.1% with respect to combustible solid waste in the pit. The solid waste composition also showed that the average percentage of total combustible solid waste was 52.3% of the total solid waste which indicated that about half of the solid waste from the pit latrines was combustible.

- Dried faecal sludge had an average calorific value of 15.0 ± 2.7 MJ/kg while the mixture of faecal sludge and solid waste had 29.1 ± 15.9 MJ/kg. The average heat capacity of dried faecal sludge alone was 2720 ± 720 J/Kg^{o}C while that of the mixture of faecal sludge and solid wastes was 4333 ± 1410 J/Kg^{o}C. The heat capacity and calorific value of the faecal sludge, when mixed with solid waste, were higher than those of faecal sludge alone. Therefore, solid wastes in pit latrines had an effect on the energy characteristics of the faecal sludge.

- The study also has shown that there are correlations between the energy characteristics (calorific value and heat capacity) of the faecal sludge and the total mass of solid waste in the pit.

- The study also demonstrated that the incineration options with low operation temperature were most suitable for faecal sludge mixed with solid waste. The study therefore found that pelletization was the most suitable method for both faecal sludge alone and faecal sludge mixed with solid waste. However, the presence of solid wastes in the faecal sludge had an effect on the choice of carbonized options because faecal sludge alone was suitable for both hydrothermal carbonization and pyrolysis, while the mixture of faecal sludge and solid waste only favoured the use of hydrothermal carbonization due to a lower heating requirement.

5.2 Recommendations

5.2.1 Recommendations for further studies

The following should be considered as potential fields for further research studies:

- The effect of the chemical composition of solid wastes on the energy characteristics of faecal sludge.
- The potential co-processing of solid waste from landfills together with faecal sludge.
- The effect of toilet chemical additives on the energy characteristics of faecal sludge.

5.2.2 Recommendations for policy

From the study, we recommend that policies should be set up to promote the co-processing of faecal sludge together with solid wastes through incineration because the presence of solid wastes has a favourable effect on the TVS and calorific value of the faecal sludge.

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APPENDICES

APPENDIX A : LETTER TO KCCA, FIELD SAMPLING SHEET

C/o Makerere University
P.O Box 7062,
Kampala

19th January 2020

To the director,
Directorate of Public Health Services and Environment,
Kampala Capital City (KCCA).
City hall, Plot 1-3 Sir Apollo Kaggwa Road
P.O.Box 7010, Kampala-Uganda.

Dear Sir/Madam,

RE: REQUEST FOR INFORMATION PERTAINING TO OUR PROJECT

We are contacting you to request for assistance regards information that is important for our project entitled; **"Energy Recovery From Solid Wastes In Pit Latrine Faecal Sludge**."

The main focus of this study is to assess the effect of solid wastes dumped in pit latrines on the potential energy recovery from faecal sludge in slums. We are aiming at determining the solid waste components and their effect of the calorific of faecal sludge so as to facilitate the identification of the most appropriate energy recovery options from faecal sludge in the selected slums.

The information needed includes previous reports and studies on faecal sludge and energy recovery from it. The information and assistance availed to us will be of good use in our study and will entirely be used for academic purposes for the study that will be carried between January 2020 and May 2020 in the case study areas; Kamwokya II and Makerere III.

We will be grateful if our request is granted.

Yours Sincerely,

Mwanda Vicent	Nambozo Jones
0703516441	0702345590
vicentadnawm@gmail.com	athiajones@gmail.com

FIELD SAMPLING SHEET

Facility Name:
Sample Location:
Sample type: ☒ Composite
☐ Grab
No. of samples:

Sample collection equipment:
Name of person collecting the sample:
Sample date:
Time sample collected:
Time sample delivered to lab:

Sample handling procedures: Sample size:
Sample container:
Sample preservation:
Laboratory destination:

Test to be conducted (units)

TVS (%TS)	☐
Moisture content (%)	☐
Ash Content (% TS)	☐
COD (mg/l)	☐
Calorific Value (MJ/kg)	☐
Heat Capacity (J/kg^{O}C)	☐
Thermal Conductivity (W/m K)	☐
Heavy metals (ppm)	☐

APPENDIX B : QUESTIONNAIRE

Name : ……………………… Address :……………………….

Instructions

Please respond by circling an objective or filling the spaces below the questions.

1. Have you ever emptied the pit latrine?
   A. Yes
   B. No
2. If yes, how often do you empty the pit latrine?

……………………………………………………………………………

3. Do you dump solid waste in the pit latrine?
   A. Yes
   B. No
4. If yes, what are the types of solid waste do you dump in the pit latrine?
   A. Hygienic product
   B. Food waste
   C. Other
5. How many people are in your household?

……………………………………………………………………………

6. Do your share the pit latrine with other households?
   A. Yes
   B. No
7. If yes, how many households share the pit latrine?

……………………………………………………………………………

APPENDIX C : EXPERIMENTAL PROCEDURES

a) Moisture Content, Total Volatile Solids and Ash Content (2540 G-for solid and semi-solid samples)

Equipment :

Crucibles, desiccator, weighing scale and muffle furnace.

Procédure :

i) Crucibles were first ignited in an oven at 103-105 °C for 30minutes before use and were then put in a desiccator for 15minutes to cool down.
ii) The mass of the crucible was measured and recorded.
iii) Approximately 30 ml of the solid FS sample was added to the crucible. The mass of the crucible plus the sample was recorded.
iv) The crucible and its constituents were placed in an oven at 105 °C for 18-24 hours.
v) The Dry samples were then removed from the oven and placed in a desiccator to cool.
vi) The weight of the dry sample and the crucible was then taken and recorded.
vii) The Dry sample was then placed in a muffle furnace and ignited at 550 °C for 2 hours.
viii) The weight of the residue and the crucible after ignition was then measured and recorded.

The moisture content (MC) , ash content and total volatile solids (TVS) were then attained basing on the expressions below:

$$\textbf{MC}\ (\%) = \frac{(C - B) - (A - B)}{(C - B)}\ \text{x}\ 100\%$$

$$\textbf{TVS}\ (\%TS) = \frac{(A - D)}{(A - B)}\ \text{x}\ 100\%$$

$$\textbf{TVS}\ (g/l) = \frac{(A - D)\ \text{x}\ 1000}{30}$$

$$\textbf{Ash Content}\ (\%\ TS) = \frac{(D - B)}{(A - B)}\ \text{x}\ 100\%$$

where:

A = Weight of dried residue + crucible, g.
B = Weight of crucible, g.
C = Weight of wet sample +crucible, g.
D = Weight of residue + crucible after first ignition, g.
V = Volume of faecal sludge added to the crucible, ml.

b) Thermal conductivity

Equipment :

Oven, Steel mould, compression machine and QTM -500 thermal conductivity meter

Procedure :

i) The sample was first oven-dried.
ii) The dry sample was then compressed in a steel mould under a force of 150 kN using a compression machine.

iii) The moulded sample was then placed under the standard probe of QTM-500 Thermal Conductivity meter and the meter was then set to read to the thermal conductivity parameter.
iv) After the sample was heated and tested for 60 seconds, the thermal conductivity in W/mK was displayed on the screen of the meter and recorded.

c) Heat Capacity (Method of Mixtures)

Equipment :
Copper calorimeter, Stirrer, thermometers, digital weighing scale, ice cubes and heating mantle.

Procedure :

i) The beaker was filled to about half way with water and heated.
ii) The sample was weighed and then lower in the beaker of hot water using a thread.
iii) Time was then allowed for the sample to be heated in the hot water.
iv) The inner chamber of the calorimeter and the stirrer were weighed together.
v) The inner chamber of the calorimeter was then filled to about half way with water cooled with ice.
vi) The inner chamber of the calorimeter, stirrer and cool water were then weighed.
vii) The inner chamber of the calorimeter was then placed into the outer calorimeter jacket and a lid was placed on. The temperature of the cool water was then measured.
viii) The temperature of the hot sample was then recorded when the temperate became steady at the point when the water boils.
ix) The sample was then quickly transferred to from the hot water to the calorimeter.
x) The lid was then placed onto the calorimeter and the water was stirred very gently. The final equilibrium temperature of the mixture was then recorded.

The specific heat capacity (C) of the sample was obtained as :

$$\mathbf{C}\ (\text{J/kgC}^{o}) = \frac{(m_c \text{ x } c_c + m_w \text{ x } c_w)\text{x } \Delta T_2}{(m_S \text{ x } \Delta T_1)}$$

Where:

C = specific heat capacity of the sample in J/kgC^o
c_w = specific heat capacity of the water = 4180 J/kgC^o
c_c = specific heat capacity of calorimeter = 380 J/kgC^o
m_s = mass of the sample
m_w = mass of water in the calorimeter
m_c = mass of the calorimeter
T_1 = temperature of the cool water in C^o
T_2 = temperature of the hot sample in C^o
T_3 = final equilibrium temperature of the mixture in C^o
$\Delta T_1 = (T_1 – T_3)$ C^o
$\Delta T_2 = (T_3 - T_2)$ C^o

d) Heavy Metals (Atomic Absorption Spectroscopy)

Equipment :

Atomic absorption spectrometer, mortar and pestle, block digestor

Procedure :

i) The sample was first crushed using a mortar and pestle.
ii) One gram of the sample was then placed in block digestor with 5ml of nitric acid and hydrochloric acid.
iii) The digest was then diluted to 50ml in a conical flask.
iv) The sample was then tested using the atomic absorption spectrometer to determine its absorbance.
v) The measured absorbance was then used to create calibration curves which were used to determine the proportions of Zn, Ni, Pb, Cu and Cd in the sample.

e) COD (5220 C – Titrimetric Mehtod)

Equipment :

Spectrophotometer,digestion tubes

Procedure :

i) A liquid was obtained after first screening the sizable debris from the sample From the filtrate, 5mls were diluted to 100 ml giving a dilution factor of 20.
ii) 2.5 ml of sample was transferred into empty digestion tubes into which 1.5ml of digestion solution was added. The thermostat was then stabilized at 150 ^oC.
iii) 3.5 ml Ag_2SO_4 was carefully run down the inside of the tube.
iv) The tubes were tightly capped and whirled several times to completely mix the contents. The tubes were then placed in the pre-heated thermostat for 2 hours.
v) After 2 hours of cooling, the particles were mixed by gently shaking and left to settle. The readings were read off from the spectrophotometer.
vi) The readings were multiplied by the dilution factor of 20 and recorded.

f) Calorific value

Equipment :

Oxygen bomb calorimeter, press,

Procedure :

i) The bomb calorimeter was first standardized using benzoic acid tablets.
ii) The sample was then prepared by milling and grinding to get a fine sample.
iii) One gram of the sample was then turned into a tablet using a press.
iv) The sample was then placed in a capsule and then placed between the electrodes.
v) The fuse wire was then connected between the electrodes and a cotton cloth was attached to the fuse wire.
vi) The bomb vessel was then assembled and the sampled was then placed inside it.
vii) The vessel was then sealed and oxygen was pumped into it at a pressure of 30 bars.
viii) The bomb vessel was then immersed in two litres of distilled water in the bomb calorimeter.
ix) The cover of the bomb calorimeter was then placed on.
x) The standardised bomb calorimeter was switched on and the sample was burnt.
xi) The reading of the calorific value of the sample was then read from the display.

APPENDIX D : DETAILED TABLES SHOWING THE ANALYSIS OF RESULTS

Table D - 1 Masses of solid waste from the different pit latrines

Category	Mass (kg)								
	Pit 1	Pit 2	Pit 3	Pit 4	Pit 5	Pit 6	Pit 7	Average	SD
Organics	1.68	0.76	2.18	0.82	0.24	3.94	0.24	1.41	1.33
Polyethene	0.51	1.95	1.90	1.10	0.10	5.41	6.21	2.45	2.40
Textile	1.42	3.84	2.07	2.00	0.16	5.18	3.79	2.64	1.71
Plastic	0.67	0.21	0.28	0.15	0.28	1.49	0.43	0.50	0.47
Glass	0.21	0.07	0.04	0.00	0.35	3.36	0.00	0.58	1.23
Sanitary Towels	2.46	3.96	2.16	0.61	0.38	0.84	3.50	1.99	1.43
Rubber	0.04	0.00	0.05	0.00	0.00	0.43	0.09	0.09	0.15
Metals	0.10	0.00	0.05	0.00	0.00	1.00	0.15	0.19	0.36
Paper	6.38	2.78	8.48	0.64	3.10	0.00	0.00	3.05	3.29
Rubble	13.12	2.62	0.89	1.11	4.50	67.87	0.00	12.87	24.66
Other	19.28	0.00	0.00	4.08	2.19	1.54	13.00	5.73	7.47
Total	45.87	16.19	18.10	10.51	11.30	91.06	27.41		

Table D - 2 Percentage composition of combustible solid waste

Category	Percentage composition of combustible solid waste (%)								
	Pit 1	Pit 2	Pit 3	Pit 4	Pit 5	Pit 6	Pit 7	Average	SD
Organics	12.8	5.6	12.7	15.4	5.6	22.8	1.7	10.9	7.2
Polyethene	3.9	14.4	11.1	20.7	2.3	31.3	43.5	18.2	15.0
Textile	10.8	28.4	12.1	37.6	3.8	30.0	26.6	21.3	12.4
Plastic	5.1	1.6	1.6	2.8	6.6	8.6	3.0	4.2	2.7
Sanitary Towels	18.7	29.3	12.6	11.5	8.9	4.9	24.5	15.8	8.8
Rubber	0.3	0.0	0.3	0.0	0.0	2.5	0.6	0.5	0.9
Paper	48.5	20.6	49.5	12.0	72.8	0.0	0.0	29.1	28.2
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	

Table D - 3 Percentage of total combustible solid waste

Pits	Total mass of solid waste A (kg)	Total mass of combustible solid waste B (kg)	Percentage of total combustible solid waste C = (B x100)/A
Pit 1	45.87	13.16	28.7
Pit 2	16.19	13.5	83.4
Pit 3	18.1	17.12	94.6
Pit 4	10.51	5.32	50.6
Pit 5	11.3	4.26	37.7
Pit 6	91.6	17.29	18.9
Pit 7	27.41	14.26	52.0
Average	31.57	12.13	52.27
SD	29.15	5.28	27.82

Table D - 4 Characteristics of fresh faecal sludge

Characteristics of fresh sludge from Pit 1								
Sample	**B (g)**	**C (g)**	**A (g)**	**D (g)**	**MC (%)**	**TVS (% TS)**	**Ash Content (% TS)**	**TVS (g/l)**
1	40.70	68.38	44.43	41.57	86.52	76.66	23.34	95.34
2	40.10	67.90	43.84	40.99	86.52	76.08	23.92	95.02
3	39.81	68.02	43.62	40.72	86.51	76.06	23.94	96.49
Average					86.52	76.27	23.73	95.62
Characteristics of fresh sludge from Pit 2								
Sample	**B (g)**	**C (g)**	**A (g)**	**D (g)**	**MC (%)**	**TVS (% TS)**	**Ash Content (% TS)**	**TVS (g/l)**
1	55.2	87.22	58.99	56.31	88.16	70.71	29.29	89.33
2	64.35	97.16	67.25	66.66	91.16	20.34	79.66	19.67
Average					89.66	45.53	54.47	54.50
Characteristics of fresh sludge from Pit 3								
Sample	**B (g)**	**C (g)**	**A (g)**	**D (g)**	**MC (%)**	**TVS (% TS)**	**Ash Content (% TS)**	**TVS (g/l)**
1	59.44	88.22	65.29	62.24	79.67	52.14	47.86	101.67
2	51.36	87.19	55.25	52.55	89.14	69.41	30.59	90.00
Average					84.41	60.77	39.23	95.83
Characteristics of fresh sludge from Pit 4								
Sample	**B (g)**	**C (g)**	**A (g)**	**D (g)**	**MC (%)**	**TVS (% TS)**	**Ash Content (% TS)**	**TVS (g/l)**
1	59.6	78.45	62.37	60.62	85.31	63.18	36.82	58.33
2	51.1	73.55	54.52	52.92	84.77	46.78	53.22	53.33
Average					85.04	54.98	45.02	55.83

Characteristics of fresh sludge from Pit 5

Sample	B (g)	C (g)	A (g)	D (g)	MC (%)	TVS (% TS)	Ash Content (% TS)	TVS (g/l)
1	64.27	108.11	69.26	66.1	88.62	63.33	36.67	105.33
2	55.05	101.00	60.06	57.09	89.10	59.28	40.72	99.00
Average					88.86	61.30	38.70	102.17

Characteristics of fresh sludge from Pit 6

Sample	B (g)	C (g)	A (g)	D (g)	MC (%)	TVS (% TS)	Ash Content (% TS)	TVS (g/l)
1	39.28	67.97	40.99	39.39	94.05	93.67	6.33	53.31
2	38.20	63.78	39.99	38.45	93.02	86.14	13.86	51.27
3	45.04	71.52	46.95	45.43	92.80	79.47	20.53	50.49
Average					93.29	86.43	13.57	51.69

Characteristics of fresh sludge from Pit 7

Sample	B (g)	C (g)	A (g)	D (g)	MC (%)	TVS (% TS)	Ash Content (% TS)	TVS (g/l)
1	42.25	70.97	46.38	43.69	85.61	65.25	34.75	89.88
2	42.08	72.29	46.55	43.62	85.19	65.49	34.51	97.71
3	40.08	71.87	44.70	41.74	85.49	64.15	35.85	98.63
Average					85.43	64.96	35.04	95.41

Where:

A - Weight of dried residue + dish, g.
B - Weight of dish, g.
C - Weight of wet sample + dish, g.
D - Weight of residue + dish after ignition at 550 C^{O}, g

Table D - 5 Thermal conductivity measurements for dried faecal sludge from the different pits

Pits	Measurements (W/mK)			
	1	2	3	Average
1	0.5406	0.5946	0.5496	0.5616
2	0.1847	0.1895	0.1930	0.1891
3	0.1806	0.1919	0.2600	0.2108

Table D - 6 Heat capacity measurements for waste from different pits

Heat Capacity for waste from pit 1

Component	m_s (g)	m_c (g)	m_1 (g)	m_w (g)	T1	T2	T3	ΔT1	ΔT2	Heat Capacity, C (J/Kg^{O}C)
Organics	9.8	79.6	175.2	95.6	92.5	9.0	15.0	77.5	6.0	3396
Polyethene	8.4	79.6	170.0	90.4	93.0	6.0	13.5	79.5	7.5	4584
Textile	10.4	79.6	169.1	89.5	94.0	8.5	15.5	78.5	7.0	3467
Sanitary Towels	4.9	79.6	166.9	87.3	93.5	10.5	14.5	79.0	4.0	4083
Paper	19.9	79.6	169.1	89.5	93.0	11.5	20.5	72.5	9.0	2522
Faecal sludge	16.8	79.6	214.8	135.2	93.0	13.0	19.0	74.0	6.0	2873
Organics and FS	11.2	79.6	175.0	95.4	94.0	11.0	15.5	78.5	4.5	2196
Polyethene and FS	10.3	79.6	164.6	85.0	93.5	9.0	17.0	76.5	8.0	3914
Textile and FS	10.2	79.6	169.3	89.7	93.0	12.0	15.0	78.0	3.0	1528
Sanitary Towels and FS	7.1	79.6	166.5	86.9	93.5	8.0	14.0	79.5	6.0	4183
Paper and FS	6.6	79.6	174.3	94.7	94.0	15.5	18.0	76.0	2.5	2124
FS and Plastic	8.7	79.6	174.1	94.5	93.5	6.5	17.0	76.5	10.5	6709
FS and all solid waste	5.1	79.6	174.7	95.1	93.0	11.0	15.5	77.5	4.5	4870

Heat Capacity for waste from pit 2

Component	m_s (g)	m_c (g)	m_1 (g)	m_w (g)	T1	T2	T3	ΔT1	ΔT2	Heat Capacity, C (J/Kg^{O}C)
Organics	9.9	79.6	164.0	84.4	93.0	11.0	17.0	76.0	6.0	3055
Polyethene	14.6	79.6	170.0	90.4	94.0	10.5	20.5	73.5	10.0	3803
Textile	5.8	79.6	171.5	91.9	93.0	8.0	14.5	78.5	6.5	5916
Sanitary Towels	7.9	79.6	169.8	90.2	93.5	8.0	13.5	80.0	5.5	3544
Paper	15.6	79.6	166.0	86.4	92.5	8.5	20.0	72.5	11.5	3980
Faecal sludge	11.2	79.6	172.9	93.3	94.0	12.5	16.5	77.5	4.0	1937
Organics and FS	7.8	79.6	171.0	91.4	93.0	9.0	15.0	78.0	6.0	4066
Polyethene and FS	5.2	79.6	174.8	95.2	94.0	11.0	16.0	78.0	5.0	5278
Textile and FS	4.3	79.6	164.4	84.8	92.5	10.0	14.0	78.5	4.0	4559
Sanitary Towels and FS	5.1	79.6	187.2	107.6	93.0	7.0	12.0	81.0	5.0	5810
Paper and FS	8.0	79.6	168.1	88.5	92.5	10.0	15.5	77.0	5.5	3573
FS and all solid waste	4.4	79.6	173.4	93.8	93.5	7.5	12.0	81.5	4.5	5300

Heat Capacity for waste from pit 3

Component	m_s (g)	m_c (g)	m_1 (g)	m_w (g)	T1	T2	T3	ΔT1	ΔT2	Heat Capacity, C (J/Kg^{O}C)
Organics	8.3	79.6	180.7	101.1	94.0	4.5	12.0	82.0	7.5	4990

Polyethene	4.6	79.6	163.6	84.0	94.5	3.5	9.5	85.0	6.0	5852
Textile	5.9	79.6	156.8	77.2	94.0	18.5	21.0	73.0	2.5	2049
Sanitary Towels	8.8	79.6	170.2	90.6	93.5	13.5	19.5	74.0	6.0	3768
Paper	10.3	79.6	165.4	85.8	94.5	15.5	18.0	76.5	2.5	1234
Faecal sludge	5.5	79.6	182.6	103.0	94.0	16.0	19.0	75.0	3.0	3351
FS and all solid waste	4.4	79.6	170.7	91.1	93.0	12.0	16.0	77.0	4.0	4853

Where:

m_s - mass of solid

m_c - mass of copper calorimeter

m_1 - mass of copper calorimeter and cool water

m_w - mass of cool water

T1 - temperature of solid after heating

T2 - temperature of calorimeter and cool water

T3 - final equilibrium temperature of the mixture

$\Delta T1 = T1 - T3$

$\Delta T2 = T3 - T2$

Table D - 7 Heavy metal composition of fresh faecal sludge from the pits

Heavy metals for faecal sludge from pit 1 (ppm)					
Sample	**Pb**	**Cu**	**Zn**	**Cd**	**Ni**
1	1.23	3.96	23.60	3.12	0.00
2	1.00	4.33	22.30	2.96	0.09
Average	1.12	4.15	22.95	3.04	0.05
Heavy metals for faecal sludge from pit 2 (ppm)					
Sample	**Pb**	**Cu**	**Zn**	**Cd**	**Ni**
1	2.00	12.30	36.50	1.12	0.00
2	2.00	14.50	35.40	1.33	0.00
Average	2.00	13.40	35.95	1.23	0.00
Heavy metals for faecal sludge from pit 3 (ppm)					
Sample	**Pb**	**Cu**	**Zn**	**Cd**	**Ni**
1	0.96	8.16	19.20	0.98	0.00
2	0.88	8.25	19.80	0.56	0.00
Average	0.92	8.21	19.50	0.77	0.00
Heavy metals for faecal sludge from pit 4 (ppm)					
Sample	**Pb**	**Cu**	**Zn**	**Cd**	**Ni**
1	1.36	6.66	18.62	0.99	0.00
2	1.33	5.98	17.90	0.89	0.00
Average	1.35	6.32	18.26	0.94	0.00

Heavy metals for faecal sludge from pit 5 (ppm)					
Sample	**Pb**	**Cu**	**Zn**	**Cd**	**Ni**
1	0.08	4.11	12.30	0.23	0.00
2	0.12	4.96	11.91	1.66	0.00
Average	0.10	4.54	12.11	0.95	0.00

Table D - 8 Moisture Content, TVS and Ash Content of waste from the different pits after drying

Moisture Content, TVS and Ash Content of waste from Pit 1								
Category	**Sample Lab No.**	**B (g)**	**C (g)**	**A (g)**	**D (g)**	**MC (%)**	**TVS (% TS)**	**Ash Content (% TS)**
Organic	1	15.46	20.16	18.07	15.96	44.5	80.8	19.2
Organic	11	15.44	21.55	19.25	16.28	37.6	78.0	22.0
Sanitary towels	2	23.06	29.89	26.76	24.18	45.8	69.7	30.3
Plastic	3	20.79	27.55	22.55	21.77	74.0	44.3	55.7
Paper and FS	4	20.5	32.84	26.57	22.38	50.8	69.0	31.0
Polyethene and FS	5	22.94	37.3	28.48	25.18	61.4	59.6	40.4
Paper	6	20.43	27.94	23.32	21.62	61.5	58.8	41.2
FS	7	22.48	37.79	32.16	24.83	36.8	75.7	24.3
Textile	8	24.68	34.09	28.19	26.46	62.7	49.3	50.7
Textile and FS	9	22.86	33.65	29.03	24.69	42.8	70.3	29.7
Plastic and FS	10	50.82	69.66	59.88	53.96	51.9	65.3	34.7
Organic and FS	12	20.46	29.55	24.23	21.84	58.5	63.4	36.6
Polyethene	13	24.58	37.9	31.64	29.03	47.0	37.0	63.0
Sanitary towels and FS	14	20.5	30.29	24.21	22.28	62.1	52.0	48.0
FS with all solid waste	41	24.64	35.42	29.56	25.97	54.4	73.0	27.0
Moisture Content, TVS and Ash Content of waste from Pit 2								
Category	**Sample Lab No.**	**B (g)**	**C (g)**	**A (g)**	**D (g)**	**MC (%)**	**TVS (% TS)**	**Ash Content (% TS)**
Sanitary towels and FS	15	22.49	27.13	24.76	23.68	51.1	47.6	52.4
Paper and FS	16	23.03	27.7	25.18	23.95	54.0	57.2	42.8
Textile and FS	18	22.84	28.15	26.13	24.07	38.0	62.6	37.4
Plastic and FS	19	20.8	23.94	23	22.17	29.9	37.7	62.3
FS	20	51.57	65.25	61.28	56.32	29.0	51.1	48.9
Textile	21	15.43	19.31	17.06	16.1	58.0	58.9	41.1
Paper	22	24.67	36.53	28.17	26.16	70.5	57.4	42.6
Polyethene	23	20.31	25.65	23.04	21.37	48.9	61.2	38.8
Plastic	24	20.59	24.48	21.75	20.91	70.2	72.4	27.6
Organic	25	22.52	29.44	23.83	22.9	81.1	71.0	29.0
Sanitary towels	26	20.84	32	28.21	23	34.0	70.7	29.3
Sanitary towels	26	23.09	27.26	25.8	24	35.0	66.4	33.6
Polyethene and FS	27	23.19	27.55	26.29	24.21	28.9	67.1	32.9
Polyethene and FS	27	22.9	28.87	26.73	25	35.8	45.2	54.8
Organic and FS	28	23	30.53	26.4	24.48	54.8	56.5	43.5
Organic and FS	28	20.42	25.42	23.79	21.77	32.6	59.9	40.1
FS with all solid waste	17	22.92	29.07	26.12	24.17	48.0	60.9	39.1

Moisture Content, TVS and Ash Content of waste from Pit 3								
Category	**Sample Lab No.**	**B (g)**	**C (g)**	**A (g)**	**D (g)**	**MC (%)**	**TVS (% TS)**	**Ash Content (% TS)**
Organic and FS	29	23.04	28.71	26.17	24	44.8	69.3	30.7
Organic and FS	29	15.43	19.39	17.9	16.17	37.6	70.0	30.0
Plastic and FS	30	51.2	59.68	56.27	52.81	40.2	68.2	31.8
Textile and FS	31	15.43	19.46	18.26	16.47	29.8	63.3	36.7
Textile and FS	31	22.87	27	25.69	23.86	31.7	64.9	35.1
Paper and FS	32	20.79	26.07	24.29	22.31	33.7	56.6	43.4
FS	33	22.45	29	26.28	24.31	41.5	51.4	48.6
Plastic	34	20.54	25.84	23.68	21.46	40.8	70.7	29.3
Polyethene and FS	35	20.44	24.45	22.93	21.48	37.9	58.2	41.8
Rubber	36	24.64	32.66	28.63	25.56	50.2	76.9	23.1
Sanitary towels	37	22.91	31.03	27.07	23.72	48.8	80.5	19.5
Sanitary towels and FS	38	22.96	29.81	26.93	24.43	42.0	63.0	37.0
Rubber and FS	39	23.09	31.15	27.91	24.95	40.2	61.4	38.6
Paper	40	51.13	65.37	56.75	52.46	60.5	76.3	23.7
Organic	43	22.43	30.7	23.47	22.74	87.4	70.2	29.8
Textile	44	20.56	25.32	23.73	21.7	33.4	64.0	36.0
Polyethene	45	20.77	26.86	24.36	21.52	41.1	79.1	20.9
FS with all solid waste	42	51.1	63.43	55.9	53	61.1	60.4	39.6

Table D - 9 Calorific values of waste from the different pits after drying

Calorific value of waste from Pit 1					
Category	**Weight of pellet, A (g)**	**Weight of pellet, B (g)**	**Calorific Value (MJ/kg)**		
			A	**B**	**Average**
Organic	1.0	1.0	19.3	17.9	18.6
Sanitary towels	1.0	1.0	18.2	19.9	19.1
Plastic	1.0	1.0	42.4	42.5	42.4
Paper and FS	1.0	1.0	8.8	10.3	9.5
Polyethene and FS	1.0	1.0	37.5	50.1	43.8
Paper	1.0	1.0	10.5	14.1	12.3
FS	1.0	1.0	12.2	12.9	12.6
Textile	1.0	1.0	12.3	13.7	13.0
Textile and FS	1.0	1.0	13.8	16.6	15.2
Plastic and FS	1.0	1.0	30.1	36.6	33.3
Organic and FS	1.0	1.0	15.1	17.7	16.4
Polyethene	1.0	1.0	45.6	42.5	44.1
Sanitary towels and FS	1.0	1.0	14.8	14.2	14.5
FS with all Solid waste	1.0	1.0	39.5	35.6	37.6

Calorific value of waste from Pit 2

Category	Weight of pellet, A (g)	Weight of pellet, B (g)	Calorific Value (MJ/kg)		
			A	B	Average
Sanitary towels and FS	1.0	1.0	13.2	16.4	14.8
Paper and FS	1.0	1.0	6.5	7.2	6.8
Textile and FS	1.0	1.0	12.5	12.9	12.7
Plastic and FS	1.0	1.0	29.2	35.3	32.3
FS	1.0	1.0	15.1	13.8	14.5
Textile	1.0	1.0	11.6	14.2	12.9
Paper	1.0	1.0	15.4	16.4	15.9
Polyethene	1.0	1.0	42.5	39.8	41.2
Plastic	1.0	1.0	39.7	42.8	41.3
Organic	1.0	1.0	20.2	20.5	20.4
Sanitary towels	1.0	1.0	21.6	13.8	17.7
Polyethene and FS	1.0	1.0	32.2	36.2	34.2
Organic and FS	1.0	1.0	17.3	12.1	14.7
FS with all Solid waste	1.0	1.0	46.6	40.2	43.4

Calorific value of waste from Pit 3

Category	Weight of pellet, A (g)	Weight of pellet, B (g)	Calorific Value (MJ/kg)		
			A	B	Average
Organic and FS	1.0	1.0	16.2	16.4	16.3
Plastic and FS	1.0	1.0	34.3	32.2	33.3
Textile and FS	1.0	1.0	14.4	15.8	15.1
Paper and FS	1.0	1.0	9.9	15.6	12.8
FS	1.0	1.0	18.3	17.5	17.9
Plastic	1.0	1.0	36.4	40.9	38.7
Polyethene and FS	1.0	1.0	39.8	35.4	37.6
Rubber	1.0	1.0	68.3	60.3	64.3
Sanitary towels	1.0	1.0	20.5	25.5	23.0
Sanitary towels and FS	1.0	1.0	15.1	11.1	13.1
Rubber and FS	1.0	1.0	59.1	52.6	55.8
Paper	1.0	1.0	12.6	11.5	12.1
Organic	1.0	1.0	25.1	24.2	24.6
Textile	1.0	1.0	16.9	15.3	16.1
Polyethene	1.0	1.0	48.9	40.7	44.8
FS with all Solid waste	1.0	1.0	42.2	31.3	36.8

Table D - 10 COD measurements for fresh faecal sludge from the different pits

COD for faecal sludge from pit 1	
Sample	**COD (mg/l)**
1	12400
2	11900
Average	12150.00
COD for faecal sludge from pit 2	
Sample	**COD (mg/l)**
1	9960
2	11820
Average	10890.00
COD for faecal sludge from pit 3	
Sample	**COD (mg/l)**
1	12220
2	12020
Average	12120.00
COD for faecal sludge from pit 4	
Sample	**COD (mg/l)**
1	11540
2	12020
Average	11780.00
COD for faecal sludge from pit 5	
Sample	**COD (mg/l)**
1	10200
2	11000
Average	10600.00

Table D - 11 Thermal diffusivity of the dried faecal sludge

Pit	Density (Kg/m^3)	Heat capacity (J/kgK)	Thermal conductivity (W/mK)	Thermal diffusivity (m^2/s)
1	730.73	2873	0.5616	2.68×10^{-7}
2	695.13	1937	0.1891	1.40×10^{-7}
3	775.14	3351	0.2108	8.12×10^{-8}
			Average	1.63×10^{-7}
			SD	9.52×10^{-8}

Table D - 12 Heating requirements for HTC, Pyrolysis and La DePa technologies

Hydrothermal Carbonization

Waste Category	Mean Heat Capacity	Operating Temperature Range	Average operating temperature	Heating Energy	Score
	A (J/Kg °C)	(°C)	B (°C)	E = Ax B (J/kg)	
FS and Textile	3043	180 - 250	215	654	2
FS and Polyethene	4596	180 - 250	215	988	2
FS and Paper	2848	180 - 250	215	612	2
FS and Sanitary towels	4996	180 - 250	215	1,074	2
FS and Organics	3131	180 - 250	215	673	2
FS and Plastic	6709	180 - 250	215	1,442	2
FS and Rubber	N/A	180 - 250	215	N/A	N/A
FS and all solid waste	5008	180 - 250	215	1,077	2
Faecal sludge	2720	180 - 250	215	585	2

Pyrolysis

Waste Category	Mean Heat Capacity	Operating Temperature Range	Operating Temperature	Heating Energy	Score
	A (J/Kg °C)	(°C)	B (°C)	E = Ax B (J/kg)	
FS and Textile	3043	300 - 750	525	1598	1
FS and Polyethene	4596	300 - 750	525	2413	1
FS and Paper	2848	300 - 750	525	1495	1
FS and Sanitary towels	4996	300 - 750	525	2623	1
FS and Organics	3131	300 - 750	525	1644	1

FS and Plastic	6709	300 - 750	525	3522	1
FS and Rubber	N/A	300 - 750	525	N/A	N/A
FS and all solid waste	5008	300 - 750	525	2629	1
Faecal sludge	2720	300 - 750	525	1428	1
Pelletization (La DePa Process)					
Waste Category	**Mean Heat Capacity**	**Operating Temperature Range**	**Operating Temperature**	**Heating Energy**	**Score**
	A (J/Kg ºC)	**(ºC)**	**B (ºC)**	**E = Ax B (J/kg)**	
FS and Textile	3043	180 -220	200	609	3
FS and Polyethene	4596	180 -220	200	919	3
FS and Paper	2848	180 -220	200	570	3
FS and Sanitary towels	4996	180 -220	200	999	3
FS and Organics	3131	180 -220	200	626	3
FS and Plastic	6709	180 -220	200	1342	3
FS and Rubber	N/A	180 -220	200	N/A	N/A
FS and all solid waste	5008	180 -220	200	1002	3
Faecal sludge	2720	180 -220	200	544	3

Table D - 13 Performance matrix for the different energy recovery options

Hydrothermal Carbonization								
Waste Category	**Energy Characteristics**		**Preconditions**	**Input sludge requirements**	**Heating requirements**	**Capability to enhance the calorific value**	**Pathogen Removal**	**Total Score**
FS and Textile	MC	37.2 ± 6.1	**Score**	**Score**	**Score**	**Score**	**Score**	
	HV	3043 ± 2143	1.0	1.0	1.0	1.0	1.0	5.0
	CV	14.3 ± 1.4						
FS and Polyethene	MC	43.9 ± 15.4	1.0	1.0	1.0	1.0	1.0	5.0
	HV	4596 ± 964						
	CV	38.9 ± 4.8						
FS and Paper	MC	46.2 ± 10.9	1.0	1.0	1.0	1.0	1.0	5.0
	HV	2848 ± 1025						
	CV	9.7 ± 3						
FS and Sanitary towels	MC	51.7 ± 10	1.0	1.0	1.0	1.0	1.0	5.0
	HV	4996 ± 1151						
	CV	14.7 ± 1.7						
FS and Organics	MC	47.8 ± 9.4	1.0	1.0	1.0	1.0	1.0	5.0
	HV	3131 ± 1322						
	CV	15.8 ± 1.0						
FS and Plastic	MC	40.7 ± 11	1.0	1.0	1.0	1.0	1.0	5.0
	HV	6709						
	CV	33 ± 0.6						
FS and Rubber	MC	40.2	1.0	1.0	1.0	1.0	1.0	5.0
	HV	N/A						
	CV	52.6						
FS and all solid waste	MC	54.5 ± 6.6	1.0	1.0	1.0	1.0	1.0	5.0
	HV	5008 ± 253						
	CV	39.2 ± 3.6						
Faecal sludge	MC	35.8 ± 6.3	0.5	1.0	1.0	1.0	1.0	4.5
	HV	2720 ± 720						
	CV	15 ± 2.7						
Pyrolysis								
Waste Category	**Energy Characteristics**		**Preconditions**	**Input sludge requirements**	**Heating requirements**	**Capability to enhance the calorific value**	**Pathogen Removal**	**Total Score**
FS and Textile	MC	37.2 ± 6.1	**Score**	**Score**	**Score**	**Score**	**Score**	
	HV	3043 ± 2143	1.0	0.5	2.0	0.0	1.0	4.5
	CV	14.3 ± 1.4						

FS and Polyethene	MC	43.9 ± 15.4	1.0	0.5	2.0	0.0	1.0	4.5
	HV	4596 ± 964						
	CV	38.9 ± 4.8						
FS and Paper	MC	46.2 ± 10.9	1.0	0.5	2.0	0.0	1.0	4.5
	HV	2848 ± 1025						
	CV	9.7 ± 3						
FS and Sanitary towels	MC	51.7 ± 10	1.0	0.5	2.0	0.0	1.0	4.5
	HV	4996 ± 1151						
	CV	14.7 ± 1.7						
FS and Organics	MC	47.8 ± 9.4	1.0	0.5	2.0	0.0	1.0	4.5
	HV	3131 ± 1322						
	CV	15.8 ± 1.0						
FS and Plastic	MC	40.7 ± 11	1.0	0.5	2.0	0.0	1.0	4.5
	HV	6709						
	CV	33 ± 0.6						
FS and Rubber	MC	40.2	1.0	0.5	2.0	0.0	1.0	4.5
	HV	N/A						
	CV	52.6						
FS and all solid waste	MC	54.5 ± 6.6	1.0	0.5	2.0	0.0	1.0	4.5
	HV	5008 ± 253						
	CV	39.2 ± 3.6						
Faecal sludge	MC	35.8 ± 6.3	1.0	0.5	2.0	0.0	1.0	4.5
	HV	2720 ± 720						
	CV	15 ± 2.7						
Drying								
Waste Category	**Energy Characteristics**		**Preconditions**	**Input sludge requirements**	**Heating requirements**	**Capability to enhance the calorific value**	**Pathogen Removal**	**Total Score**
FS and Textile	MC	37.2 ± 6.1	**Score**	**Score**	**Score**	**Score**	**Score**	
	HV	3043 ± 2143	1.0	0.5	3.5	0.0	0.0	5.0
	CV	14.3 ± 1.4						
FS and Polyethene	MC	43.9 ± 15.4	1.0	0.5	3.5	0.5	0.0	5.5
	HV	4596 ± 964						
	CV	38.9 ± 4.8						
FS and Paper	MC	46.2 ± 10.9	1.0	0.5	3.5	0.0	0.0	5.0
	HV	2848 ± 1025						
	CV	9.7 ± 3						
	MC	51.7 ± 10	1.0	0.5	3.5	0.0	0.0	5.0
	HV	4996 ± 1151						

FS and Sanitary towels	CV	14.7 ± 1.7						
FS and Organics	MC	47.8 ± 9.4	1.0	0.5	3.5	0.0	0.0	5.0
	HV	3131 ± 1322						
	CV	15.8 ± 1.0						
FS and Plastic	MC	40.7 ± 11	1.0	0.5	3.5	0.5	0.0	5.5
	HV	6709						
	CV	33 ± 0.6						
FS and Rubber	MC	40.2	1.0	0.5	3.5	0.5	0.0	5.5
	HV	N/A						
	CV	52.6						
FS and all solid waste	MC	54.5 ± 6.6	1.0	0.5	3.5	0.5	0.0	5.5
	HV	5008 ± 253						
	CV	39.2 ± 3.6						
Faecal sludge	MC	35.8 ± 6.3	1.0	0.5	3.5	0.0	0.0	5.0
	HV	2720 ± 720						
	CV	15 ± 2.7						
Pelletization (Conventional Pelletizer)								
Waste Category	**Energy Characteristics**		**Preconditions**	**Input sludge requirements**	**Heating requirements**	**Capability to enhance the calorific value**	**Pathogen Removal**	**Total Score**
FS and Textile	MC	37.2 ± 6.1	**Score**	**Score**	**Score**	**Score**	**Score**	
	HV	3043 ± 2143	1.0	0.5	4.0	0.0	0.0	5.5
	CV	14.3 ± 1.4						
FS and Polyethene	MC	43.9 ± 15.4	1.0	0.5	4.0	0.5	0.0	6.0
	HV	4596 ± 964						
	CV	38.9 ± 4.8						
FS and Paper	MC	46.2 ± 10.9	1.0	0.5	4.0	0.0	0.0	5.5
	HV	2848 ± 1025						
	CV	9.7 ± 3						
FS and Sanitary towels	MC	51.7 ± 10	1.0	0.5	4.0	0.0	0.0	5.5
	HV	4996 ± 1151						
	CV	14.7 ± 1.7						
FS and Organics	MC	47.8 ± 9.4	1.0	0.5	4.0	0.0	0.0	5.5
	HV	3131 ± 1322						
	CV	15.8 ± 1.0						
FS and Plastic	MC	40.7 ± 11	1.0	0.5	4.0	0.5	0.0	6.0
	HV	6709						
	CV	33 ± 0.6						

FS and Rubber	MC	40.2	1.0	0.5	4.0	0.5	0.0	6.0
	HV	N/A						
	CV	52.6						
FS and all solid waste	MC	54.5 ± 6.6	1.0	0.5	4.0	0.5	0.0	6.0
	HV	5008 ± 253						
	CV	39.2 ± 3.6						
Faecal sludge	MC	35.8 ± 6.3	1.0	0.5	4.0	0.0	0.0	5.5
	HV	2720 ± 720						
	CV	15 ± 2.7						
Pelletization (Bioburn pelletizer)								
Waste Category	**Energy Characteristics**		**Preconditions**	**Input sludge requirements**	**Heating requirements**	**Capability to enhance the calorific value**	**Pathogen Removal**	**Total Score**
FS and Textile	MC	37.2 ± 6.1	**Score**	**Score**	**Score**	**Score**	**Score**	
	HV	3043 ± 2143	1.0	1.0	4.0	0.0	0.0	6.0
	CV	14.3 ± 1.4						
FS and Polyethene	MC	43.9 ± 15.4	1.0	1.0	4.0	0.5	0.0	6.5
	HV	4596 ± 964						
	CV	38.9 ± 4.8						
FS and Paper	MC	46.2 ± 10.9	1.0	1.0	4.0	0.0	0.0	6.0
	HV	2848 ± 1025						
	CV	9.7 ± 3						
FS and Sanitary towels	MC	51.7 ± 10	1.0	1.0	4.0	0.0	0.0	6.0
	HV	4996 ± 1151						
	CV	14.7 ± 1.7						
FS and Organics	MC	47.8 ± 9.4	1.0	1.0	4.0	0.0	0.0	6.0
	HV	3131 ± 1322						
	CV	15.8 ± 1.0						
FS and Plastic	MC	40.7 ± 11	1.0	1.0	4.0	0.5	0.0	6.5
	HV	6709						
	CV	33 ± 0.6						
FS and Rubber	MC	40.2	1.0	1.0	4.0	0.5	0.0	6.5
	HV	N/A						
	CV	52.6						
FS and all solid waste	MC	54.5 ± 6.6	1.0	1.0	4.0	0.5	0.0	6.5
	HV	5008 ± 253						
	CV	39.2 ± 3.6						
Faecal sludge	MC	35.8 ± 6.3	1.0	1.0	4.0	0.0	0.0	6.0
	HV	2720 ± 720						

	CV	15 ± 2.7						
Pelletization (LaDePa Process)								
Waste Category	**Energy Characteristics**		**Preconditions**	**Input sludge requirements**	**Heating requirements**	**Capability to enhance the calorific value**	**Pathogen Removal**	**Total Score**
FS and Textile	MC	37.2 ± 6.1	**Score**	**Score**	**Score**	**Score**	**Score**	
	HV	3043 ± 2143	1.0	1.0	3.0	0.0	1.0	6.0
	CV	14.3 ± 1.4						
FS and Polyethene	MC	43.9 ± 15.4	1.0	1.0	3.0	0.5	1.0	6.5
	HV	4596 ± 964						
	CV	38.9 ± 4.8						
FS and Paper	MC	46.2 ± 10.9	1.0	1.0	3.0	0.0	1.0	6.0
	HV	2848 ± 1025						
	CV	9.7 ± 3						
FS and Sanitary towels	MC	51.7 ± 10	1.0	1.0	3.0	0.0	1.0	6.0
	HV	4996 ± 1151						
	CV	14.7 ± 1.7						
FS and Organics	MC	47.8 ± 9.4	1.0	1.0	3.0	0.0	1.0	6.0
	HV	3131 ± 1322						
	CV	15.8 ± 1.0						
FS and Plastic	MC	40.7 ± 11	1.0	1.0	3.0	0.5	1.0	6.5
	HV	6709						
	CV	33 ± 0.6						
FS and Rubber	MC	40.2	1.0	1.0	3.0	0.5	1.0	6.5
	HV	N/A						
	CV	52.6						
FS and all solid waste	MC	54.5 ± 6.6	1.0	1.0	3.0	0.5	1.0	6.5
	HV	5008 ± 253						
	CV	39.2 ± 3.6						
Faecal sludge	MC	35.8 ± 6.3	1.0	1.0	3.0	0.0	1.0	6.0
	HV	2720 ± 720						
	CV	15 ± 2.7						

where

MC - Moisture Content in %

HV - Heat capacity in J/Kg^{o}C

CV - Calorific Value in MJ/kg