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ESTIMATING THE POTENTIAL FOR RESOURCE RECOVERY FROM PRODUCTIVE SANITATION IN URBAN AREAS

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SUMMARY IN ENGLISH

To-date, sanitation has mainly been approached from a public and environmental health perspective and this implies that excreta and other organic waste streams are seen not only as a hazard to quickly get rid of but also as a very costly menace to manage. However, looking at sanitation management from a resource recovery perspective provides an avenue for solutions with multiple co-benefits. Revenues from sanitation end-use products can act as an incentive for improving sanitation infrastructure while also covering part or all of the investment and operation costs for the same. Until now, estimating the potential for resource recovery from sanitation systems and technologies has largely been done on a case by case basis according to project or geography with no standardized universal tools or methodologies being used across the world. This study is aimed at developing a generic model for the rapid estimation of the quantities of various resources that can be recovered from sanitary waste streams in urban areas.

Key waste streams from sanitation systems in low and middle income countries were identified and their major characterization parameters identified. The mathematical relationships between key waste stream characterization parameters and the potential amounts of resource products derived from treatment were determined and then used to develop the model in MS Excel. The model was then tested with waste stream flow rates and characterization data (for faecal sludge, sewage sludge and organic municipal solid waste) from the city of Kampala with two scenarios; the current collection amounts (390 m^3 of faecal sludge, 66 tonnes of sewage sludge and 700 tonnes of organic solid waste) and the potential amounts with increased collection efficiency and coverage (900 m^3 of faecal sludge, 282 tonnes of sewage sludge and 2199 tonnes of organic solid waste). The results were shared with Kampala city authorities to obtain feedback.

The results showed that there is significant potential in utilizing the daily amounts of the three waste streams collected in Kampala. With increased collection coverage and efficiency, they could altogether yield; up to 361,200 Nm^3 of biogas per day which could meet the daily energy needs of 824,000 people that are currently met by firewood. Alternatively, the three sources could produce, 752 tonnes of solid combustion fuel per day which could meet the daily energy needs of 1,108,700 people that are currently met by firewood. As a third alternative, the three sources could produce 198 tonnes of Black Soldier Fly prepupae per day which could substitute for 134 tonnes of dry fish per day currently used as animal feed ingredient and up to 909 tonnes of compost fertilizer per day which is enough to substitute two tonnes of urea that is currently used by farmers. The model thus proved to be a simple way to provide decision support by making rapid estimations of the potential for resource recovery in urban areas, without the burden of having to do full scale feasibility studies. It is expected that this model could be a useful complement to the excreta flow diagrams (SFDs) developed within the Sustainable Sanitation Alliance (SuSanA) and hence give a holistic picture of the potential of a closed loop approach to excreta and waste management in cities.

Key words – Sanitation; Organic solid waste; Resource recovery; Waste reuse; Modelling; Developing countries.

SUMMARY IN SWEDISH (SAMMANFATTNING)

Sanitet ses oftast ur ett offentligt eller miljömässigt perspektiv. Detta leder till att exkrement och andra strömmar av organiska avfall ses som faror, vilka man snabbt vill bli av med och som dessutom är dyra att hantera. Om sanitet istället ses från ett resursåtervinnings perspektiv kan ett antal fördelaktiga lösningar iakttas. Inkomster från slutprodukter av sanitetsprojekt kan agera som incitament för att förbättra sanitetsinfrastruktur samt täcka flertalet eller alla investerings och driftskostnader. Fram till nyligen har uppskattningar av potential för resursåtervinning från sanitetssystem vanligen genomförts på olika sätt för olika projekt och geografiska platser. Inga standardiserade eller universella verktyg eller metoder har använts världen över. Syftet med denna studie är att utveckla en generell modell för snabb uppskattning av resursmängder som kan återvinnas från avfallsströmmar i urbana områden.

Nyckelströmmar av avfall från sanitetssystem i länder med låga eller medelinkomster identifierades och de viktigaste karaktäriseringsparametrarna identifierades. The matematiska förhållandena mellan parametrar som definierar nyckelströmmar av avfall och de potentiella mängder produkter som framställs från dessa strömmar, utvärderades. Resultatet användes för att bygga en modell i MS Excel. Modellen testades med flödesmängder av avfallsströmmar och karaktäriseringsdata (för fekalt slam, avloppsslam och organiskt kommunalt fast avfall) från staden Kampala med två olika scenarier; de nuvarande insamlingsmängderna (390 m3 fekalt slam, 66 ton avloppsslam och 700 ton organiskt fast avfall) och de potentiella insamlingsmängderna med ökad insamlingseffektivitet (900 m3 fekalt slam, 282 ton avloppsslam and 2199 ton organiskt fast slam). Resultatet delades med auktoriteter i Kampala stad för utvärdering.

Resultatet visade att det finns signifikant potential för utnyttjande av de dagliga mängderna av de tre olika avfallsströmmar som samlas in i Kampala. Med ökad effektivitet och områdestäckning av insamling kan upp emot 361,200 Nm3 biogas per dag produceras, vilket kan möta det dagliga energibehovet av 824,000 människor, som i dagsläget hanteras med hjälp av ved. Alternativt så kan de tre källorna producera 752 ton fast bränsle per dag, vilket kan möta energibehovet av 1,108,700 människor, som i dagsläget hanteras med hjälp av ved. Som ett tredje alternativ kan de tre källorna producera 198 ton puppor av svarta soldatflugor per dag, som kan agera som ett alternativ till de 134 ton torkad fisk per dag som i dagsläget används som föda till boskap. Dessutom kan pupporna användas som alternativ till 909 ton kompostgödningsmedel vilket är tillräckligt för att ersätta två ton urea som i dagsläget används av bönder i området. Modellen visade sig vara en simpel metod för att snabbt uppskatta potentialen för resursåtervinning i urbana områden och dessutom agera som beslutstöd, utan bördan att genomföra en ful förstudie. Modellen förväntas vara användbar som ett komplement till de flödesdiagram för exkrement (SFD:er) som utvecklats inom sanitetsorganisationen Sustainable Sanitation Alliance (SuSanA) och kan därför ge en holistisk bild av potentialen för angreppssättet som ett låst kretslopp av exkrement och avfall i städer, innebär.

Nyckelord – Sanering; Organiskt fast avfall; Resurs återhämtning; Återanvändning av avfall; Modellering; U-länder.

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ABBREVIATIONS AND SYMBOLS

AD	Anaerobic Digestion
BOD	Biochemical Oxygen Demand
BSF	Black Soldier Fly
C	Carbon
COD	Chemical Oxygen Demand
CV	Calorific Value
FS	Faecal Sludge
HIC	High Income countries
KCCA	Kampala Capital City Authority
kg	kilogram(s)
LMIC	Low and Middle Income Countries
NGOs	Non-Governmental Organizations
NPK	Nitrogen, Phosphorus and Potassium
NWSC	National Water and Sewerage Company
SFDs	Shit Flow Diagrams (Excreta Flow Diagrams)
SOM	Soil Organic Matter
SSA	Sub Saharan Africa
TK	Total Potassium
TN	Total Nitrogen
TP	Total Phosphorus
UNICEF	United Nations Children's Fund
US	United States of America
WHO	World Health Organization
WWTP	Wastewater treatment Plant

1. INTRODUCTION

1.1. Background

Globally, 2.4 billion people still lack access to basic sanitation especially in the global south (WHO and UNICEF, 2014) and this means that their excreta ends up in the public domain through open defecation and other unsafe excreta disposal practices. The consequences of this are public health hazards resulting in high morbidity and mortality especially among children less than 5 years of age, high frequencies of diarrhea and mammoth numbers infected with Helminth parasites among other diseases (Stenström et al., 2011; Rosemarin et al., 2008). While the lack of access to improved sanitation affects both urban and rural areas, the negative effects from poor sanitation facilities are exacerbated by increasing population trends in urban areas, again especially in the global south where most of the future population growth is expected to occur (Parfitt et al., 2010; Ezeh et al., 2012; Wolfram et al., 2012).

While the improved sanitation coverage in urban areas across the world increased from 76% to 80% between 1990 and 2012, the actual number of people without sanitation in urban areas actually increased by 215 million to 756 million over the same period (WHO and UNICEF, 2014). This is largely attributed to urban population growth trends. For this reason, city authorities along with governments, Non-Governmental Organizations (NGOs) and donor agencies are making greater efforts to invest in increasing access to improved sanitation facilities (Trémolet et al., 2013). Sustainable Development Goal 6, target 2 specifically aims at addressing this challenge: "*By 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations*" (UN Water, 2015). Improved sanitation refers to facilities that hygienically separate human excreta from human contact and includes several kinds of latrines under this definition (WHO and UNICEF, 2012).

While having access to toilet facilities is indeed important, there is another facet of the sanitation crisis which does not receive as much attention and this is the damage to lakes, coastal areas and other related ecosystems from untreated sanitation effluents. Wastewater effluent and other sanitation products like faecal sludge and sewage sludge contain nutrients like nitrogen (N) and phosphorus (P) which when disposed of into surface waters cause eutrophication and oxygen depletion which severely affect marine life. Eutrophication also affects surface water bodies in urban areas where the population has access to universal sanitation coverage.

According to Henze and Comeau (2008), raw wastewater can have as much as 100 mg/L of total nitrogen (TN) and 25 mg/L of total phosphorus (TP). While regulations such as those of the European Union may require treatment processes to achieve concentration levels of 10 mg/L for total nitrogen and 1 mg/L for total phosphorus in the effluent (European Council, 1991), even modest amounts of these nutrients can still trigger high extents of eutrophication. The landfilling of faecal sludge and sewage sludge can also greatly damage land and groundwater over time through the leaching of nutrients (especially nitrates which are more mobile than phosphates) and other contaminants (Fytili and Zabaniotou, 2008; Lüthi et al., 2009).

At the same time, cities are challenged with the question of how to feed ever-growing populations and how to provide energy to power city infrastructure and households in light of the pending resource scarcity with regard to water, fertilizers and fossil fuels (Wiltshire et al., 2013; Schewe et al., 2014). Global reserves of phosphate minerals which provide an irreplaceable plant nutrient in chemical fertilizers are estimated to be depleted within the next 100 years (Ashley et al., 2011; Cordell et al., 2011) just like fossil fuel resources (Shafiee and Topal, 2009). Studies have also shown that over the past 50 years, population growth has surpassed food production (Ray et al., 2013) and energy demand has grown exponentially along with the associated negative effects of global warming that accrue mainly from the consumption of fossil fuels (Madlener and Sunak, 2011). There is a growing research community exploring the option of turning the need for sanitation into an opportunity to recover resources which also address the need for fertilizers, fuel and water, as explained in more detail below.

To date, sanitation has mainly been approached from a public health perspective where human sanitary waste is viewed as a hazard to quickly contain and dispose of (Lüthi et al., 2011; Spångberg et al., 2014). Consequently, current methods of waste treatment and disposal primarily shift the problem from one sphere of society to another. However, approaching waste management from a resource recovery perspective provides an avenue for solutions that cover multiple challenges simultaneously.

The valorization of sewage and faecal sludge from sanitation systems for biogas provides an alternative source of renewable energy and can increase and improve energy supply in a city. Recycling nutrients from both organic municipal solid waste (MSW) and excreta also provides an avenue for boosting agricultural productivity hence reducing the reliance on mineral fertilizers. These and many other options for recovering resources from organic waste would not only effectively deal with the public health hazards from the haphazard disposal of human waste but would contribute to providing renewable resources for growing cities and also reduce harmful impacts to ecosystems like eutrophication.

Reuse of excreta for beneficial purposes is not a new phenomenon in many parts of the world. Historical evidence from societies in Asia (especially Japan, Korea and China) as well as in Central and South America indicates that the reuse of excreta as fertilizer and soil conditioner was widely practiced until the advent of chemical fertilizers in the 19th century (Brown, 2003). Excreta was also used in aquaculture to grow fish for human consumption in many parts of South-East Asia while in the urban centers of Yemen, dried faeces were obtained from source-separation sanitation systems in storied buildings and used as fuel for cooking food (Lüthi et al., 2011). These practices were supported by elaborate sanitation systems geared towards reuse and well organized logistical and graded pricing systems for managing the sector (Lüthi et al., 2011).

As city populations grew, the advent of piped water supply and flush toilets in the 19th century, the shift of agriculture further away from cities and the introduction of cheap chemical fertilizers effectively led to the demise of excreta reuse in most cities, though the practice remained active but on small scale in some areas. What has happened, however is the increased clandestine use of untreated wastewater for irrigation and to fertilize urban agriculture, a growing practice in some 50 countries affecting the health of at least 700 million people (Wichelns et al., 2015).

Presently, efforts have been made to tap into the resources that could be recovered from sludge and wastewater along with organic solid waste in some cities. A number of cities, especially in Europe, have developed sophisticated collection and treatment systems and have identified niche products for reuse that are of high economic value like biogas for use in vehicles. In low and middle income countries however, wide-scale adoption of sanitation resource recovery has not yet been realized and in practice, waste is often disposed of into the open environment where it becomes a hazard for human health and ecosystems (Peal et al., 2014a). One of the underlying causes for this is that the full potential for economically justified resource recovery from waste is not well understood (Peal et al., 2014b), hence the need for a method which would allow cities to estimate the resource recovery potential. A tool that can estimate just how much energy, nutrients and/or water can be recovered from the total amount of waste produced in a city could catalyze policy changes and action at all levels of city stakeholders.

This study therefore aimed at developing a tool that can be used to estimate the potential for resource recovery in a city within a framework of closed loop integrated waste management, with a focus on sanitary waste systems.

1.2. Problem statement

Most cities in the global South are faced with the challenge of providing adequate sanitation coverage to their inhabitants in the face of increasing population growth. However, the solutions employed are often not comprehensive and do not cover the full sanitation value chain as they are mainly unsustainable end-of-pipe solutions. Providing infrastructure for the collection, transportation and treatment of excreta and solid waste is costly and the disposal of treatment end-products is even more costly to human health and ecosystems in the long term. Resource recovery can be a strategy not only for covering a significant portion of sanitation and waste management investment and operation costs but also for tackling the problem of resource scarcity. However, cities often do not invest in resource recovery because they have little knowledge of the potential resources contained in sanitary waste, and the market for organic waste is not very developed. Hence there is a need for a simple tool which will allow waste managers to evaluate the potential for resource recovery and the associated economic benefits.

1.3. Aim and objectives of the study

1.3.1. *Main aim*

The main aim of this study was to enumerate the potential resource recovery and associated economic benefits possible from human sanitary and organic waste in low and middle income countries. This was to be accomplished by developing a model that can be used by waste managers and planners in cities to assess the potential types and amounts of resources they can recover from organic waste. The model was intended to be generic and simple to use so that it can easily be adopted by a wide range of cities in low and middle-income countries. The term city in this case refers to any urban area with a large and permanent population with the typical complex systems for urban sanitation, utilities, housing and transportation, among others.

1.3.2. *Specific objectives*

1. To identify the most important resources available from sanitary waste, their economic value as well as typical technologies used for treatment and/or resource recovery.

2. To develop a generic mathematical model that outputs the resource recovery potential based on waste stream flow data.
3. To calibrate and apply the model to the city of Kampala (Uganda) in order to test how it would work in practice.

The specific research questions addressed were as follows:

- What are the main sanitation systems and technologies are used in low and middle income countries?
- What are the major waste streams from these sanitation systems?
- What are the major resource recovery options that are being explored currently and which ones hold promise for the future?
- What are the key treatment technologies used for each of these resource recovery options?
- What methods are currently used to determine what resource amounts are recoverable?
- What are the most important parameters that determine the amounts of end-products that can be obtained from each waste steam?
- What is the mathematical relationship between these key parameters and the amounts of end-products that can be obtained from each waste stream?

1.4. Relevance of project

With the recently agreed Sustainable Development Goals, there is increasing concern for the conservation of natural resources which cities largely depend on in various forms. By identifying the resources that can be recovered from sanitary waste in sewage treatment plants and estimating their recovery potential, the model developed in this project will enable cities to reduce the pressure on natural resources. It will also contribute to moving cities closer to a circular economy, at least as far as organic waste streams are concerned.

1.5. Study Scope

This study is limited to the sanitary waste streams typically handled by urban wastewater and sludge treatment systems as well as organic solid waste systems, both centralised and decentralized, small and large scale. The model is also developed specifically for application to low and middle income countries, though certain modifications can be made in the future to make it applicable universally.

2. LITERATURE REVIEW

2.1. Biogeochemical cycles of nutrients and carbon

Some of the most important chemical elements for plant and animal life are nitrogen, phosphorus, potassium, sulphur and carbon. The reason why nitrogen, phosphorus and potassium are added to agricultural soils as fertilizers is because they are often a limiting factor for plant growth. Nitrogen is an essential building block of amino and nucleic acids, proteins, hormones, coenzymes and chlorophylls. In the form of nitrogen gas (N_2), it forms the largest part of the earth's atmosphere (Emsley, 2011). Phosphorus is also an essential component of nucleic acids as well as adenosine triphosphate, several coenzymes and phospholipids which are found in all biological membranes (Greenwood and Earnshaw, 2012). Potassium makes processes like photosynthesis, nitrogen fixation, osmotic regulation and protein synthesis possible in plants (Soetan et al., 2010). Carbon occurs in all known organic life in various forms. It is the second most abundant element in the human body after oxygen (Emsley, 2011).

As shown in Figures 1 to 4, these elements exist in various forms and keep changing as they go through their biogeochemical cycles through the atmosphere, the terrestrial biosphere (land), the seas/oceans, sediments and the earth's interior (mantle and crust). These biogeochemical cycles are heavily influenced by human activities as they interact with the terrestrial biosphere. For example, through burning fossil fuels and biomass and manufacturing concrete, humans have over the past two centuries significantly increased the amount of carbon in the atmosphere in the form of carbon dioxide. Carbon dioxide is one of the most important greenhouse gases and is largely responsible for global warming (Lashof and Ahuja, 1990). The combustion of fossil fuels and biomass along with increased animal production, cultivation of legumes and production of chemical fertilizers have also intensified the flows of nitrogen and resulted in increased ammonia emissions and leakage of nitrates into the environment (Hellstrand, 2015).

Several studies have shown that the biggest flows of nitrogen and phosphorus are through food; from agricultural production through food retail and household consumption all the way to wastewater treatment plants through sewage (Wu et al., 2016; Kalmykova et al., 2012; Hellstrand, 2015; Cordell et al., 2009). The average human being excretes about 4.5 kg of nitrogen, 0.6 kg of phosphorus and 1.2 kg of potassium every year and this is approximately the same amount needed to grow the amount of food they need annually (Drangert, 1998). As can be seen from Figure 5, the fertilizer consumption in Africa can almost be covered by reusing human excreta on farmland, something also confirmed by Rosemarin et al. (2008) and Cordell et al. (2009).

Considering the fact that existing phosphate reserves are limited yet phosphorus is a limiting nutrient for plant growth (Ashley et al., 2011), the widespread reuse of human excreta and other organic wastes on farmland would greatly reduce the reliance on chemical fertilizers. In Africa for example, an average of 30kg of nutrients per hectare is lost from about 85% of arable land annually due to surface run-off, according to Lüthi et al. (2009). This indicates a great need for nutrient recycling to mitigate the loss of soil fertility. However, most of the nutrients from excreta currently end up being deposited within sludge at landfills and/or within effluent to surface waters where they result in eutrophication. It has been estimated that more than 90% of sewage in low and middle income countries is discharged directly into rivers, lakes, and coastal waters without treatment of any kind (Lüthi et al., 2009). Consequently, about 54% of lakes in Asia and 28% of those in Africa are impaired by eutrophication, mainly as a result from the release of wastewater effluent and runoff from agricultural areas (Nyenje et al., 2010). This is also a challenge to high income countries considering that by 2007, about 222 out of the 571 big cities of Europe (with a population greater than 150,000) did not comply with the wastewater treatment requirements of the Urban Waste Water Treatment (UWWT) Directive and 17 of these cities actually had no treatment at all (Lüthi et al., 2009).

2.2. Cities and resource flows

By 2020, it is estimated that 67% of the developing world population will be concentrated in urban areas (Montgomery, 2008). Cities are associated with high levels of consumption of water, food and energy and they consequently exert great pressures on natural resources

(Buhaug and Urdal, 2013; Bao and Fang, 2012; Salvati, 2013). Of all the water on earth, only 2.5% is fresh water and the biggest part of this is ice and permafrost which implies that only a small portion is accessible for human use (Postel et al., 1996; Oki and Kanae, 2006). According to Davis (2014), the average person in a developing country uses between 4 and 400 litres of water per day compared to 130-578 litres in High Income Countries (HIC) and many cities face water scarcity (Schewe et al., 2014). Still, the biggest portion of available water resources in low and middle income countries (LMIC), about 82%, is dedicated towards agricultural production (irrigation) in order to sustain city livelihoods (WBCSD, 2005).

Feeding the populations of growing cities will require an increase in agricultural production and an accompanying increase in the demand for fertilizer to provide plant nutrients. The linear model of the existing systems implies that these nutrients are transferred from the rural areas where the majority of food is grown to urban areas and ultimately dumped in surface waters as effluent or septage and/or at landfills as sludge, leading to further pollution. Only a small portion is returned to agricultural land as fertiliser, hence necessitating the application of increased chemical fertilisers (Lüthi et al., 2011).

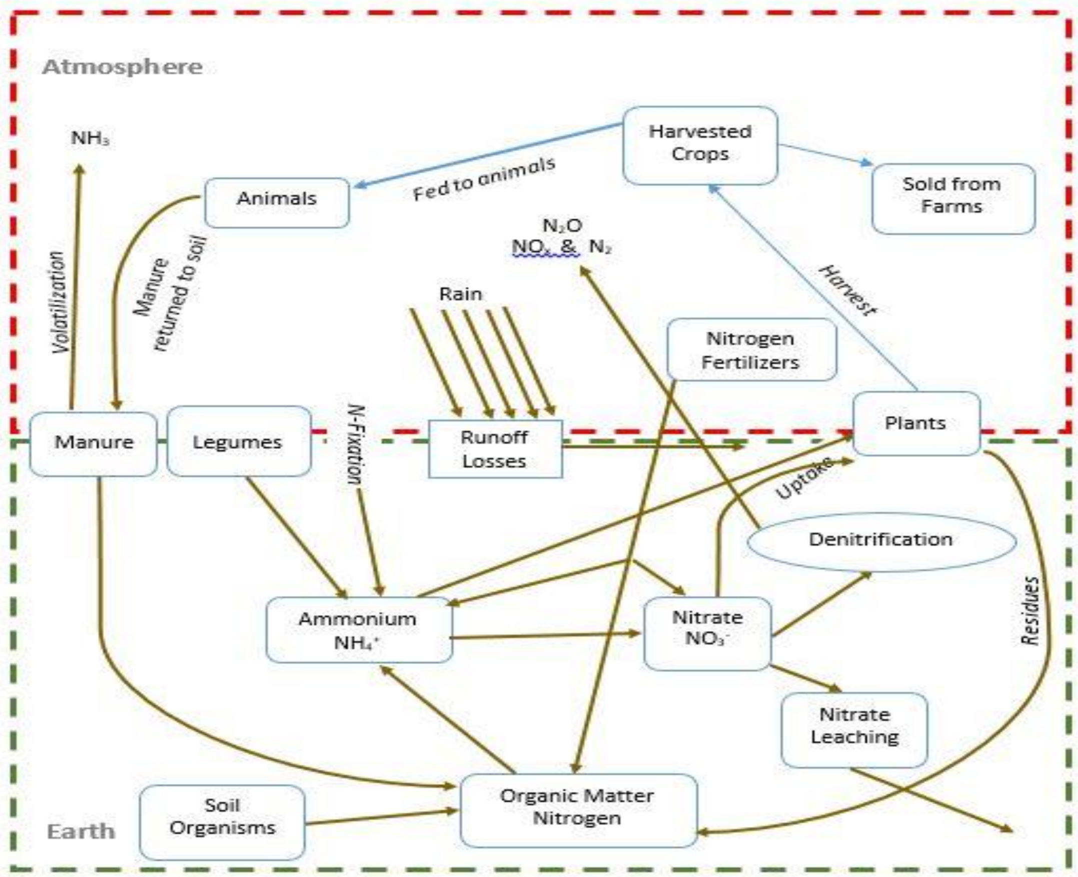

Figure 1: Nitrogen cycle
Source: University of Minnesota (1999)

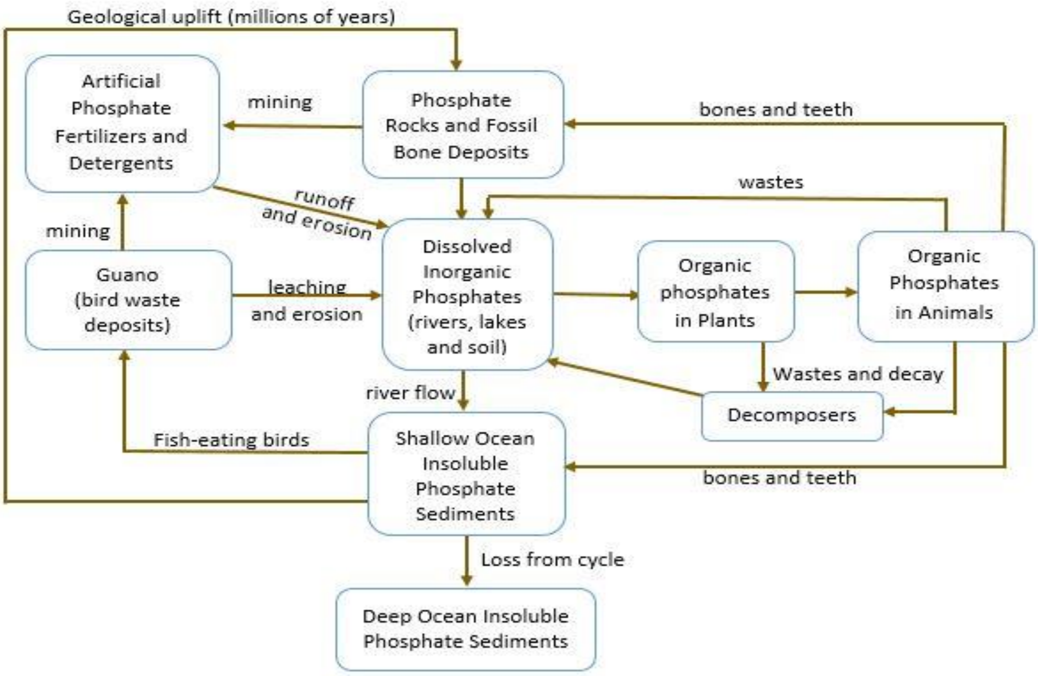

Figure 2: Phosphorus cycle
Source: McDaniel College (n.d)

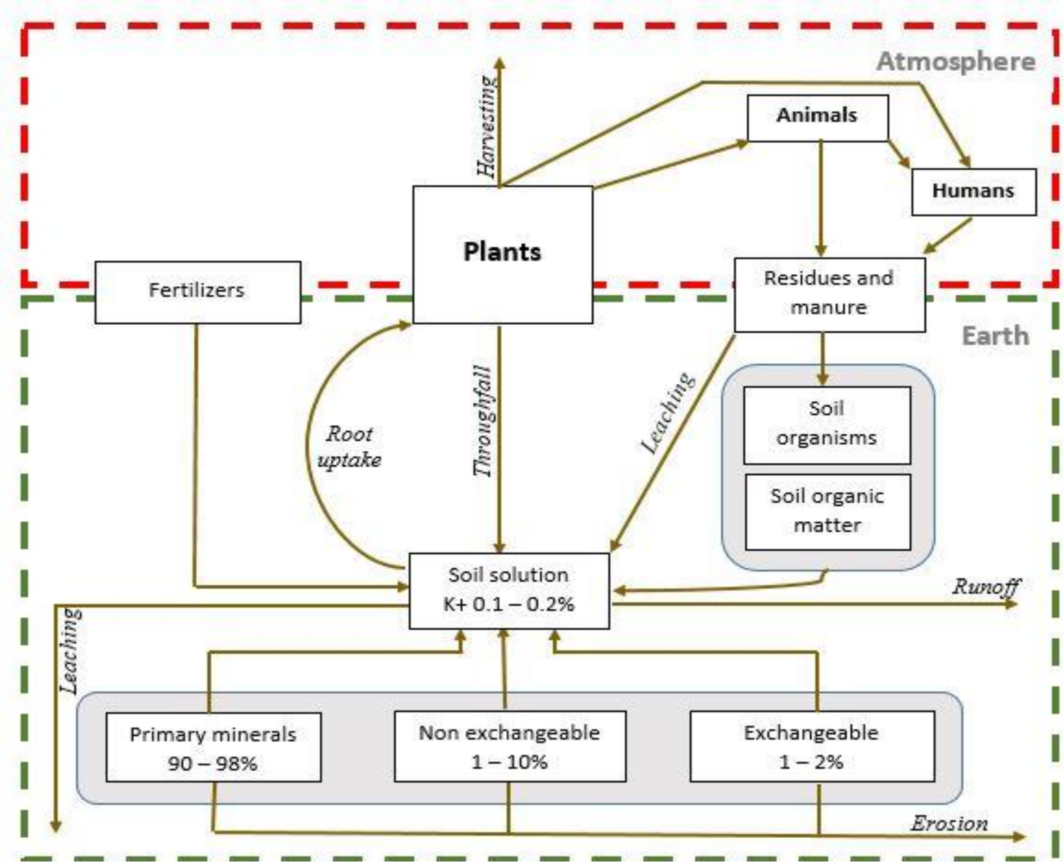

Figure 3: Potassium cycle.
The percentages indicate the amount of potassium in soils in different forms, each with varying availability to plants. Source: University of British Columbia (2014)

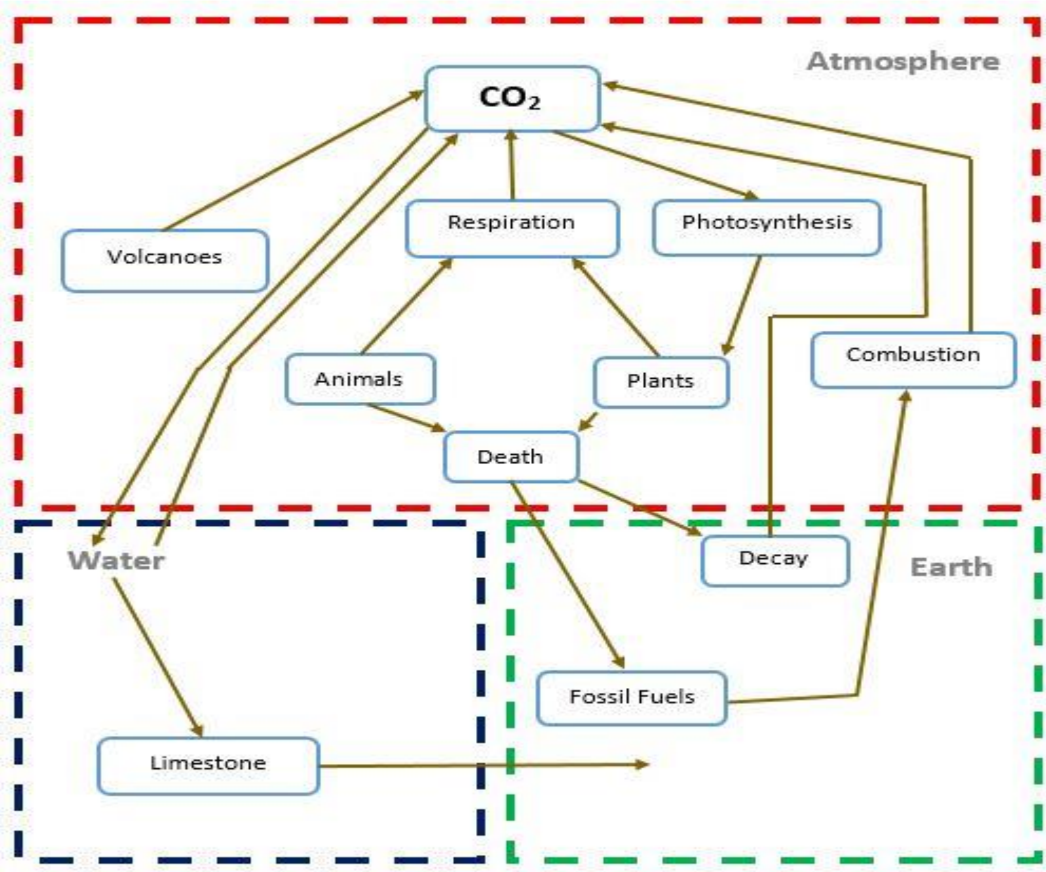

Figure 4: The carbon cycle
Source: Marrieta College (2006)

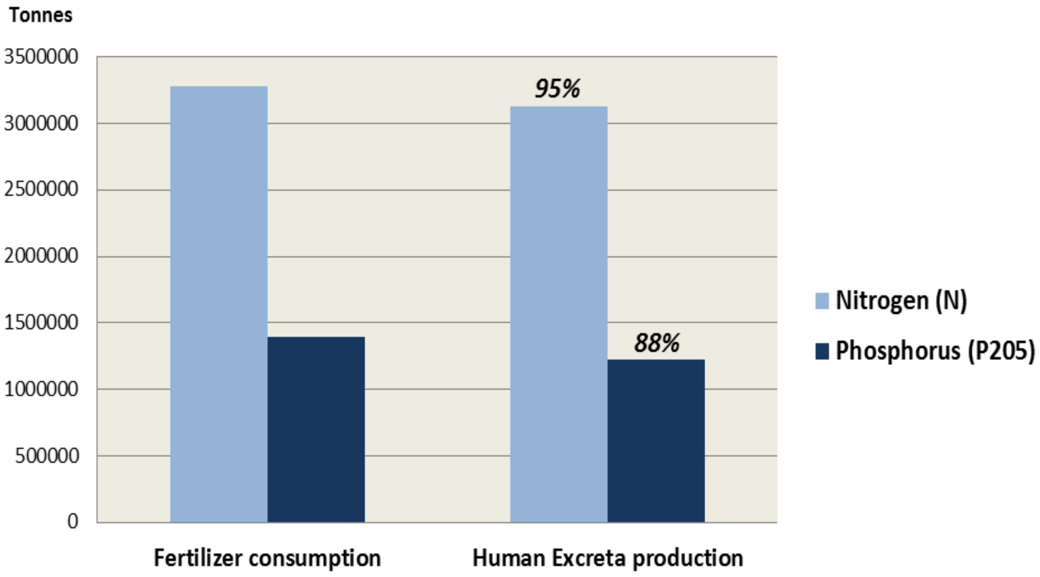

Figure 5: Fertilizer consumption vs nutrients available in human excreta in Africa in 2012.
Source: Fertilizer consumption figures taken from FAO-STAT (2012). N and P in human excreta derived from protein supply (FaoSTAT, 2012) using the method proposed by Jönsson and Vinnerås (2004). Percentages are the theoretical chemical fertilizer replacement capacity found in human excreta assuming no losses.

Cities currently account for two-thirds of the world's total energy consumption (IEA, 2010) especially for transportation and they are largely dependent on fossil fuels which still dominate the energy market (Droege, 2004). This implies that cities are responsible for 70% of global CO_2 emissions (Madlener and Sunak, 2011). In Sub-Saharan Africa, the biggest portion of energy at the household level is consumed for cooking and because of financial constraints, families mostly rely on firewood and charcoal which has led to unprecedented depletion of forest cover (Avery et al., 2011), hence clearing key carbon sinks.

A lot of human waste is generated in cities, considering the large concentration of inhabitants. The average person generates 128 g/day of faeces and 1.42 l/day of urine (Rose et al., 2015). This excreta could be embedded in up to 200 litres or even more, of wastewater every day. The average per capita generation of solid waste ranges from 0.5 to 1.7kg (Chandler et al., 1997) and of this, up to 80% may be organic (Troschinetz and Mihelcic, 2009) especially in low and middle income countries. For a city of one million people, these waste streams could amount up to 200,000 m^3 of wastewater (including plain excreta, blackwater and greywater) and 1,700 tonnes of solid waste. These waste streams have potential value due to the nutrients they contain as can be seen in Table 1 for the case of urine and faeces.

Resource recovery could be a cure to both ends of the sanitation crisis and provide multiple benefits through the productive use of the nutrient, organic matter, water and energy content of human excreta and wastewater which is what characterizes productive sanitation systems (Gensch et al., 2012). The benefits could include minimizing the consumption and pollution of water resources, supporting the conservation of soil fertility and boosting agricultural productivity and increasing access to renewable energy in communities. Productive sanitation systems would not only be an incentive for increasing access to improved sanitation facilities but would also provide a beneficial way of dealing with the nutrient-rich effluent and other products from treatment processes.

2.3. Sanitation systems in cities: a brief overview

According to Maurer et al. (2012) a sanitation system is defined as a set of technologies, which in combination, treat human excreta from the point of generation to the final point of reuse or disposal. Tilley et al. (2014) go further to elaborate that a sanitation system is comprised of *products* or *wastes* (Table 2) that travel through *functional groups* which contain *technologies* that can be selected based on the context of a community or city. The functional groups are the different stages that excreta consecutively goes through which together form the sanitation service chain (Figure 6) as described in Peal et al. (2014b).

Table 1: Characterization of urine and faeces with respect to nutrients and calorific value
Source: Rose et al. (2015)

Parameter	Units	Urine	Faeces
Total Nitrogen, TN	g/cap/day	2 - 35	0.9 - 4.9
Total Phosphorus, TP	g/cap/day	0.4 - 2.5	0.35 - 2.7
Total Potassium, K	g/cap/day	0.027 - 2.87	0.20 - 2.52
Calorific Value, CV	kcal/cap/day	91 - 117	49 - 347

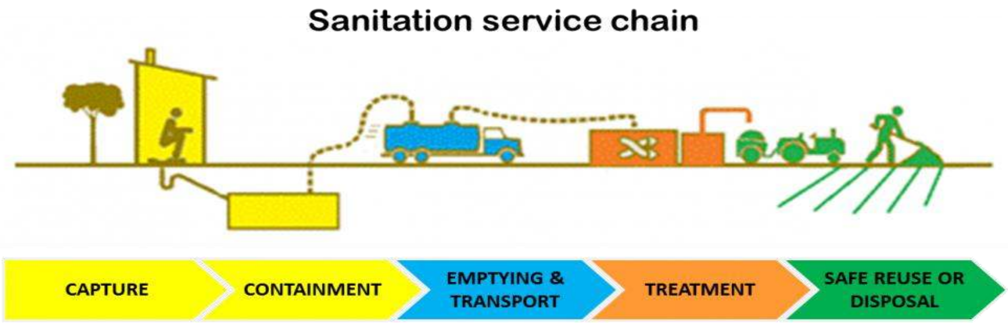

Figure 6: The sanitation service or value chain
Source: Sandford (2015)

It is important to note though that a sanitation system does not only involve technologies but it also includes the management, operation and maintenance (O&M) required to ensure that the system functions safely and in a sustainable manner.

2.3.1. *Types of sanitation systems*

There are two broad types of sanitation systems and these are off-site or sewer-based systems and on-site sanitation systems. Sewer-based systems typically include a user interface with a water closet toilet from where blackwater joins the grey water and they flow in sewers to centralised or small scale wastewater treatment plants. In some cities, domestic waste water from households is mixed with industrial effluent and in some cases, these (or one of them) are combined with storm runoff. This therefore implies that the characteristics of wastewater vary widely from city to city depending on the waste streams that are allowed into the sewers.

Municipal wastewater treatment typically involves three major steps; primary treatment where the aim is liquid-solids separation; secondary treatment whose aim is the removal of organics (BOD/COD reduction) and nutrients; and tertiary treatment whose aim is the further removal of nutrients, pathogens and other micro-pollutants. There are several technologies that can be used for each of these steps, employing mechanical, biological and chemical processes. A review of these technologies is beyond the scope of this thesis but it has been the focus of several works like Alleman and Prakasam (1983), Tchobanoglous et al. (1991) and Tilley et al. (2014) among others.

In typical treatment plants using activated sludge technology for example, the wastewater undergoes some degree of solids-liquid separation within primary treatment producing liquid effluent and primary sludge and later, excess activated sludge (or secondary sludge) after secondary treatment. The effluent can go through further tertiary treatment to remove nutrients and/or pathogens while the sludge can go through further treatment before disposal or reuse and in some cases, it can go through anaerobic digestion to obtain biogas, after which the digested sludge can be treated further before disposal or reuse.

On-site sanitation systems are those whereby the (partial) treatment of excreta or sewage takes place at the same location where it is generated (WHO, 2006). They are used by over 2.7 billion people worldwide (Strande et al., 2014) especially in the Global South but also in areas that are far from the sewer grid in developed countries.

Table 2: Waste streams from sanitation systems
Source: Adapted from Tilley et al. (2014) pp.10-13

Waste stream	Definition
Urine	This is the liquid produced by the body to rid itself of urea and other waste products. In this context, the urine product refers to pure urine that is not mixed with faeces or water. Depending on diet, human urine collected from one person during one year (approx. 300 to 550 l) contains 2 to 4 kg of nitrogen. With the exception of some rare cases, urine is sterile when it leaves the body.
Faeces	To (semi-solid) excrement that is not mixed with urine or water. Depending on diet, each person produces approximately 50 l per year of faecal matter. Fresh faeces contain about 80% water. Of the total nutrients excreted, faeces contain about 12% n, 39% p, 26% k and have 107 to 109 faecal coliforms in 100 ml.
Excreta	It consists of urine and faeces that is not mixed with any flushwater. Excreta is small in volume, but concentrated in both nutrients and pathogens. Depending on the quality of the faeces, it has a soft or runny consistency.
Flushwater	This is the water discharged into the user interface to transport the content and/or clean it. Freshwater, rainwater, recycled greywater, or any combination of the three can be used as a flushwater source.
Brownwater	This is the mixture of faeces and flushwater, and does not contain urine. It is generated by urine diverting flush toilets and, therefore, the volume depends on the volume of the flushwater used. The pathogen and nutrient load of faeces is not reduced, only diluted by the flushwater. Brownwater may also include anal cleansing water (if water is used for cleansing) and/or dry cleansing materials.
Blackwater	This is the mixture of urine, faeces and flushwater along with anal cleansing water (if water is used for cleansing) and/or dry cleansing materials. Blackwater contains the pathogens of faeces and the nutrients of urine that are diluted in the flushwater.
Greywater	This is the total volume of water generated from washing food, clothes and dishware, as well as from bathing, but not from toilets. It may contain traces of excreta (e.g., from washing diapers) and, therefore, also pathogens. Greywater accounts for approximately 65% of the wastewater produced in households with flush toilets.
Sludge	Sludge is a mixture of solids and liquids, containing mostly excreta and water, in combination with sand, grit, metals, trash and/or various chemical compounds. A distinction can be made between *faecal sludge* and *wastewater sludge*. Faecal sludge comes from onsite sanitation technologies, i.e., it has not been transported through a sewer. It can be raw or partially digested, a slurry or semisolid, and results from the collection and storage/treatment of excreta or blackwater, with or without greywater. Faecal sludge includes both sludge from pit latrines and that from septic tanks. For a more detailed characterization of faecal sludge refer to Strande et al. (2014). Wastewater sludge (also referred to as sewage sludge) is sludge that originates from sewer-based wastewater collection and (semi-) centralized treatment processes. The sludge composition will determine the type of treatment that is required and the end-use possibilities.
Effluent	This is the general term for a liquid that leaves a technology, typically after blackwater or sludge has undergone solids separation or some other type of treatment. Effluent originates at either a collection and storage or a (semi-) centralized treatment technology. Depending on the type of treatment, the effluent maybe completely sanitized or may require further treatment before it can be used or disposed of.

The most common technologies used within on-site sanitation systems include pit latrines and water closet or pour flush toilets with septic tanks and soak pits or drain fields (Semiyaga et al., 2015; Graham and Polizzotto, 2013; Tumwebaze et al., 2013). Faecal sludge (FS) accumulates in these systems and depending on the context, the system may be emptied and the sludge dumped or taken for treatment or the system may be abandoned when full (Still and Foxon, 2012).

When taken for treatment, faecal sludge can be treated separately or it can be co-treated with sewage from sewers like it is done in Kampala (Murungi and van Dijk, 2014). When treated separately, among the several treatment techniques available, FS may be dewatered and co-treated with solid waste by composting for example (Strande et al., 2014). Wastewater and faecal sludge are rich in nutrients (Table 3) and this is why they make such a great resource that should not be wasted.

Both on-site and off-site sanitation systems have all the stages of the sanitation service chain as shown in Figure 6. The difference between them is that even if the products will end up treated at a centralised location, the products from an on-site system are first collected and stored on site for some time in a pit or septic tank. As far as the transport stage is concerned, off-site systems are drained by sewers while on-site systems have to engage some sort of manual or mechanized technique to empty the pits or septic tanks.

2.3.2. *Management of municipal solid waste*

Municipal solid waste (MSW) consists of the waste materials that are discarded from households, institutions and commercial areas in urban areas on a daily basis. Other terms synonymous with solid waste include; refuse, garbage, trash and rubbish. MSW includes items such as glass, plastics, paper, metal and organic material. The composition of MSW depends on a number of factors like income level, economic activities, lifestyles and location. It varies by country and region as can be seen in Figure 7. In low income countries, the biggest part of MSW is organics and this consists of yard, kitchen and market waste as well as spent fruits and crop residues (Vögeli et al., 2014). The management of MSW is in most cases the mandate of the local government and in some low income countries, it is the single largest budget item for cities (Hoornweg and Bhada-Tata, 2012).

Table 3: Characteristics of the sanitary waste categories with mean and range values Adapted from: Semiyaga et al. (2015) except where stated otherwise

Parameter	Units	Pit latrine sludge	Septic tank sludge	Raw sewage sludge
Total solids, TS	%	3–20	<3	<1–9
Total volatile solids	% TS	45–60	45–73	60–80
COD	mg/L	30,000 – 225,000	10,000	500–2,500
COD/BOD		6–7	7.14	2.5
Total Kjedhal Nitrogen, TKN	mg N/L	3,400 – 5,000	1,000	–
NH4-N	mg/L	2,000 – 9,000	120–1200	30–70
Total phosphorus, TP	mg P/L	450 – 500	150	9 – 63*
Helminth eggs	No. of eggs/g TS	30,000 – 40,000	4,000	300–2,000
Calorific Value	MJ/kg TS	13 – 17**	14 – 22**	10 – 29*

Other sources: * Strande et al. (2014)
**** Muspratt et al. (2014)**

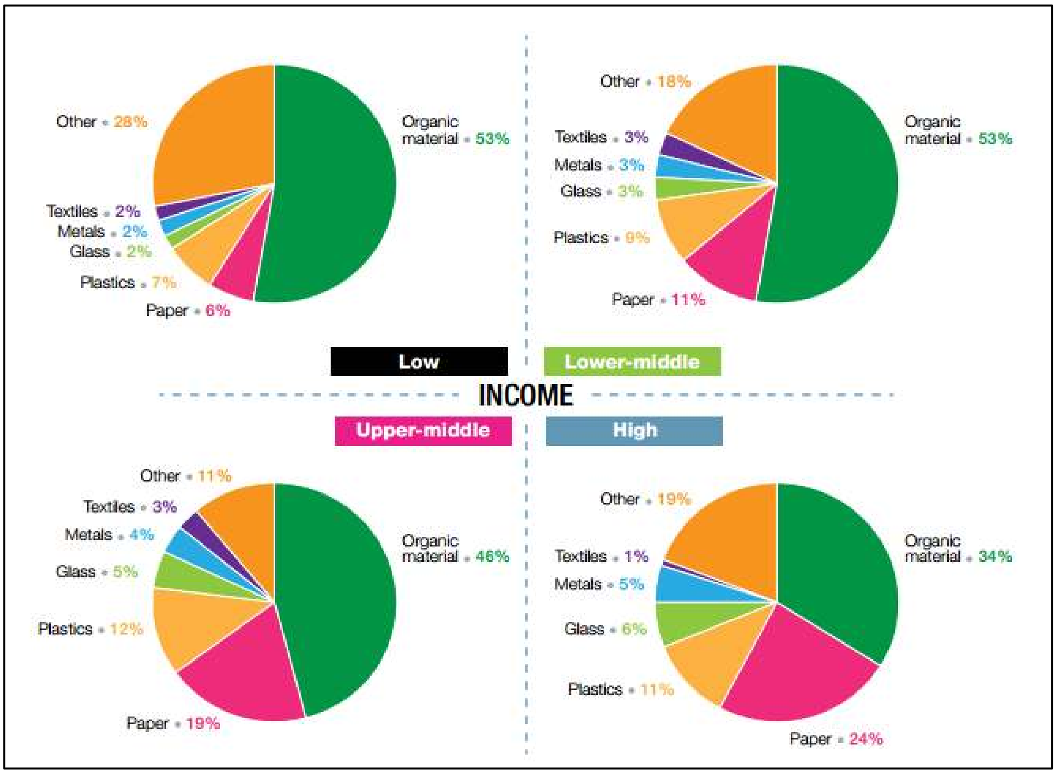

Figure 7: Variation in MSW composition grouped by country income levels Source: Wilson et al. (2015)

To some extent, plastics, metal, glass and paper are recycled in low and middle income countries but most of the organics are landfilled or simply disposed of at dump sites (Hoornweg and Bhada-Tata, 2012). In instances where organic waste is collected and treated, the common treatment methods include; incineration, composting, anaerobic digestion, vermicomposting and thermochemical treatment like gasification, pyrolysis, carbonization and co-firing (Burnley, 2014; Chandrappa, 2012).

2.4. Resource recovery: what are the options?

A number of processes and technologies exist for the treatment of sanitary waste and any option could be taken depending on the end use envisioned. The choice of treatment technology also depends on the type of waste stream, space, cost, regulations and existing infrastructure among other factors (Spuhler, 2015). The following section discusses possible treatment technologies with respect to the recoverable resources.

2.4.1. *Recovery of energy*

> *"Eat the food as you would a loaf of barley bread; bake it in the sight of the people, using human excrement for fuel"*
>
> – Ezekiel 4:12 NIV

Knowledge of the energy value in excreta seems to have existed as far back as the 6th century BC (Ezekiel 4:9-15 NIV). In modern times however, the earliest record of the use of excreta for energy seems to be from the location of present-day Yemen where dried faeces from source-separation sanitation systems were used as fuel for cooking food (Lüthi et al., 2011). The calorific value of excreta from the different streams of sanitation products has been widely recorded in literature from a number of studies (Muspratt et al., 2014; Komakech, 2014; Niwagaba et al., 2015) as detailed in Tables 1 and 3.

The energy value can be extracted from sanitation products mainly in the form of sludge. For example, the anaerobic digestion (AD) of sludge can generate biogas from which electricity, heat and vehicle fuel can be obtained after further processing in gas engines, turbines and gas-upgrading equipment respectively (Figure 8). AD has been employed in many cities in high income countries for treating sewage sludge from wastewater treatment plants (WWTPs), mainly driven by the high economic value of upgraded biogas and the increasing demand for renewable energy sources (Strande et al., 2014; Komakech, 2014). Faecal sludge can also be used for AD. Besides sludge, some WWTPs employ Upflow Anaerobic Sludge Blanket (UASB) reactors as the secondary treatment step for their wastewater and this also generates biogas (Tilley et al., 2014). A recent study has estimated that if biogas was produced from all faeces generated worldwide, it could provide energy for up to 180 million homes and be worth over 9 billion US dollars per year (Schuster-Wallace et al., 2015).

Raw biogas contains about 50-70% methane (CH_4) and the rest is other gases like carbon dioxide, hydrogen, nitrogen and hydrogen sulphide (Mårtensson, 2007). When used for vehicle fuel, the methane content must be at least 95% (Mårtensson, 2007). One cubic meter of raw biogas has the equivalent of 1.51kWh of electricity or 1.5 kg of firewood (Strande et al., 2014). Any large-scale treatment system for biogas needs to have quality assurance especially when dealing with various waste streams/substrates. This also ensures a high quality of the AD residue so it can be used as fertiliser. Some biogas plants have come up with specific recipes to produce high yield of biogas (Mårtensson, 2007). As far as the choice of treatment technology and plant size is concerned, the location and the waste streams available have to be considered. For waste flows in large cities a larger centralised plant may be the best choice for the sewage and municipal waste streams but when the waste streams are sourced from an even wider area, several small plants may be the best option (Mårtensson, 2007).

Faecal sludge and wastewater sludge can also be incinerated and hence generate heat or electricity. Incineration is practiced in many areas in the US and Europe (Werther and Ogada, 1999)but is quite rare in the Global South due to technological difficulties (Strande et al., 2014). As shown by the calorific value of FS and sewage sludge in Table 3, they can be incinerated feasibly especially if the costs of drying prior to combustion are outweighed by the gains from the process (Strande et al., 2014).

Other possible ways to extract energy from sanitation products include pyrolysis or gasification and production of briquettes. At temperatures between 350 – 500°C in oxygen-depleted conditions, pyrolysis of faecal sludge and sewage sludge can occur resulting in a large quantity of char and several gaseous compounds like CO_2 and CH_4. At over 700°C, gasification occurs and results in the generation of syngas which is a combination of carbon monoxide and hydrogen (Rulkens, 2007). Syngas can be used in gas engines or turbines to generate electricity or it can be processed into a liquid fuel and its calorific value ranges from 7 to 9.5 MJ/m^3 when produced from wastewater sludge (Domínguez et al., 2006). Briquettes can also be used for household cooking and/or for heating in industrial applications where suitable (Ward et al., 2014; Semiyaga et al., 2015).

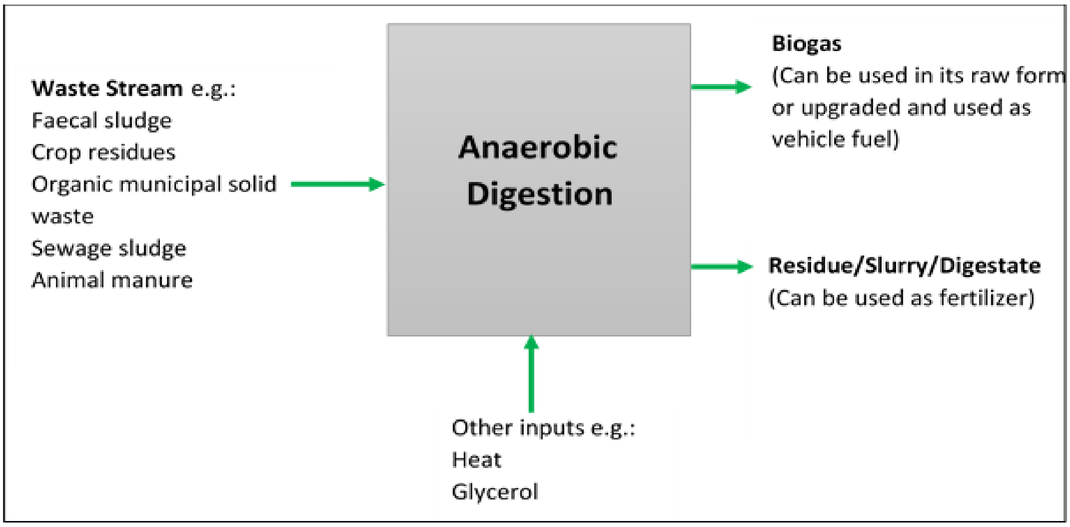

Figure 8: Inputs and outputs from the anaerobic digestion process

2.4.2. *Organic waste based fertilizers and soil conditioner*

One key problem in the nutrient balance between cities and rural areas is that by producing all the food in the rural areas and ferrying to be consumed in cities, there is a continuous flow of nutrients from rural areas to cities. In the end, rural areas are left with a deficit of NPK nutrients and cities are left with an excess of the same nutrients that they then need to get rid of. Urban areas produce several significant waste streams but they typically do not do much agriculture since most of the urban population is engaged in other sectors of the economy. As such, fertilizer may not have much use right in the city with the exception of some limited space used for urban gardens.

Rural and peri-urban areas have most of the agricultural activity and hence need the nutrients but they have little volumes of waste due to smaller population sizes. Transporting nutrients from cities to rural areas might exacerbate the transport and logistics problems already existing in the waste management sector (Kinobe, 2015), especially in low and middle income countries where most of the cities exist alongside poorly planned slum conditions with poor infrastructure (Semiyaga et al., 2015). This is in addition to the fact that the transport sector is one of the biggest contributors to global warming and subsequently, climate change (Madlener and Sunak, 2011).

The use of sanitation products in agriculture is one of the oldest known forms of waste reuse. Records from China describe disciplined schemes of collection, transportation and application of excreta on agricultural land as fertilizer in a closed-loop system that preserved soil fertility for over 4,000 years without polluting water systems (King, 1911). The widespread use of organic fertilizer from excreta was significantly reduced with the arrival of chemical fertilizer at the start of the 20th century (Lüthi et al., 2011).

As shown in Table 1, human excreta contain much of the nutrients necessary to sustain agricultural production. Studies have estimated that conventional sanitation systems dump the equivalent of about 50 million tons of fertilizer into receiving waters annually (CGIAR, 2013) and this is almost a third of the amount of fertilizer that was consumed from 2008 to 2009 (FAO, 2009). Similarly, a study of 150 Malian households using ecological sanitation found that in their excreta, they produce amounts of NPK nutrients equivalent to about 30% of their annual expenditure on chemical fertilizers (Pettersson and Wikström, 2016). Excreta-derived products can be used in agriculture as fertilizer to replace chemical NPK and as soil conditioner to maintain soil organic matter. Various approaches can be used to apply sanitation products to agricultural land including the following:

- Composting of faecal sludge or sewage sludge and co-composting with organic municipal solid waste (Figure 9). In Northern Ghana for example, about 90% of all FS is used for agriculture (Cofie et al., 2005). According to Danso (2004) and Diener et al. (2014) however, compost does not have a high market value. Even though surveys among farmers in Ghana indicate that they appreciate its nutrient value, they can't pay an amount that covers production costs.
- Application of treated sludge residue from anaerobic digestion
- Deep row entrenchment of faecal and sewage sludge that has received no further treatment
- Application of the residue from vermicomposting of sludge
- Application of the treated wastewater effluent or untreated effluent from sanitation systems. This also serves as irrigation especially in water-scarce areas.
- Application of the biochar from gasification or pyrolysis. This however mainly improves the soil structure like water retention and aeration capacity (Chan et al., 2008; Singh et al., 2010; Chen and Cheng, 2007) since the carbon, nitrogen and sulphur content is lost in the pyrolysis/gasification process.

Abubaker et al. (2012) shows that biogas residues can give as much relative yields as mineral fertilizer, though not as much as pig slurry. The application of fertilizers derived from human wastes however comes with concerns about their content of heavy metals and residues from pharmaceuticals and pesticides. For example, an investigation of over 60 trace metals by the Swedish Environmental Protection Agency found that the concentration of these elements per kg of phosphorus applied to land was higher in sewage sludge than in both farmyard manure and the most common commercial chemical fertilizers on the Swedish market (Eriksson, 2001). On the other hand, it has been demonstrated by Odlare et al. (2011) through an 8-year experiment that using AD residues and compost does not have much negative effect on the soil levels of heavy metals and that there are also no significant negative changes to the chemical and microbial nature of the soil.

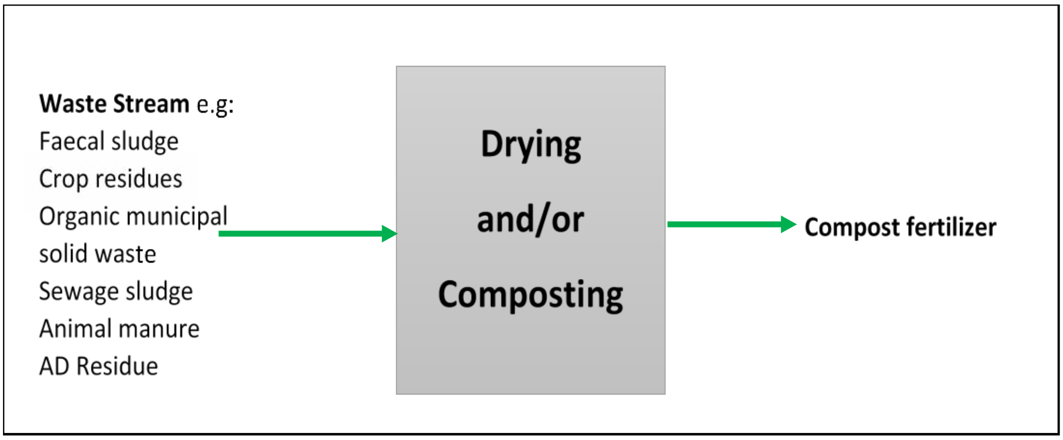

Figure 9: Inputs and outputs from the composting process to obtain fertilizer

A more recent study has also found that the half-life of selected pharmaceuticals and pesticides in residues from black soldier fly larvae composting is shorter than in control treatments with no larvae which implies that that fly larvae composting could impede the spread of pharmaceuticals and pesticides into the environment (Lalander et al., 2016). In Sweden, the REVAQ certification system (Persson and Svensson, 2015) has contributed to improving the quality of sludge. Cadmium levels are lower in REVAQ certified sludge than some chemical phosphate fertilizers (e.g. from Morocco) derived from sedimentary sources that contain significant levels of natural cadmium (Rosemarin, 2016).

Using compost and other organic waste residues increases the soil organic matter which greatly contributes to soil fertility and soil aggregation (Ekane, 2010). While the goal of applying fertilizer to arable land is greater yields, soil management is also crucial for the long-term sustainability of agriculture. Organic matter is an important source of macro- and micronutrients, and it stabilizes soil structure reducing soil erosion, increasing water-holding capacity and also activating soil biota (Johnston et al., 2009). The greatest benefit for agriculture is achieved when organic waste residues and inorganic fertilizers are used in an integrated manner. This includes optimizing earthworm biomass (Ekane, 2010).

2.4.3. ***Animal feeds***

Sanitation products have also been used as feed for animals in a number of ways. When drying beds are used for faecal sludge and sewage sludge treatment, species like *Echinochloa pyramidalis* can be planted in the beds and harvested as fodder for horses, goats, sheep, dairy cows and rabbits, among other animals. Studies in Cameroon and Senegal have shown that such plants have high market value (Kengne et al., 2008). When stabilization ponds are used for treating wastewater and/or effluent, the nutrients therein can increase the growth of plankton for fish feed and other aquatic plants that can be used as animal feed. However, there are concerns over the transfer of pathogens from the wastewater through fish to humans and there is still inadequate knowledge on the technical aspects of this resource recovery approach (Strande et al., 2014).

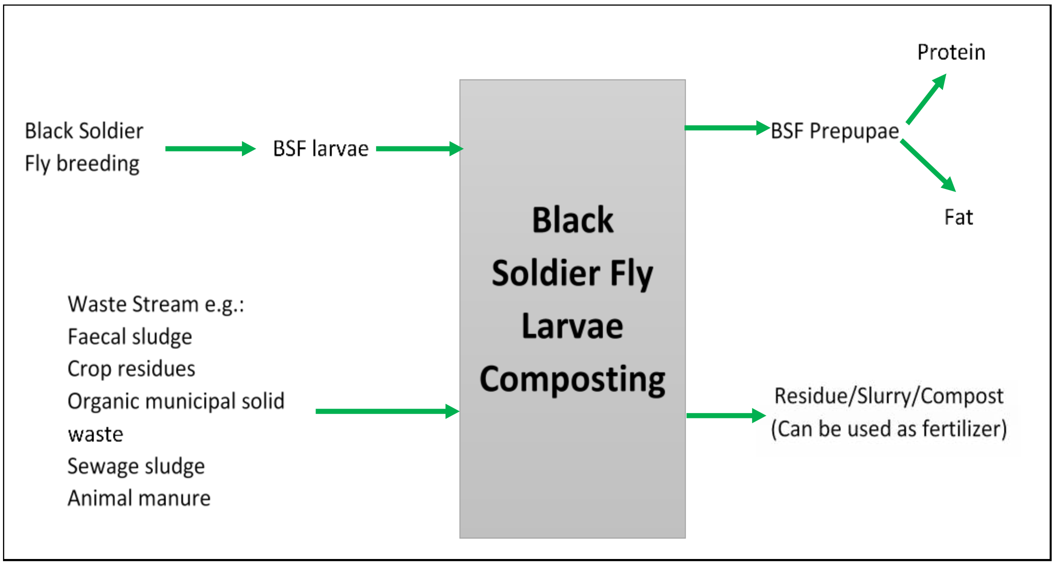

Figure 10: Inputs and outputs from the Black soldier fly composting process

One promising avenue for obtaining animal feed is through the breeding of Black Soldier Fly (BSF) larvae (*Hermetia illucens*) which in their pre-pupa stage have high protein and fat content that can be as high as 35-44% (Nguyen, 2010) when fed on faecal sludge. The protein yields are just as high when other organic waste streams like organic municipal solid waste and animal manure are used as feedstock (Diener, 2010; Mutafela, 2015). The company AgriProtein in South Africa has established factories and is producing protein and oil fat on a commercial scale from breeding BSF (Mutafela, 2015). The residue left by the larvae can also be marketed as a fertilizer/soil conditioner (Figure 10).

2.4.4. ***Irrigation***

Untreated and treated liquid sanitation waste streams are used for irrigation in various instances around the world and are particularly useful in water-scarce regions (CGIAR, 2013). In the case of untreated streams, wastewater from sewers or faecal sludge from latrines and septic tanks are applied directly to plants while treated streams typically involve effluent from secondary and/or tertiary treatment of wastewater or faecal sludge. Application can be on lawns and municipal landscapes but also on food crops, and for this reason, it is necessary to take precautions to prevent the transfer of pathogens that could affect human health through multiple exposure pathways (Dickin et al., 2016). The World Health Organization (WHO) created guidelines for the safe reuse of sanitation products for irrigation (WHO, 2006).

2.4.5. ***Construction materials***

Increasingly, sewage sludge is being used in the production of construction materials in Europe, the USA and in parts of Asia (Spinosa et al., 2011). In some cement industries, sewage sludge is used as a solid dry fuel and the ash from the process is also added to the clinker which offsets the need for some raw materials like clay (Okuna and Yamada, 2000). In Switzerland for example, 23% of all sewage sludge generated in 2006 was valorized in clinker kilns for cement production (Vadenbo et al., 2014). The use of sewage sludge in making bricks has also been investigated with promising results (Tay and Show, 1997; Weng et al., 2003). Based on some similarities, faecal sludge could also be used for similar materials but no studies have been carried out specifically on faecal sludge (Semiyaga et al., 2015).

2.5. Modeling estimates for resource recovery

In the context of this thesis, a model could be described as “a representation of an idea, an object or even a process or a system that is used to describe and explain phenomena that cannot be experienced directly” (SLH, 2011). In scientific work, models are essential tools that allow researchers to link theory with experiment in such a way that an imagined reality can have a simplified representation from which predictions can be made and tested.

In many instances, models have been used for a number of applications in sanitation, wastewater and solid waste handling. Planning for sanitation often involves using decision support models (Palaniappan et al., 2008; Loetscher and Keller, 2002; Bouabid, 2013) while other tools are used to model the life cycle impacts of sanitation systems and technology options (Björklund et al., 1999; Komakech et al., 2015; Tidåker et al., 2006). There are models that have also been developed to determine the investment and operating costs of sanitation infrastructure options (Loetscher and Keller, 2002) while others focus on determining the process parameters for treatment technologies. Other models have been developed so as to optimize logistics systems (Hug et al., 2012; Kinobe, 2015; Bischoff, 2015).

As far as resource recovery from sanitation is concerned however, there seems to be a dearth of dynamic and comprehensive models for this purpose in literature. Several studies have been done in estimating resource recovery potential from sanitation systems (Kjerstadius et al., 2015; Meinzinger, 2010; Komakech, 2014; Diener et al., 2014; Mårtensson, 2007; Woods et al., 1999). However, most of these have focused either on a few specific sanitation technologies or systems, one or a few specific reuse products or on a limited geographic area without developing a dynamic tool that could be utilized in many contexts and for a wide range of waste streams and reuse products. Even those studies where models have been used based on material flow analysis, the focus was on a specific substance and city/region (Hellstrand, 2015; Cordell et al., 2011; Kalmykova et al., 2012; Wu et al., 2016).

A study by Diener et al. (2014) estimated the potential for resource recovery from faecal sludge in three cities in SSA. While it included a number of reuse options, it was not done with a standardized methodology that could be easily applied to other cities and produce results in a short time. Kjerstadius et al. (2015) investigated the potential for energy and nutrient recovery from five different systems for handling wastewater and food waste, using mass balances of TS, VS, N and P. Their methodology, however, aimed at producing a set of indicator data for use in future sustainability assessments for wastewater treatment systems in a Swedish context and was limited to 5 specific combinations of sanitation technologies which meant it could not be applied in a generic way.

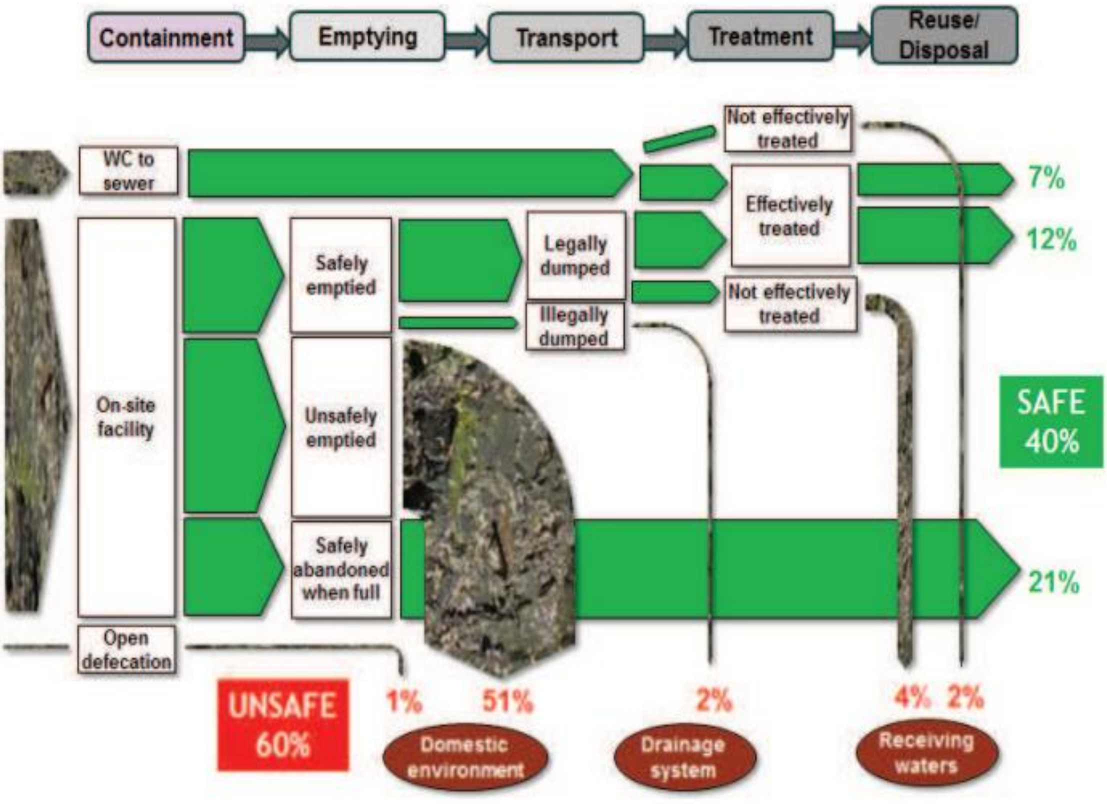

Figure 11: SFD for the city of Kampala, Uganda
Source: Peal et al. (2014a)

A methodology to map the flows of sanitary waste in entire cities in low and middle income countries has been developed by the World Bank Water and Sanitation Program (WSP) with a consortium of organizations in the Sustainable Sanitation Alliance (Blackett et al., 2015; Peal et al., 2014b). The approach which results in the so-called "Shit Flow Diagrams" (SFDs) is able to reveal the presence of various flows of excreta in a city and show the extent of what is collected and treated safely by existing sanitation systems and what ends up unsafely disposed of into the environment (Figure 11).

This SFD methodology which is based on coverage data creates a perfect opportunity for coupling with a tool quantifying actual flows to determine the potential value of reuse products obtained from combined excreta sources. In this way, the model developed from this study could complement the SFDs and hence give a holistic picture of the potential of a closed loop approach to excreta and waste management in cities.

3. METHODOLOGY

3.1. Literature Review

The background information and calculations for developing the model in this project were largely based on published data. The literature used included peer-reviewed articles from scientific journals, text books and grey literature and a range of sources was used including scientific databases like Scopus, Web of Science and Google Scholar. A number of search terms were used in searching for relevant literature including; waste or wastewater; organic waste "resource recovery"; "food waste" and "resource recovery" or recycling; (organic waste or waste water or sanitation or municipal solid waste) and (resource recovery or reuse); "waste management" and "resource recovery"; organic solid waste and "resource recovery" or recycling etc. For the characterization data, primary sources (i.e. direct measurements reported in peer-reviewed publications) were given preference over secondary data (e.g. text books, project reports, and meta-analysis).

3.2. Development of the model

A mathematical model was developed in MS Excel (2013) to estimate the possible recoverable amounts of byproducts from sanitation systems. MS Excel was selected as a modelling platform mainly because it is widely available on many computers in low and middle income countries. Even those computers that do not have MS Excel often have some other form of spreadsheet software and in addition, users can easily acquire alternative open source spreadsheet softwares that are part of office suites like OpenOffice or LibreOffice (Beal, 2012). This therefore makes it easy for the resulting model to be adopted by a wide range of users.

The MS Excel workbook with the model was designed to contain four worksheets;

- *Instructions,* which has step by step guidelines on how to use the model
- *Model,* which is the main component of data manipulation and which displays the results (resource values) as a result of the input
- *Data,* which has characterization and transformation data for the various waste streams and,

- *Graphs,* which produces bar graphs from the calculations in order to visually compare the different model outcomes and scenarios.

The *Model* worksheet was designed such that a user can enter the waste stream flow rates in their city or urban area and also the existing or likely local monetary values (prices) of the resource recovery end-products. The worksheet then displays the minimum, typical and maximum amounts of resource products that can be recovered from each respective waste stream. Each of these are displayed in a separate column. The minimum and maximum values give the user an idea of the lowest and highest amounts of resources they could obtain from their waste streams while the typical values portray what could normally be expected, based on averages.

The *Data* worksheet was designed to have characterization and transformation data for all the waste streams included in the model. It includes columns for minimum, typical and maximum values which were filled in based on published data sources. For those parameters where literature had only ranges of minimum and maximum values with no typical values, an average was calculated and placed in the "typical" column. This was clearly indicated in the model so as to differentiate between directly reported typical values and derived values. The units in which the data are quoted in the model as well as the sources of the data are also included. The minimum, typical and maximum values in the *Model* worksheet are calculated according to the values in the similarly named parameter columns in the *Data* worksheet.

The *Graphs* worksheet was designed to provide bar graphs for a comparison between different resource recovery options with respect to the nutrient and energy content and potential revenues generated.

3.2.1. ***Scope of the model***

The resource recovery options in the model included energy recovery from anaerobic digestion and solid combustion fuels, protein and energy recovery from Black Soldier Fly larvae and nutrient recovery from compost, the residues of anaerobic digestion and fly larvae composting. The use of faecal sludge and/or wastewater effluent for irrigation and aquaculture was not included in the model even though these are widespread practices. This is because the amount of recoverable liquid from these waste streams varies a lot depending on the treatment technique used among other factors. This therefore makes a steady estimation of potential reusable products difficult whether the waste stream is treated or untreated. When treated prior to use, the variety of treatment technologies used like activated sludge, trickling filters, waste stabilization ponds, constructed wetlands and anaerobic baffled reactors (Tchobanoglous et al., 2003; Tilley et al., 2014) implies that it is difficult to make a generic estimate of what re-usable amount of effluent remains after the treatment.

The use of faecal sludge and sewage sludge to produce construction materials was not included since it is not yet widely practiced and in many low income countries, the availability of cheap local construction materials negates the need for alternative sources of materials (Diener et al., 2014; Semiyaga et al., 2015).

The characterization data included in the *Data* worksheet only covers those parameters that have a major influence on the recoverable amounts of end-products. Due to limitations of time, the model at this point was restricted to a few waste streams, namely; faecal sludge, sewage sludge and organic municipal solid waste. However due to the modular nature of the model, it can be widened in subsequent future versions to include more resource recovery options and more waste streams.

3.2.2. ***Mathematical calculations in the model***

This section mainly covers the mathematical relationships between the various parameters used in the model and the possible amounts of resources that can be recovered. The section is arranged according to resource recovery options, i.e. energy, protein and nutrient recovery. For each option, the key characteristic parameter of the waste stream that determines the amount of recoverable resource was identified as well as the related mathematical relationship. This was then incorporated into the model using MS Excel functions as described in the following sub-sections.

Recovery of Energy: Biogas

The amount of biogas that can be obtained from an anaerobic digestion process depends on a number of factors including the type, composition, temperature and mixing of the feedstock (Vögeli et al., 2014). In this study, the type and composition of substrate was used to determine the possible amount of biogas than can be recovered and in particular, the volatile solids which represents the organic fraction of the waste stream. The biogas yield from a waste stream is typically stated in terms of the Bio-methane Potential (BMP) which can be measured in various ways but the most accurate is in terms of Nm^3 CH$_4$/kg VS (Vögeli et al., 2014).

The potential amount of biogas B_v, (Nm^3) that can be generated from the anaerobic digestion of the various waste streams was calculated according to Eq. 1 and 2. It should be noted that Eq. 1 applies to waste streams recorded in m^3/day (like faecal sludge) while Eq. 2 is for waste streams recorded in tonnes/day (sewage sludge and organic MSW).

$$B_v = WS_v \times 1000 \times \frac{TS_v}{10^9} \times \frac{VS_m}{100} \times BMP \times \frac{100}{60} \quad (1)$$

$$B_v = WS_m \times \frac{TS_m}{100} \times \frac{VS_m}{100} \times BMP \times \frac{100}{60} \quad (2)$$

Where;

WS_v = amount of waste stream (faecal sludge) in m^3/day,

WS_m = amount of waste stream (sewage sludge or organic MSW) in tonnes/day,

TS_v= amount of total solids in the waste stream in mg/L,

TS_m= amount of total solids in the waste stream as a percentage of the total mass,

VS_m = amount of volatile solids in the waste stream, as a percentage of total solids,

BMP = biomethane potential of the waste stream in Nm^3 CH$_4$/tonne VS$_{added}$.

The following assumptions were made:

- The biogas to be produced from the process is typical and with a methane content of about 60% (Schuster-Wallace et al., 2015).
- A typical biogas digester will operate at about 30°C since most biogas plants in the world use mesophilic digestion to optimize biogas yields while avoiding the high costs that can come with heating the digesters to achieve thermophiles digestion (Karellas et al., 2010).

- An optimal Carbon:Nitrogen (C:N) ratio is available in the feedstock (waste stream). The optimal C:N ratio (based on mass) in anaerobic digesters ranges between 16 and 25 according to Deublein and Steinhauser (2011) and Vögeli et al. (2014).
- Where necessary, some water would have to be added to the waste stream to achieve an optimum moisture content for the anaerobic digestion to yield enough biogas.
- These values assume a VS reduction of at least 50 – 60% (Kjerstadius et al., 2015; Diener et al., 2014).

According to Vögeli et al. (2014), 1 Nm^3 of raw biogas (with 60% methane content) contains approximately 6 kWh or 21.6 MJ of energy and this was used to calculate the energy content in the biogas across all waste streams as per (Eq. 3).

$$\text{Energy content in biogas (MJ)} = B_v \times 21.6 \tag{3}$$

Where B_v is the amount of biogas in Nm^3.

The revenue that can potentially be generated from the biogas was calculated according to Eq. 4.

$$\text{Potential revenue from the biogas} = B_v \times B_p \tag{4}$$

Where B_p is the prevailing local price of biogas or its equivalent (e.g. propane) in US$/$Nm^3$.

The effluent or residue from the anaerobic digestion process can be used as soil fertilizer/conditioner so this was also included in the calculation. The calculations were based on values of the percentage dry mass reduction (DMR) of the feedstock in the biogas digester. These values were obtained from the literature and included in the *Data* worksheet. To calculate the minimum possible amount of residue that can be obtained from the anaerobic digestion process, the value of the maximum DMR was used and vice versa. The amount of residue, R_{AD} (tonnes) was calculated as follows for faecal sludge (Eq. 5) and sewage sludge and organic MSW (Eq. 6) respectively.

$$R_{AD} = WS_v \times 1000 \times \frac{TS_v}{10^9} \times \frac{100-DMR_{AD}}{100} \times \frac{100}{TS_{AD}} \tag{5}$$

$$R_{AD} = WS_m \times \frac{TS_m}{100} \times \frac{100-DMR_{AD}}{100} \times \frac{100}{TS_{AD}} \tag{6}$$

Where;

DMR_{AD} = Dry Matter Reduction in the residue from the anaerobic digestion process, in %

TS_{AD} = Amount of total solids in the anaerobic digestion residue as a percentage of the total mass

All the other parameters are as described above.

The revenue that can be potentially generated from the anaerobic digestion residue was calculated according to Eq. 7.

$$\text{Potential revenue from the AD residue} = R_{AD} \times SC_p \tag{7}$$

Where SC_p is the price of soil conditioner or compost fertilizer in US$/tonne and R_{AD} is the amount of AD residue in tonnes.

According to Wang et al. (2010) and Harrison et al. (2013), there is negligible nutrient (NPK) removal from waste streams treated by anaerobic digestion and so it was assumed that 100% of the nutrients remain in the substrate and are hence within the residue that exits the biogas digester or reactor. This was used to estimate the nutrient content in the residue according to Eq. 8 for faecal sludge and Eq. 9 for sewage sludge and organic MSW.

$$\text{Amount of nutrients (tonnes)} = WS_v \times 1000 \times \frac{NUT_v}{10^9} \tag{8}$$

$$\text{Amount of nutrients (tonnes)} = WS_m \times \frac{TS_m}{100} \times \frac{NUT_m}{10^6} \tag{9}$$

Where;

NUT_v = Concentration of the nutrient in the waste stream in mg/L

NUT_m = Concentration of the nutrient in the waste stream in mg/kg TS

The nutrient content in terms of percentages was calculated according to Eq. 10.

$$\text{Nutrient content in AD residue (\%)} = \frac{NUT_{AD}}{R_{AD}} \times 100 \tag{10}$$

Where NUT_{AD} is the amount of nutrient in tonnes and R_{AD} is the amount of AD residue in tonnes.

Eq. 8, 9 and 10 were used similarly for each of the nutrients (nitrogen, phosphorus or potassium).

Recovery of Energy: Solid Combustion Fuel

When considering the use of excreta or other organic waste as a fuel for combustion, the most important parameter is the calorific value of the waste stream. This gives the quantity of the total energy contained therein. As raw material for solid fuels for combustion, excreta and other organic wastes are typically used in powder, pellet or lump form (Diener et al., 2014), therefore estimates of their amounts in this study were calculated in terms of mass (tonnes). The amount of solid fuel that can be obtained is dependent on the level of dryness achieved in the waste stream's treatment. Some companies that have expressed willingness to use faecal sludge as a fuel for their industrial combustion processes require a dryness of 90% dry mass, since it provides for easier handling and transport (Diener et al., 2012). Research has shown that briquettes have more efficient combustion with a moisture content below 10% (Grover and Mishra, 1996). Therefore, the assumption was made that a dry solid fuel from sanitary waste streams has to achieve a dryness level of 90% total solids for effective handling and efficient combustion.

Therefore, the amount of solid fuel that can be obtained at 90% dryness, F_m (tonnes), is calculated as follows with Eq. 11 for faecal sludge and Eq. 12 for sewage sludge and organic MSW:

$$F_m = WS_v \times 1000 \times \frac{TS_v}{10^9} \times \frac{100}{90} \tag{11}$$

$$F_m = WS_m \times \frac{TS_m}{100} \times \frac{100}{90} \tag{12}$$

The energy content in the solid fuel, E_F (MJ), based on the dry matter, was calculated using a similar approach to that used by Diener et al. (2014) as follows with Eq. 13 for faecal sludge and Eq. 14 for sewage sludge and organic MSW.

$$E_F = WS_v \times 1000 \times \frac{TS_v}{10^9} \times \frac{100}{90} \times 1000 \times CV \tag{13}$$

$$E_F = WS_m \times \frac{TS_m}{100} \times \frac{100}{90} \times 1000 \times CV \tag{14}$$

Where CV is the calorific value of waste stream in MJ/kg TS.

The revenue that can potentially be generated from the solid combustion fuel was calculated according to Eq. 15.

Potential revenue from the solid combustion fuel = $F_m \times F_p$ (15)

Where F_m is the amount of solid fuel in tonnes and F_p is the price of the solid combustion fuel in US\$/tonne.

Recovery of Animal Protein Feed and Energy from Black Soldier Fly Prepupae

When organic waste streams are treated using BSF larvae composting, one of the most important parameters to monitor is the Biomass Conversion Rate (BCR). The BCR depends on the amount of feedstock added to the BSF bioreactor and the efficiency of consumption by the BSF larvae (Mutafela, 2015). The BCR expresses the ratio of the amount of prepupae dry matter to the amount of feedstock dry matter as a percentage. That way, it shows the extent to which the added feedstock is converted to prepupae biomass. It is calculated as shown in Eq. 16:

$$BCR = \frac{PP_{TS}}{WS_{TS}} \times 100 \tag{16}$$

Where PP_{TS} is the amount of harvested prepupae in terms of dry mass (tonnes) and WS_{TS} is the amount of total solids in the waste stream (tonnes) that is added as a feedstock into the BSF bioreactor.

A number of laboratory and pilot studies have reported a wide range of BCR values for different waste streams. For faecal sludge, BCR values could range from 1.6% to 22.9% as reported by Banks (2014) while for organic municipal solid waste, the BCR could range from 3.97% to 14.5% (Mutafela, 2015; Lalander et al., 2015; Diener et al., 2011). It was assumed that the BCR values for sewage sludge would be similar to those for faecal sludge. Therefore the calculation for the amount of BSF prepupae, BSF_m (tonnes), was made according to Eq. 17 for faecal sludge and Eq. 18 for sewage sludge and organic MSW:

$$BSF_m = WS_v \times 1000 \times \frac{TS_v}{10^9} \times \frac{\text{BCR}}{100} \times \frac{100}{40} \tag{17}$$

$$BSF_m = WS_m \times \frac{TS_m}{100} \times \frac{\text{BCR}}{100} \times \frac{100}{40} \tag{18}$$

Where BCR is the Biomass Conversion Rate for the BSF prepupae and the other parameters are as described previously.

When freshly harvested from a bioreactor, BSF prepupae have a dry matter content that ranges between 35% to 45% (Makkar et al., 2014). An average dry matter content of 40% was adopted in this study to indicate the amount of BSF prepupae obtained in terms of wet mass, hence the $\frac{100}{40}$ term in Eq. 17 and 18.

BSF prepupae contains 40% protein and 30% fat (Diener, 2010) so the protein and fat content in the amounts of BSF prepupae were calculated according to Eq. 19 and Eq. 20 respectively:

Protein content in the BSF prepupae (tonnes) = $BSF_m \times 0.4$ (19)

Fat content in the BSF prepupae (tonnes) = $BSF_m \times 0.3$ (20)

Where BSF_m is the amount of BSF prepupae in tonnes.

BSF prepupae can also be used to make biodiesel from the fat content. According to Green (2014), 1 tonne of BSF prepupae can yield up to 175 litres of biodiesel. Biodiesel has an energy content of 33.3 MJ/L (Wilcock, 2005). This was used to calculate the potential energy that can be obtained from the BSF prepupae, E_{BSF} (MJ), according to Eq. 21:

$$E_{BSF} = BSF_m \times 175 \times 33.3 \tag{21}$$

The potential revenues that can be generated from the BSF prepupae were calculated according to Eq. 22:

Potential revenues from BSF prepupae = $BSF_m \times BSF_p$ (22)

Where BSF_m is the amount of BSF prepupae in tonnes and BSF_p is the prevailing local price of the BSF prepupae in US$/tonne.

In making these calculations, the following assumptions were made:

- the goal of the process is to have maximum prepupae production for maximum resource recovery
- optimal feeding rates for the BSF larvae are utilised
- the BSF breeding is done in an optimised reactor so that the amount of BSF prepupae obtained only depends on the amount waste stream used as feedstock.

The effluent or residue from BSF breeding bioreactor can be used as soil conditioner and therefore this was included in the calculation. The calculations were based on values of the percentage wet mass reduction (WMR) of the feedstock in the BSF bioreactor. These values were obtained from the literature and included in the *Data* worksheet. To calculate the minimum possible amount of residue that can be obtained, the value of the maximum WMR was used and vice versa. Eq. 23 was used for faecal sludge and Eq. 24 for sewage sludge and organic MSW as follows:

$$R_{BSF} = WS_v \times 1000 \times \frac{TS_v}{10^9} \times \frac{100}{40} \times \frac{100-WMR_{BSF}}{100} \quad (23)$$

$$R_{BSF} = WS_m \times \frac{TS_m}{100} \times \frac{100}{40} \times \frac{100-WMR_{BSF}}{100} \quad (24)$$

Where R_{BSF} is the amount of BSF residue (tonnes) and WMR_{BSF} is the Wet Mass Reduction in the BSF bioreactor in % and all the other parameters are as previously described.

The revenues that can potentially be generated from the residue after fly larvae composting were calculated according to Eq. 25:

Potential revenue from BSF residue = $R_{BSF} \times SC_p$ (25)

Where SC_p is the price of soil conditioner or compost fertilizer in US$/tonne and R_{BSF} is the amount of BSF residue in tonnes.

Treating sanitary waste streams with BSF larvae composting results in some reduction of the nutrients and this is evident in the residue (van Huis et al., 2013). If the residue is to be used as soil conditioner however, it is necessary to know the nutrient content therein so this was included in the calculations. The calculations are based on values of the percentage nutrient reduction (NR) of the feedstock in the BSF bioreactor. These values are obtained from the literature and included in the *Data* worksheet. To calculate the minimum possible amount of nutrients that could remain in the residue from the BSF bioreactor, the value of the maximum NR is used and vice versa. The expected nutrient content in the BSF residue is therefore calculated using Eq. 26 for faecal sludge and Eq. 27 for sewage sludge and organic MSW:

$$NUT_{BSF} = WS_v \times 1000 \times \frac{NUT_v}{10^9} \times \frac{100-NR_{BSF}}{100} \quad (26)$$

$$NUT_{BSF} = WS_m \times \frac{TS_m}{100} \times \frac{NUT_m}{10^6} \times \frac{100-NR_{BSF}}{100} \quad (27)$$

Where NR_{BSF} is the percentage reduction of nutrients in the BSF bioreactor residue for each of the nutrients. All the other parameters are as described before.

The nutrient content in terms of percentages is calculated according to Eq. 28;

Nutrient content in BSF residue (%) = $\frac{NUT_{BSF}}{R_{BSF}} \times 100$ (28)

Where NUT_{BSF} is the amount of each nutrient in the BSF residue in tonnes and R_{BSF} is the amount of BSF residue in tonnes. Eq. 26, 27 and 28 were used similarly for each of the nutrients (nitrogen, phosphorus or potassium).

Recovery of nutrient: Soil conditioner/fertilizer

When considering the use of excreta-derived waste streams as soil conditioner, it is necessary to consider the size of the available waste stream available and the nutrient content to determine if they are sufficient for the targeted crops (Strande et al., 2014). The amount of soil conditioner that can be obtained is dependent on the level of dryness achieved in the waste stream treatment. It is necessary to dry the sludge to a sufficient level to decrease the overall weight and hence the associated transportation costs, yet increased drying can also result in increased energy costs. For that matter, a value of 60% TS was adopted for this study as a benchmark value for dryness of sludge that is to be applied to farmland. It is assumed that this level of dryness can be achieved without incurring prohibitively high costs since the majority of low and middle income countries lie within the Tropics and can harness the sun for more efficient drying techniques.

The composting process also brings about some reduction in the mass of the waste stream material. Values of the dry mass reduction during composting (CMR) were obtained from the literature and included in the *Data* worksheet and in the calculations. To calculate the minimum possible amount of soil conditioner that can be obtained from composting, the value of the maximum CMR was used and vice versa. Therefore, the amount of soil conditioner that can be obtained at 60% dryness, SC_m(tonnes), was calculated using Eq. 29 for faecal sludge and Eq. 30 for sewage sludge and organic MSW as shown below:

$$SC_m = WS_v \times 1000 \times \frac{TS_v}{10^9} \times \frac{100-CMR}{100} \times \frac{100}{60} \quad (29)$$

$$SC_m = WS_m \times \frac{TS_m}{100} \times \frac{100-CMR}{100} \times \frac{100}{60} \quad (30)$$

Where CMR is the percentage reduction in dry mass as a result of composting.

The revenue that can potentially be generated from the soil conditioner if put on sale was calculated according to Eq. 31.

Potential revenue from soil conditioner = $SC_m \times SC_p$ (31)

Where SC_p is the price of soil conditioner or compost fertilizer in US\$/tonne and SC_m is the amount of soil conditioner (in tonnes) obtained from the composting process.

Treating sanitary waste streams by composting results in some reduction of the nutrients (Anwar et al., 2015). Therefore, if the compost is to be used as soil conditioner, it is necessary to know the nutrient content taking into account any losses. The calculations for the nutrient content were based on values of the percentage nutrient reduction (NR) from the composting process. These values were obtained from the literature and included in the *Data* worksheet. To calculate the minimum possible amount of nutrients that could remain in the resulting soil conditioner, the value of the maximum NR was used and vice versa. The expected nutrient content in the soil conditioner, NUT_{SC} (tonnes), was therefore calculated using Eq. 32 for faecal sludge and Eq. 33 for sewage sludge and organic MSW:

$$NUT_{SC} = WS_v \times 1000 \times \frac{NUT_v}{10^9} \times \frac{100-NR_C}{100} \tag{32}$$

$$NUT_{SC} = WS_m \times \frac{TS_m}{100} \times \frac{NUT_m}{10^6} \times \frac{100-NR_C}{100} \tag{33}$$

Where NR_C is the percentage reduction of nutrients in the composting process for each of the nutrients. All the other parameters are as previously described.

The nutrient content in terms of percentages was calculated according to Eq. 34.

$$\text{Nutrient content in the soil conditioner (\%)} = \frac{NUT_{SC}}{SC_m} \times 100 \tag{34}$$

Where NUT_{SC} is the amount of each nutrient in the soil conditioner in tonnes and SC_m is the amount of soil conditioner in tonnes. Eq. 32, 33 and 34 were used in the same way for each of the three major nutrients; nitrogen, phosphorus and potassium.

In calculating the amounts of nutrients in the soil conditioner, this study did not take into account the application rates on farmland since it is assumed that this would vary in each case depending on the crops grown and other local soil conditions. To maximize cost efficiency and avoid environmental pollution from over-application of nutrients, there are methods that have been established for calculating application rates and these can be explored for this purpose (Strande et al., 2014).

In calculating the potential amounts of each product that could be obtained from the various waste streams, losses due to handling and spillage at various stages of the treatment process were not included. This was simply because they are largely dependent on the user and the specific technologies used, not the initial amount of waste stream that is available for resource recovery.

3.2.3. *Generation of graphs for comparison*

From the results of the calculations, bar graphs were generated in the *Graphs* worksheet for every waste stream so as to compare different end-use products on the basis of optimizing the potential nutrients or energy recovered or revenues generated. These bar graphs show the typical values that can be obtained along with bars indicating the minimum and maximum values possible.

3.3. Application of the model for the case of Kampala City

Kampala is the capital city of Uganda which is located in East Africa (Figure 12). Kampala was used as a case study to test the developed model.

3.3.1. *Site description*

Kampala has a population of 1.5 million people (UBOS, 2016) . About 90% of the population uses on-site sanitation systems, 6% - 9% are connected to the centralised sewer system and about 1% practicing open defecation (Bischoff, 2015). The commonly used on-site sanitation technologies include Ventilated Improved Pit (VIP) latrines, unlined pit latrines, septic tanks and public toilets. The distribution of users among these technologies/systems is depicted in Figure 13.

Figure 12: Map of Africa with Uganda and Kampala highlighted
Source: Google Maps (2016)

The mandate for managing sanitation services in Kampala city lies between the National Water and Sewerage Company (NWSC) which is the principal water utility in the country and the Kampala Capital City Authority (KCCA) which is in charge of the general management of the city's public services. The Private Emptiers Association is also a key player in the sector as they bring together all the companies and individuals involved in the provision of pit emptying services. The city has four centralised waste water treatment plants and one landfill that are operational at the moment as shown in Figure 14. The biggest ones in terms of capacity are at Lubigi and Bugolobi and the others are much smaller (Table 4).

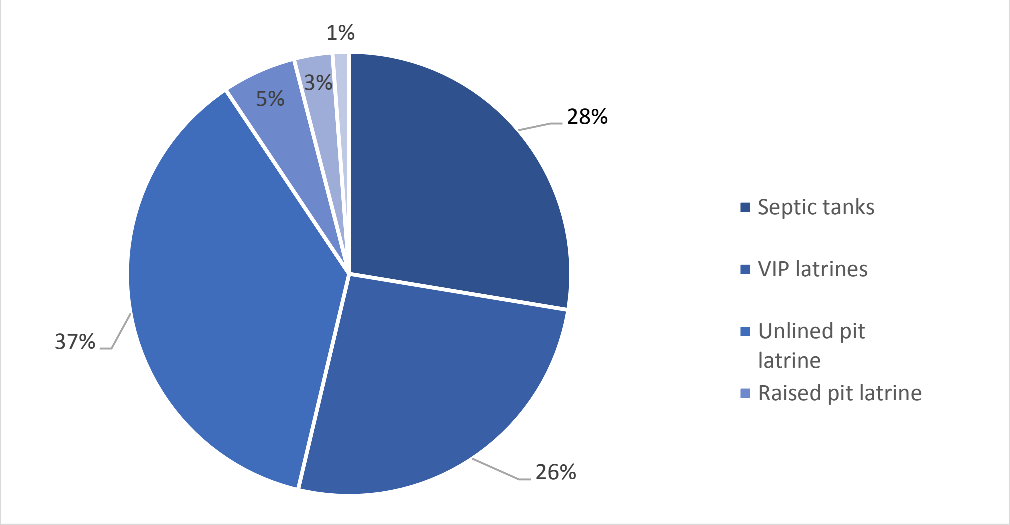

Figure 13: On-site sanitation technologies and the percentage of users in Kampala

Figure 14: Location of waste water treatment plants and landfill in Kampala
Source: Bischoff (2015)

The wastewater from the areas that are connected to sewers is sent to one of the four treatment plants depending on location as can be seen from Figure 14. For those areas where people use on-site sanitation, vacuum trucks empty the sludge and deliver it to either the plant at Bugolobi or Lubigi. However, not all faecal sludge ends up at the treatment plants since there is a significant number of unlined pit latrines which cannot be safely emptied by vacuum trucks (IWMI, 2012). Moreover, some households either cannot afford the costs associated with vacuum truck emptying or their locations are inaccessible so they empty the faecal sludge manually and it ends up in the open environment. In spite of their design capacities, the wastewater treatment plants altogether only receive a total of about 15,000 m^3 of sewage and 600 m^3 of faecal sludge per day on average according to NWSC (Maiteki, 2016).

Table 4: Operational wastewater treatment plants in Kampala City

Location	Design Capacity (m^3/day)		Technology	Effluent Destination
	Sewage	Faecal Sludge		
Bugolobi WWTP	12000		Settling Tanks, Anaerobic Digestion (non-functional), Trickling filters and Unplanted drying beds	Nakivubo Channel & finally Lake Victoria
Lubigi WWTP	5000	400	Thickening tanks, Waste Stabilization Ponds, Unplanted drying beds	Lubigi Channel & finally Lake Victoria
Ntinda WSP	1000		Waste Stabilization Ponds	Ntinda Wetland
Naalya WSP	1000		Waste Stabilization Ponds	Naalya Wetland

3.3.2. *Testing the model*

To optimize the model results for the Kampala case, waste stream characterization data from Kampala was used. This data was obtained from reports and other grey literature from organizations operating in Kampala as well as scientific reports, journal articles and conference proceedings of studies that have been conducted in the city. For parameters where Kampala data was unavailable, substitutes were obtained from literature for similar cities in other low and middle income countries. In some cases, reasonable assumptions based on literature were made to fill the gaps and these were well documented (Appendix 6 – 8).

To test the model for the case of Kampala, two scenarios were modelled; 1) resource recovery based on the waste stream amounts that are currently collected and delivered to treatment facilities and 2) resource recovery based on the potential amounts that could be obtained with improved extensive collection of the three waste streams.

3.3.3. *Scenario 1: Current collection of waste streams*

At the moment, a total of 600 m^3 of FS is collected and delivered to the treatments plants at Bugolobi and Lubigi on average every day according to information from NWSC (Maiteki, 2016). However, data from the KCCA sanitation office which over sees the entire city indicates an amount of 390 m^3 and therefore this figure was used in testing the model. The areas that are connected to the sewer line in Kampala deliver 13,000 m^3 of sewage to the treatment plants at Bugolobi and Lubigi and a total of 2000 m^3 to the plants at Ntinda and Naalya, making a daily total of 15,000 m^3 sewage. At both Bugolobi and Lubigi, FS is treated together with sewage so it is difficult to measure the actual amount of sludge generated from the sewage alone. Considering that these two plants have both primary and secondary treatment processes, estimates were made as follows:

Primary sedimentation typically yields 150 kg of dry solids of sludge per 1000m^3 of sewage while secondary treatment using trickling filters like those used at Bugolobi yields 70 kg of dry solids of sludge per 1000 m^3 of sewage (Tchobanoglous et al., 2003). This would mean a total of 2250 kg dry solids of primary sludge and 1050 kg dry solids of secondary sludge for Kampala, summing up to 3300 kg (3.3 tons) of dry solids per day. Taking a typical total solids concentration of 5% for sludge from primary treatment and trickling filters (Tchobanoglous et al., 2003), the amount of 3.3 tons of dry solids would come from a total of 66 tons of sewage sludge in wet weight.

Of the solid waste that is generated in the city, about 40% is collected and delivered to the landfill at Kiteezi and this amounts to about 946 tons/day on average. Of this amount, 93% is organic MSW which could total up to 880 tons/day. Information from the KCCA sanitation office indicates that the actual amount is closer to 700 tonnes however so this is the figure that was used for testing the model.

3.3.4. *Scenario 2: Increased collection efficiency and coverage for all waste streams*

Of the current amount of faecal sludge which is collected and delivered to the treatment plants (390m^3/day), half comes from households and the other half from institutions like schools, markets, commercial centers and public toilets (Schöbitz et al., 2014). However, about 64% of the households use unlined pit latrines and hence their faecal sludge remains either uncollected since the vacuum trucks cannot pump from unlined pits or it is illegally emptied by manual emptiers. If the faecal sludge from these households is collected and delivered to the treatment plant, the overall total amount collected could be up to 900 m^3/day (Lukooya, 2015), including the amount coming from institutional facilities.

The current amount of sewage that is delivered to the four treatment plants in Kampala comes from a sewer-line coverage of about 6 – 9% (Schöbitz et al., 2014). There are plans to increase this coverage to 30% of the city (NWSC, 2008). Therefore, the current sewage amount of 15,000 m^3/day could potentially increase to 64,000 m^3/day. Using the same estimates of sewage sludge as for the first scenario, this would mean a daily total of 282 tons of sewage sludge in wet weight.

As far as the solid waste is concerned, the current amount collected and delivered to Kiteezi landfill is only about 40% of what is generated in the city. If collection covered 100% of what is generated, this amount could potentially reach 2,365 tonnes/day (Komakech, 2014). The organic component (93%) could amount to 2,199 tons/day.

3.3.5. *User feedback*

Following these two scenarios, the model was shared with staff from the Environmental Sanitation Department at the Kampala Capital City Authority. They tested the model and put in their own data on waste stream flows (390m^3/day of faecal sludge and 700 tonnes of organic MSW) and provided feedback on their experience. Their detailed responses are included in Appendix 1.

4. RESULTS AND DISCUSSION

In this section, the results from applying the model to the city of Kampala are presented and discussed in detail. A discussion of the key aspects of the model is also presented.

4.1. Results from Kampala

The full view of the model results from testing with Kampala data are shown in Appendix 3 – 5. A summary of the average amounts of the various products that could be obtained from all three waste streams combined is also shown in Table 5. It shows the products that could be obtained from the waste streams that are currently collected (scenario 1) as well as what could be obtained with increased collection efficiency and coverage (scenario 2).

4.1.1. *Scenario 1: Resource recovery based on current collection.*

Based on the average amounts of waste streams currently collected in a day (390 m^3 of faecal sludge, 66 tonnes of sewage sludge and 700 tonnes of organic municipal solid waste), it was found using the model that Kampala could generate a total of 115,495 Nm^3 of biogas if all the daily amounts of the waste streams were treated with anaerobic digestion. These same amounts of waste streams would also generate about 118 tonnes of AD residues that can be used as soil conditioner/fertilizer, and altogether, the biogas and residue could generate daily revenues amounting to US$38,700. Alternatively, the amount collected daily from the three waste streams could generate a total of 241 tonnes of solid combustion fuel with an energy content of 3700 GJ. This is much higher than the energy content that would be realized from the biogas (2500 GJ).

Table 5: Average amounts of products that could be obtained from the daily collection of all waste streams in Kampala, assuming that the waste is used for one recovery option only.

Resource recovery options	Current daily collection (Scenario 1)				Potential daily collection (Scenario 2)			
	Faecal Sludge (390 m^3)	Sewage Sludge (66 tonnes)	Organic MSW (700 tonnes)	Total	Faecal Sludge (900 m^3)	Sewage Sludge (282 tonnes)	Organic MSW (2199 tonnes)	Total
Biogas (Nm^3)	3379	1087	111029	**115495**	7798	4644	348790	**361231**
Solid Combustion Fuel (tonnes)	13	4	225	**241**	30	16	706	**752**
Black Soldier Fly Prepupae (tonnes)	3	1	60	**64**	7	4	187	**198**
Soil conditioner (tonnes)	16	4	272	**292**	36	19	854	**909**

If used for breeding black soldier fly prepupae, the three waste streams would altogether yield a daily total of 64 tonnes of BSF prepupae along with 170 tonnes of residue which can be used as soil conditioner on farmland. This could altogether generate daily revenues amounting to US$13,500. If all three waste streams were composted to make soil conditioner, they would generate a total of 292 tonnes of soil conditioner with potential revenues of US$1,460 daily.

It should be noted once again that the results from the model represent mutually exclusive scenarios i.e. using the whole daily amount of the waste stream for one resource recovery product at a time.

4.1.2. *Scenario 2: Increased collection efficiency and coverage*

For this scenario, it was found based on the model calculations that Kampala could generate a total of 361,000 Nm^3 of biogas from their daily collection of faecal sludge (900 m^3/day), sewage sludge (282 tonnes/day) and organic municipal solid waste (2,199 tonnes/day). This would be produced together with 367 tonnes of residue that can be used as soil conditioner or fertilizer and in total, the biogas and residue could generate daily revenues amounting to US$121,000. Alternatively, the daily collection of the three waste streams could also generate a total of 752 tonnes of solid combustion fuel with an energy content of 11,657 GJ. This is much higher than the energy content that would be realized from the biogas in this scenario (7803 GJ).

If used for breeding black soldier fly prepupae, the three waste streams would altogether yield a total of 198 tonnes of BSF prepupae along with 526 tonnes of residue which can be used as soil conditioner on farmland. This could altogether generate daily revenues amounting to US$42,200. If all the three waste streams were composted to make soil conditioner, they would generate a total of 909 tonnes of soil conditioner with potential revenues of US$4,500 daily.

4.1.3. *Potential revenues from resource recovery in Kampala*

It can be seen from the graphs in the model (Figures 15 to 20) that the greatest potential revenues would come from using the various waste streams to make solid fuel for combustion. This is generally in agreement with Diener et al. (2014) who found that in the three African cities of Accra (Ghana), Dakar (Senegal) and Kampala (Uganda), the greatest financial value from the reuse of faecal sludge would come from using it to generate energy. The graphs also revealed that using any of the waste streams only for making soil conditioner (through composting) would generate the least revenues at the point of sale. Again, this also confirms similar findings made by Diener et al. (2014). It is important to note that this comparison only considers revenues from sales of the products at prevailing local prices of compost, and not the equivalent value in chemical fertilizer. It also does not take into account the revenues that would accrue from the increased crop yields of applying waste-derived soil conditioner/fertilizer on agricultural land.

However, if the effects of using each of these end products is taken into consideration, the comparison might change dramatically. For example, it has been demonstrated that increases in the crop yield from using excreta-based fertilizers could be up to 30% (Warman and Termeer, 2005; Ekane, 2010). About 60% of the food consumed in Kampala is grown in and around the city (IWMI, 2012; Sabiiti et al., 2014) and this implies that such an increase in yield would be of great value to the city's farmers. Considering the value of the potential increases in agriculture yields would of course imply that the effects of using the other products also has to be considered so as to have an objective comparison, for example the increase in livestock yields from using black soldier fly prepupae as protein feed.

Excreta-based compost often has a low market value (Diener et al., 2014) and in some cities in Sub-Saharan Africa, the price that farmers are willing to pay would be insufficient to cover the costs associated with composting itself (Strande et al., 2014). However, if the actual fertilizer value of the compost were calculated basing on market prices for the equivalent chemical fertilizer.

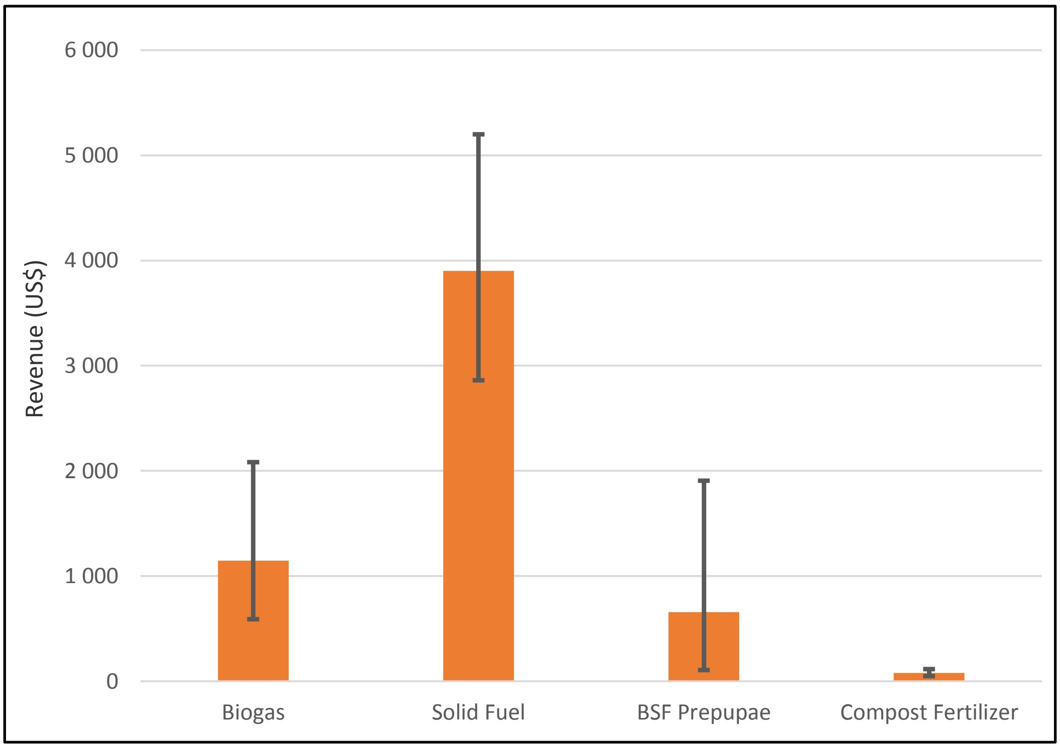

Figure 15: Potential revenues from resource recovery using the current daily collection of faecal sludge (Scenario 1 – 390 m³).
The columns indicate the typical values expected while the error bars indicate the minimum and maximum values possible.

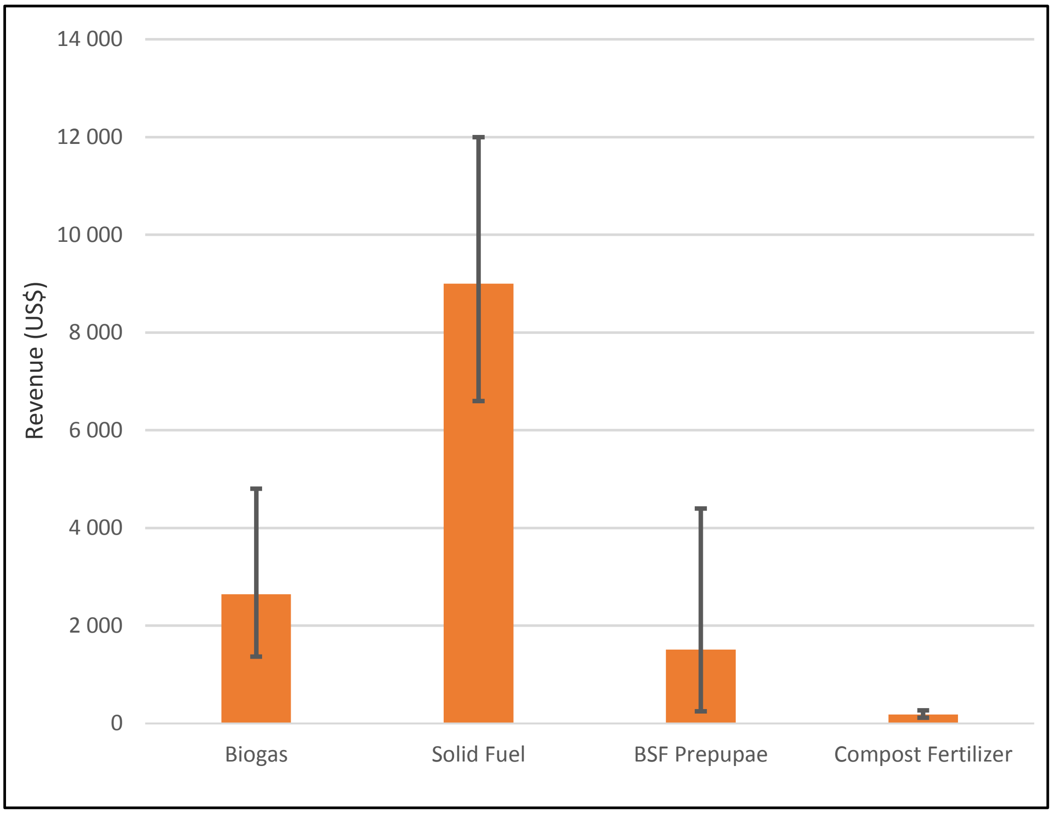

Figure 16: Potential revenues from resource recovery using the potential daily collection of faecal sludge (Scenario 2 – 900 m³)

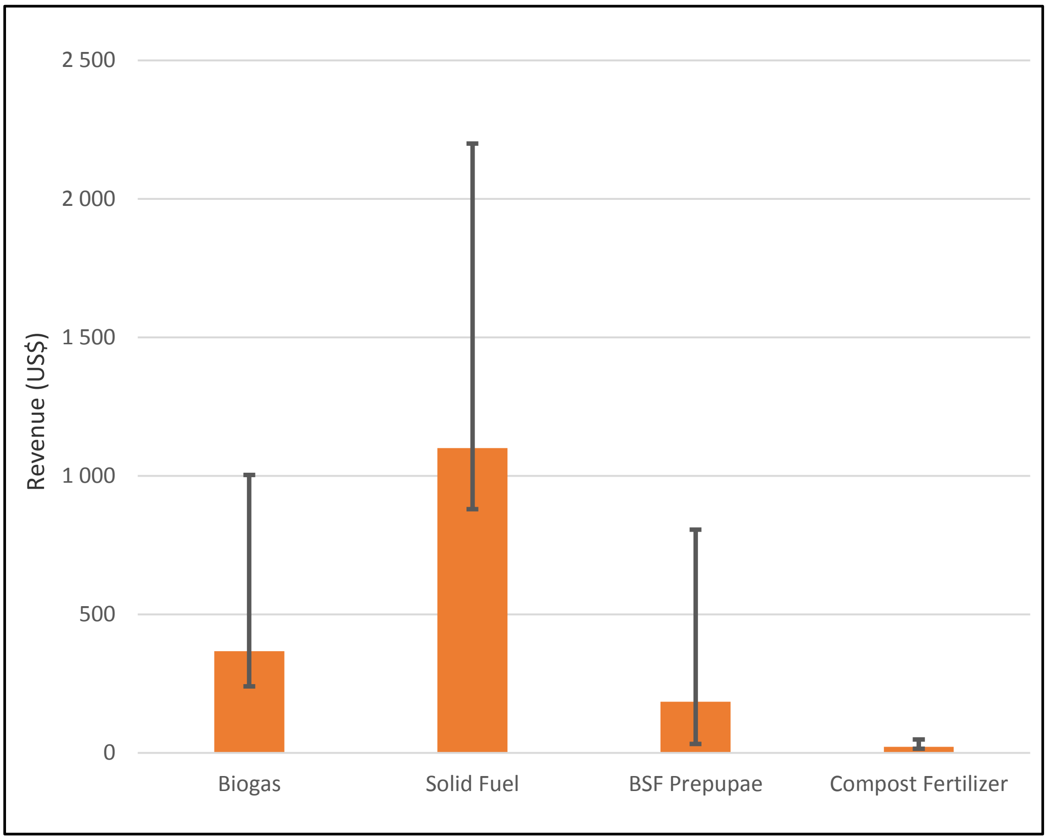

Figure 17: Potential revenues from resource recovery using the current daily generation of sewage sludge (Scenario 1 – 66 tonnes)

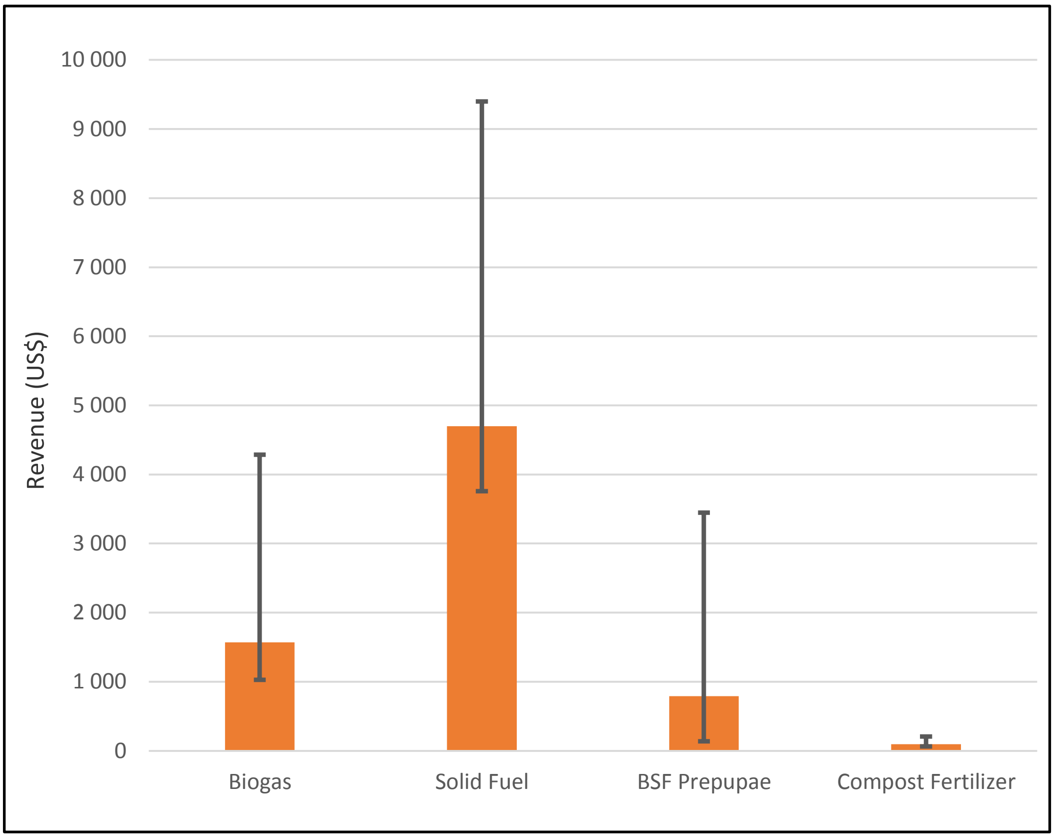

Figure 18: Potential revenues from resource recovery using the potential daily generation of sewage sludg***e (Scenario 2 – 282 tonnes)***

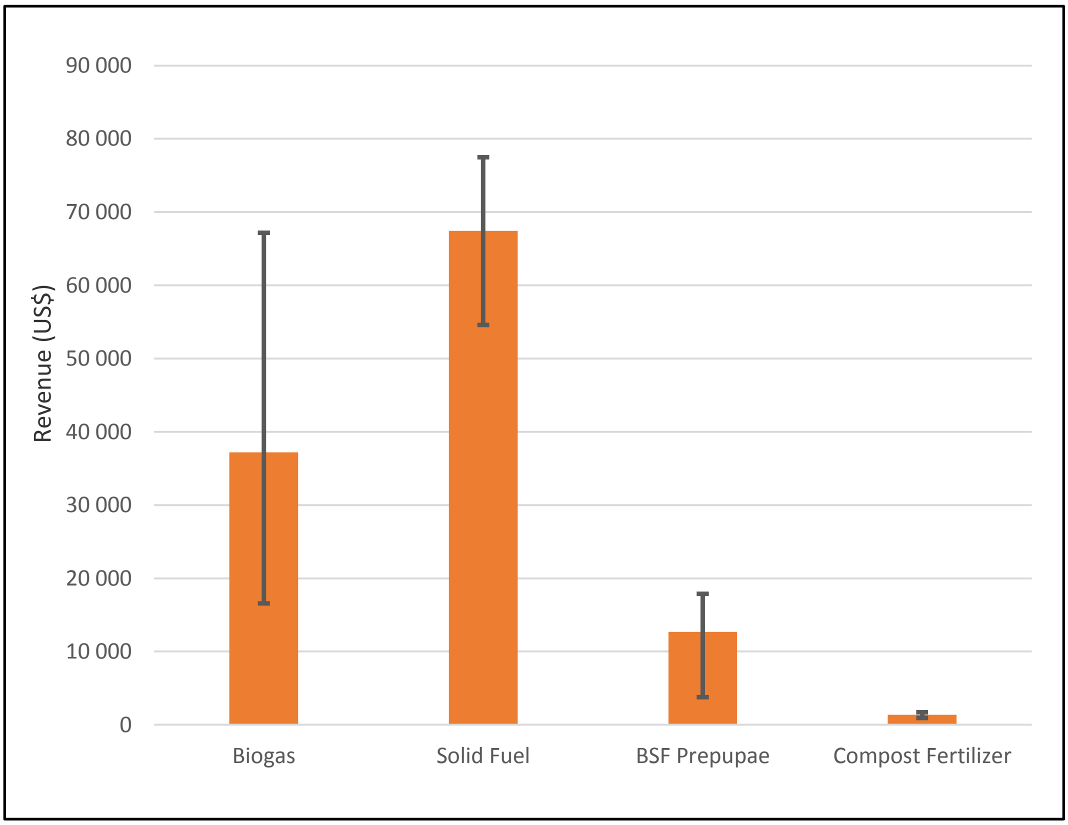

Figure 19: Potential revenues from resource recovery using the current daily collection of organic MSW (Scenario 1 – 700 tonnes)

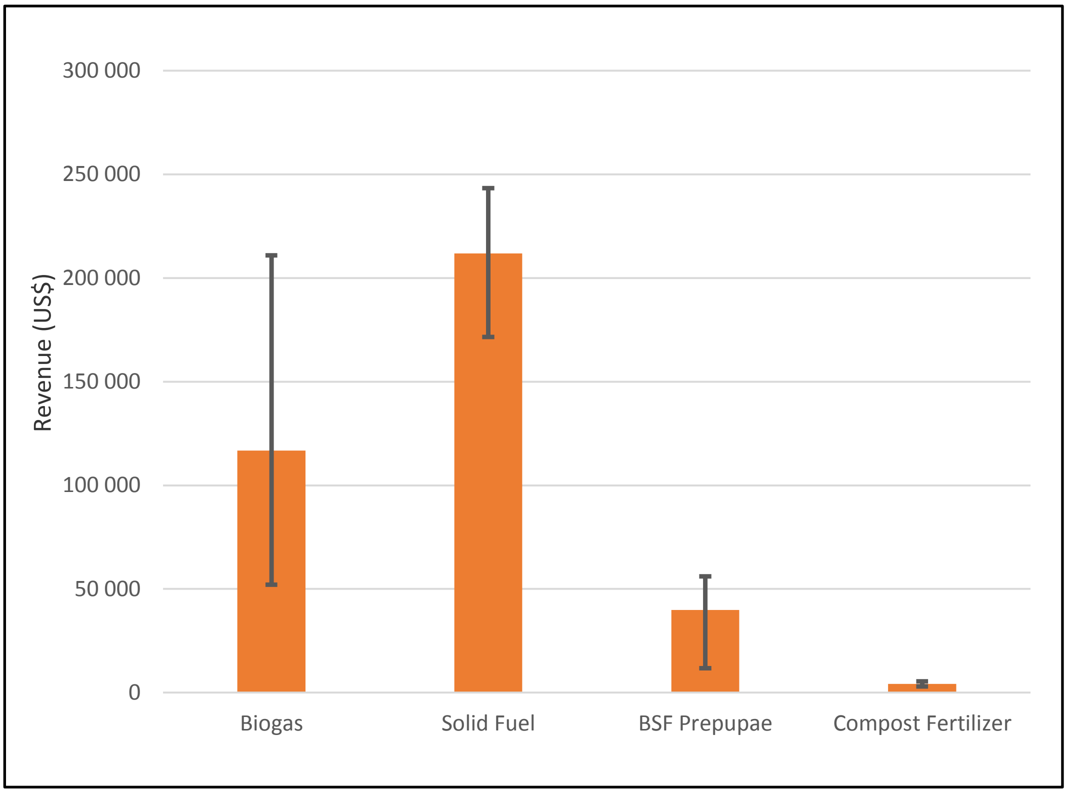

Figure 20: Potential revenues from resource recovery using the potential daily collection of organic MSW (Scenario 2 – 2199 tonnes)

In Uganda, urea which is one of the most commonly used fertilizers is sold at about US$718 per tonne (Zorya et al., 2011) and it has a nitrogen content of 45% (Mitchell, 1999). If the nitrogen content in urea (450 kg/tonne of fertilizer) is valued at that price of US$718, then every tonne of nitrogen within urea would be valued at US$1,596. The current daily collection of the three waste streams, if composted, can generate about 292 tonnes of soil conditioner/fertilizer with a nitrogen content of 0.90 tonnes.

Based on the value of nitrogen in urea, the nitrogen in this faecal sludge-based fertilizer alone would be worth US$1,436, not considering the rest of the nutrients therein. This shows that if the soil conditioner is valued based on its nutrient content and not just the prevailing local price that farmers are willing to pay, it could command much higher revenues. Though this would be advantageous to those selling the soil conditioner, it would eliminate many farmers who would not afford the high prices if they reach levels similar to the prices of chemical fertilizers. High price is one of the major factors that is restricting the consumption of chemical fertilizers among Ugandan farmers (Zorya et al., 2011).

4.1.4. *Energy recovery from the waste streams in Kampala*

From the graphs generated in the model (Figures 21 to 26), it can also be seen that using the various waste streams to make solid fuel for combustion would generate the most energy value. In Uganda, biomass accounts for over 90% of the energy consumed countrywide and in Kampala itself, over 78% of the population relies on woody biomass for cooking (World Bank Group, 2015). The same situation applies to the rest of Sub-Saharan Africa where 90-100% of the household energy demand is for cooking and 75% of that is from firewood (Smith, 2011). In urban areas, the per capita consumption of firewood and charcoal is

240 kg/year and 120 kg/year respectively. This has greatly contributed to a huge loss of forest cover in the country, about 55,000 hectares lost per year, mainly due to the increasing demand for woody biomass (International Resources Group, 2006). Considering that the woody biomass demand and supply balance was estimated to move into an acute deficit of 10.7 million tonnes/year by 2016 (MEMD, 2012), it makes sense to consider the substitution of firewood and charcoal with solid fuels derived from sanitary wastes.

According to Strande et al. (2014), 1 Nm^3 of biogas has the energy equivalent of 1.5 kg of firewood. The amount of biogas that could potentially be generated per day could substitute 173 tonnes of firewood based on the current collection scenario and 542 tonnes of firewood based on the scenario of improved collection. These are the amounts of firewood which meet the energy needs of 263,472 and 824,100 people in the city daily, respectively. A few biogas digesters connected to pit latrines have recently been built in some households in the Bwaise area and public schools like Mengo Primary School, all in Kampala (IWMI, 2012). KCCA is planning to construct more of these in other schools. This confirms that the city authorities realize the potential of resource recovery through biogas and its benefits.

Furthermore, based on the calorific value of firewood – 16 MJ/kg TS (Diener et al., 2014), the output of solid fuel that could be generated from the three waste streams combined could substitute for about 231 tonnes of firewood based on the current collection scenario and 729 tonnes of firewood based on the scenario of improved collection. These are the firewood amounts used by 351,331 people and 1,108,745 people daily, respectively. This implies that with improved collection efficiency and coverage for all the three waste streams, the energy demand for cooking for at least half of the day-time population of Kampala could be met through energy recovery.

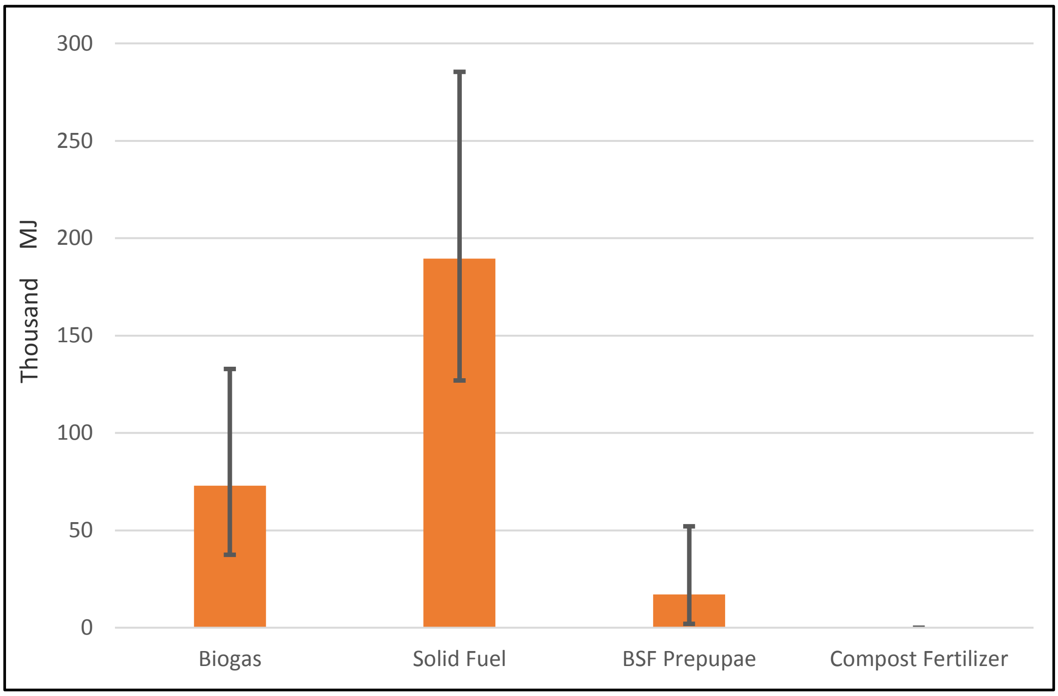

Figure 21: Potential energy content from resource recovery using the current daily collection of faecal sludge (Scenario 1 – 390 m^3).
The columns indicate the typical values expected while the error bars indicate the minimum and maximum values possible.

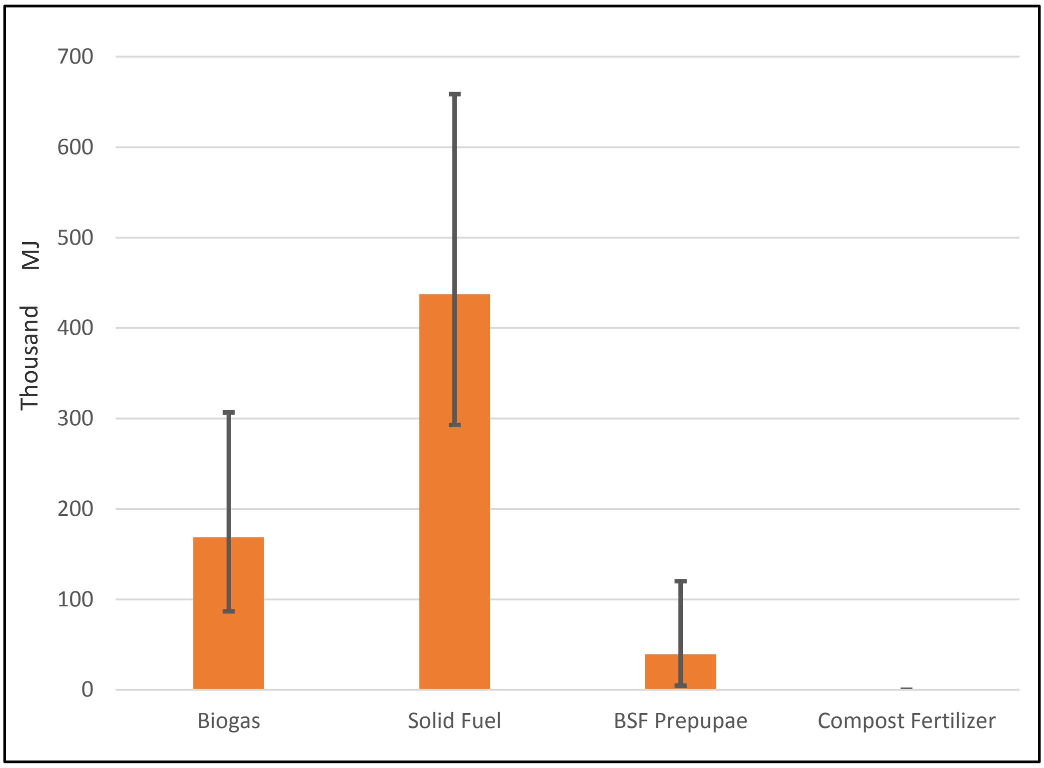

Figure 22: Potential energy content from resource recovery using the potential daily collection of faecal sludge (Scenario 2 – 900 m³)

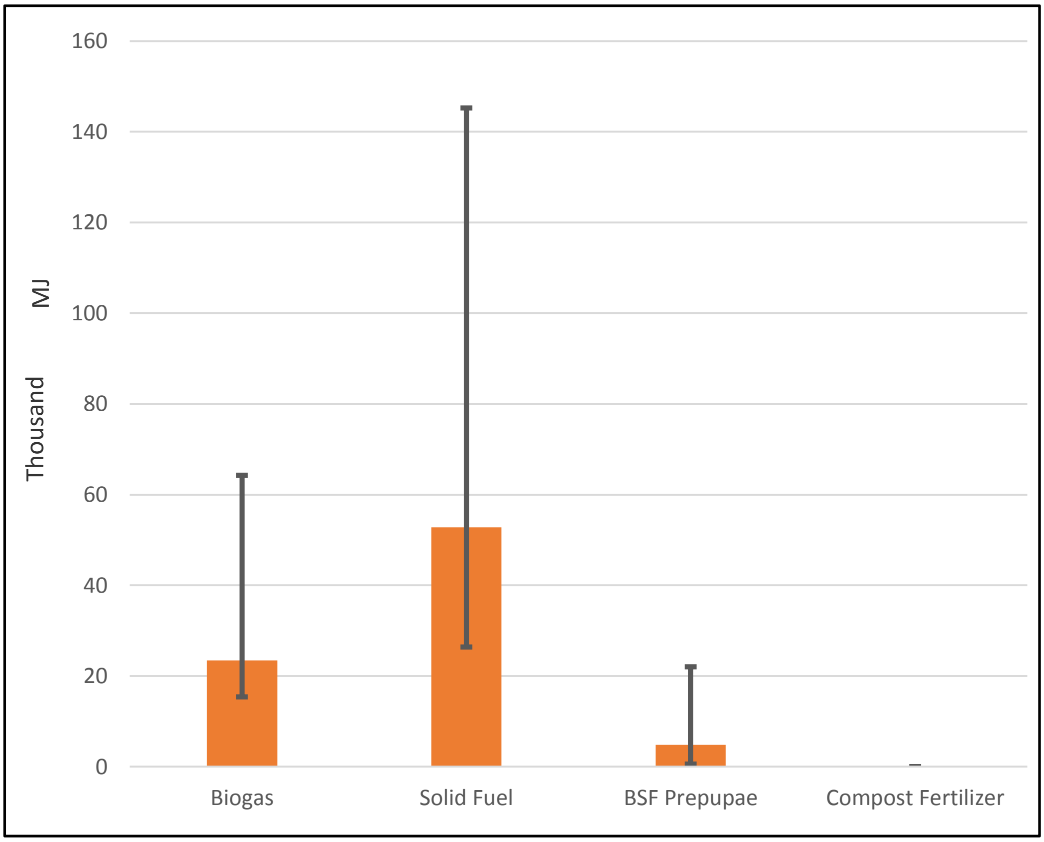

Figure 23: Potential energy content from resource recovery using the current daily generation of sewage sludge (Scenario 1 – 66 tonnes).

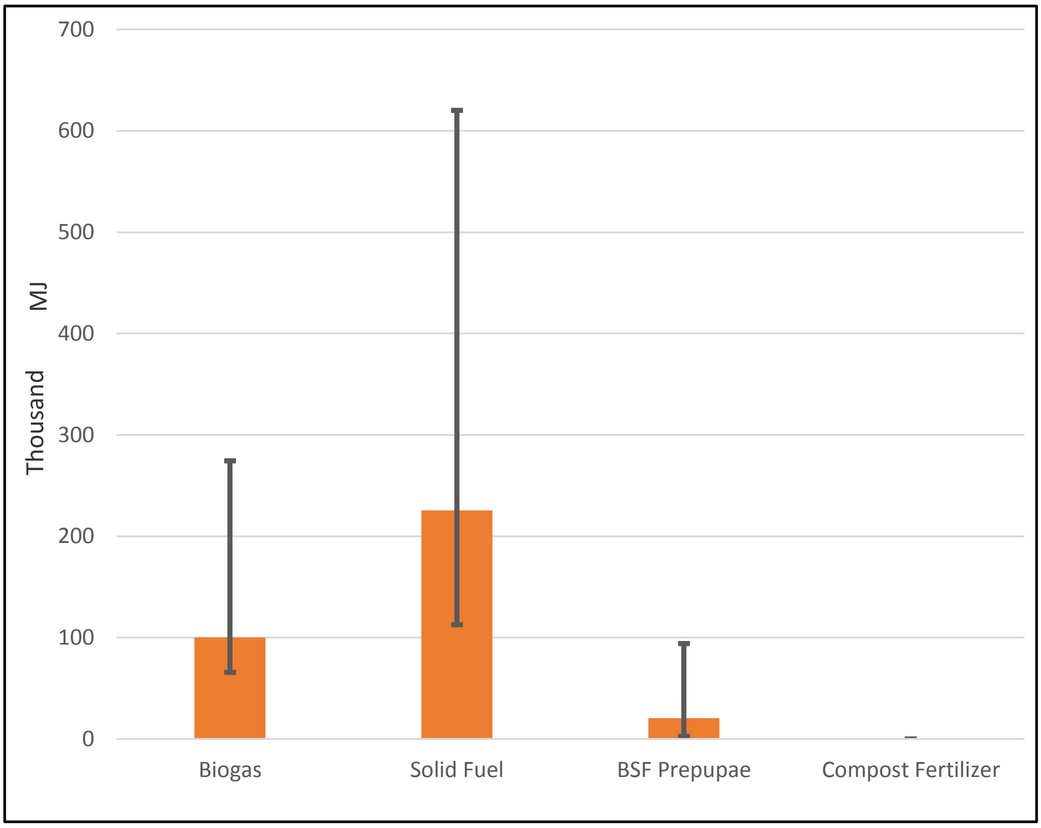

Figure 24: Potential energy content from resource recovery using the potential daily generation of sewage sludge (Scenario 2 – 282 tonnes)

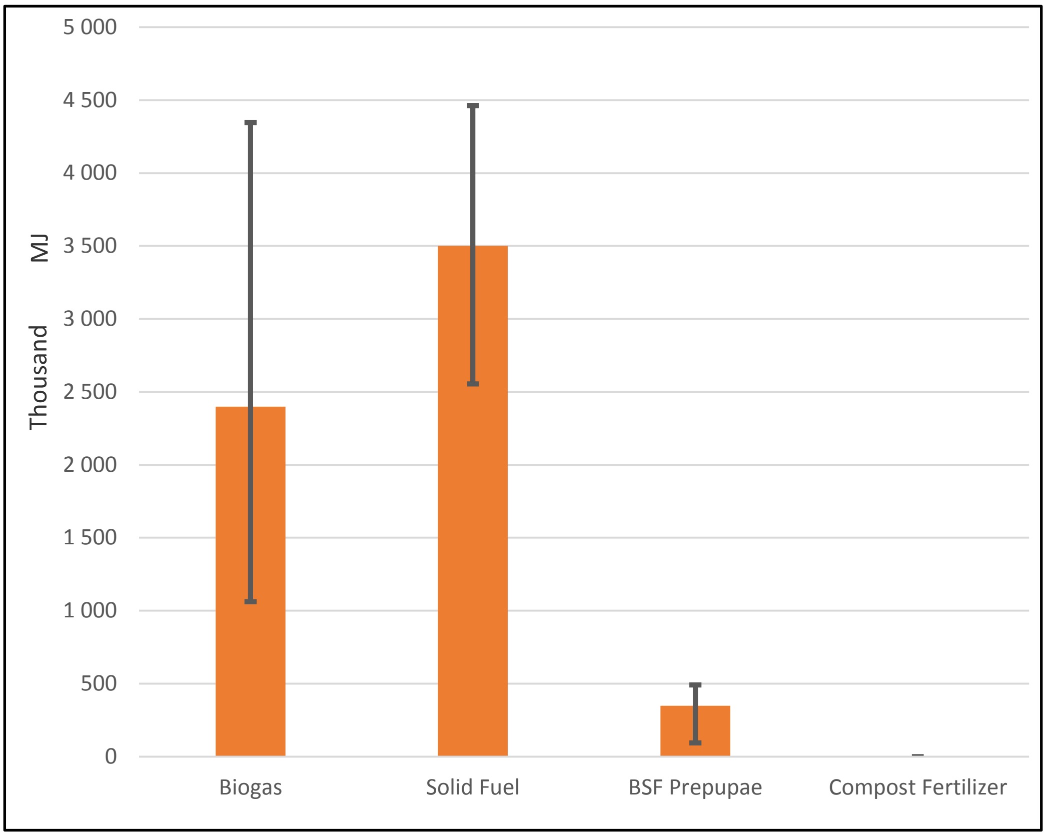

Figure 25: Potential energy content from resource recovery using the current daily collection of organic MSW (Scenario 1 – 700 tonnes).

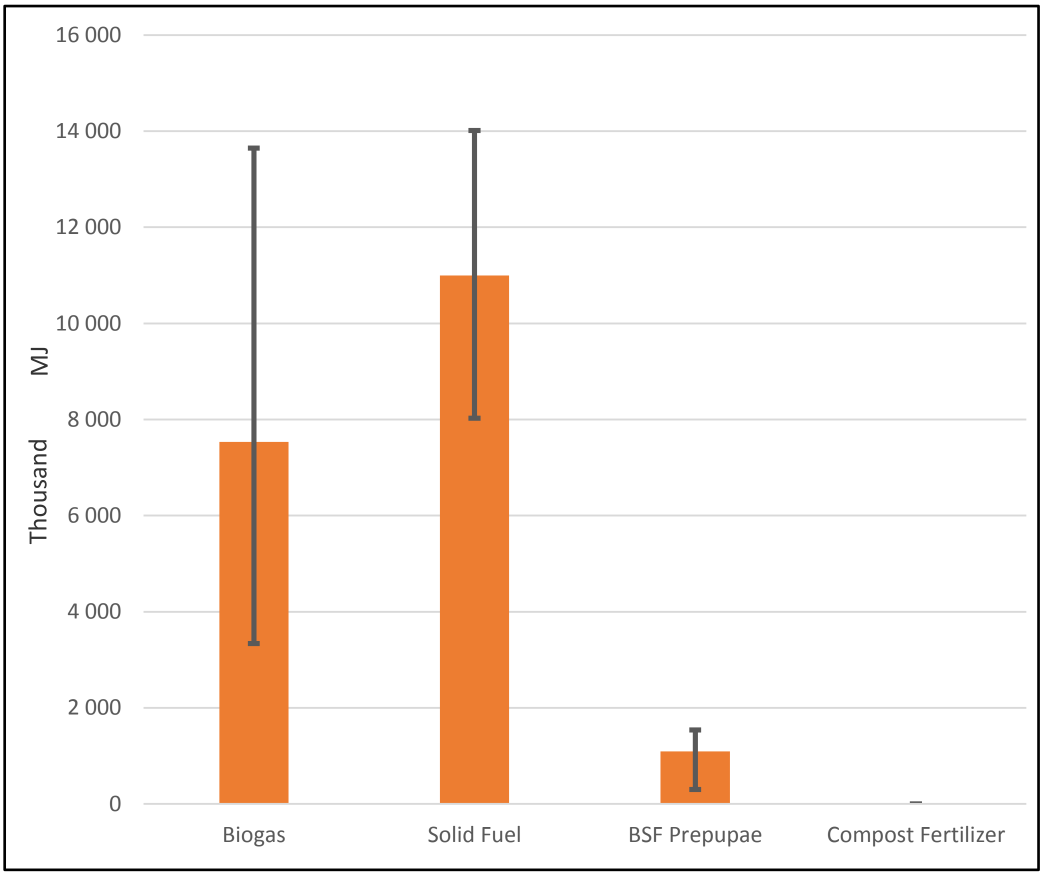

Figure 26: Potential energy content from resource recovery using the potential daily collection of organic MSW (Scenario 2 – 2199 tonnes)

4.1.5. *The potential for recovery of animal protein feed in Kampala*

From the model, it can be seen that using the three waste streams to generate animal protein through black soldier fly prepupae would result in 64 and 198 tonnes of black soldier fly prepupae per day for the two scenarios respectively. In Kampala, farmers mix animal feed including small dried fish to provide protein. Dried fish consists of 60% protein (Diener et al., 2014) and therefore with the BSF prepupae's protein content of 40%, 1 tonne of dried fish can be substituted with 1.5 tonnes of BSF prepupae. The potential amounts of BSF prepupae of 64 tonnes and 198 tonnes from the two scenarios respectively could substitute about 43 tonnes and 134 tonnes of dried fish, from the current daily collection of the three waste streams and from the potential increased daily collection, respectively. Considering that there is overfishing in lakes and marine areas, BSF prepupae could be a viable alternative to dried fish in animal feed. A few species of insects are already being used in making animal feed in Uganda (van Huis et al., 2013) and the Food and Agriculture Organization of the United Nations (FAO) has also recognized and enumerated a list of insects that can be used for animal feeds, among which BSF lies (Banks, 2014).

In Kampala, no farmers are using BSF yet but there are pilot projects by Water for People turning faecal sludge into protein feed and training of entrepreneurs in the technology (Atwijukye, 2016). This implies that there is potential for this to pick up. In South Africa for example, the company AgriProtein has set up full-scale facilities to convert sanitary waste streams into protein and fat for animal feed as well as fertilizer using black soldier fly composting (Mutafela, 2015).

If the fat content in the BSF prepupae from all the three waste streams combined is used to make biodiesel, it would result in a total energy value of 370 GJ and 1,152 GJ from the two scenarios of the daily waste stream collection and the potential increased daily collection in the future, respectively. This is obviously too little compared to the energy value that could be harvested through the option of solid fuel or biogas. The viability of using black soldier fly prepupae to make biodiesel is still debatable and the technology has not yet matured (Green, 2014). For that reason, it might not make sense therefore to pursue the generation of biodiesel from the waste streams in place of the biogas and solid fuel options.

4.1.6. ***The potential of nutrient recovery in Kampala***

In Kampala, a number of farmers are already using sewage sludge from the wastewater treatment plants at Bugolobi and Lubigi for application to their farmland (Diener et al., 2014). This implies that there is already a market for soil conditioner as a product. While this is an example of a centralised plant for generating soil conditioner, there are also many households that make compost from their organic solid waste as well as other waste streams like manure and slaughterhouse waste (IWMI, 2012). This indicates that there is potential for soil conditioner as a product, with increased efficiency in the collection of the various waste streams.

As previously described, urea is one of the most common chemical fertilizers in Uganda and it has a nitrogen content of 45%. Considering that there is 0.9 tonnes of nitrogen in the 292 tonnes of daily compost derived from the three waste streams combined (Figures 27 to 32), this could substitute 2 tonnes of urea valued at about US$1436. This calculation does not take into account the provision of organic matter to the soil by the sanitary waste-derived compost, a quality that chemical fertilizers do not have. However, there is competition for the organic waste from those that would prefer to use it as animal feed. Many households feed their cattle, goats and other domestic animals with peelings from bananas, potatoes and cassava, among other sources (IWMI, 2012). No comprehensive data have been found on the extent of this practice in Kampala but it is nevertheless important to consider the trade-offs between these two uses of organic solid waste (mainly food waste).

From the graphs in the model (Figures 26 – 31), it can be seen that the greatest amount of nutrients lies in faecal sludge and the least amount is in organic municipal solid waste. Since the biggest portion of the nutrients in faecal sludge and sewage sludge is nitrogen while the biggest percentage of nutrients in organic solid waste is potassium, it makes sense to co-compost all the waste streams together so as to optimize the amount of nutrients in the final compost obtained. If the waste streams are to be treated separately, then it would be appropriate for faecal sludge to be used for nutrient recovery while organic solid waste is used for other purposes like energy recovery. However, the organic solid waste is still valuable for use as a soil conditioner because of its organic matter content.

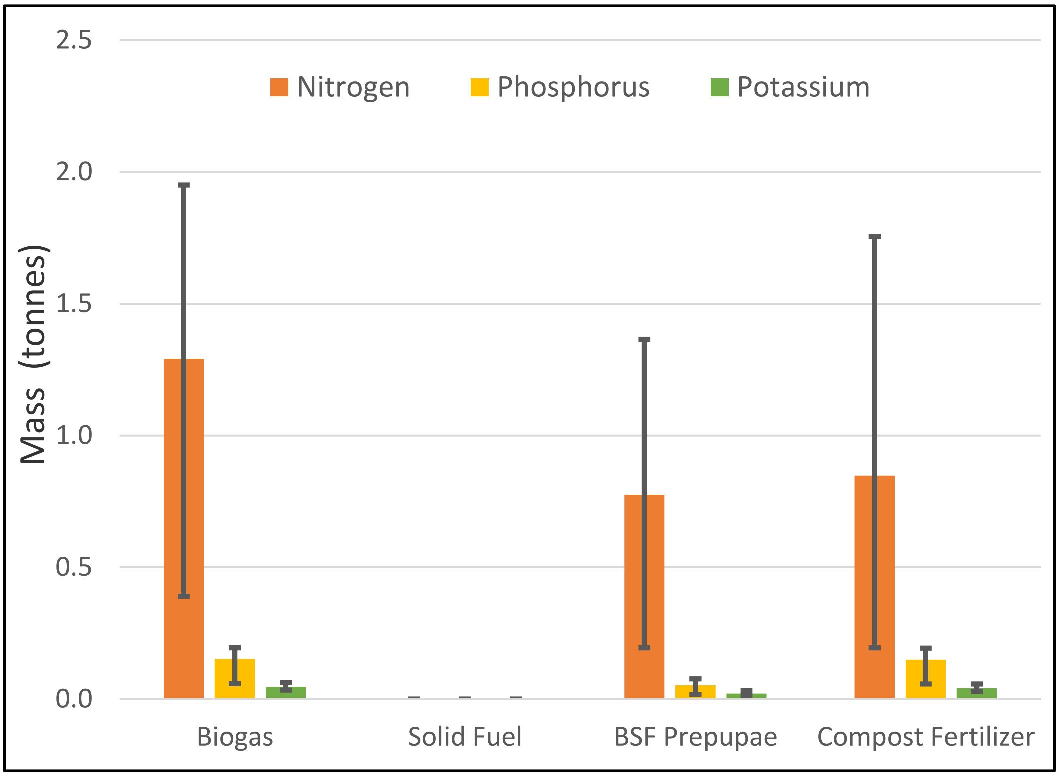

Figure 27: Potential nutrient content from resource recovery using the current daily collection of faecal sludge (Scenario 1 – 390 m³). The columns indicate the typical values expected while the error bars indicate the minimum and maximum values possible.

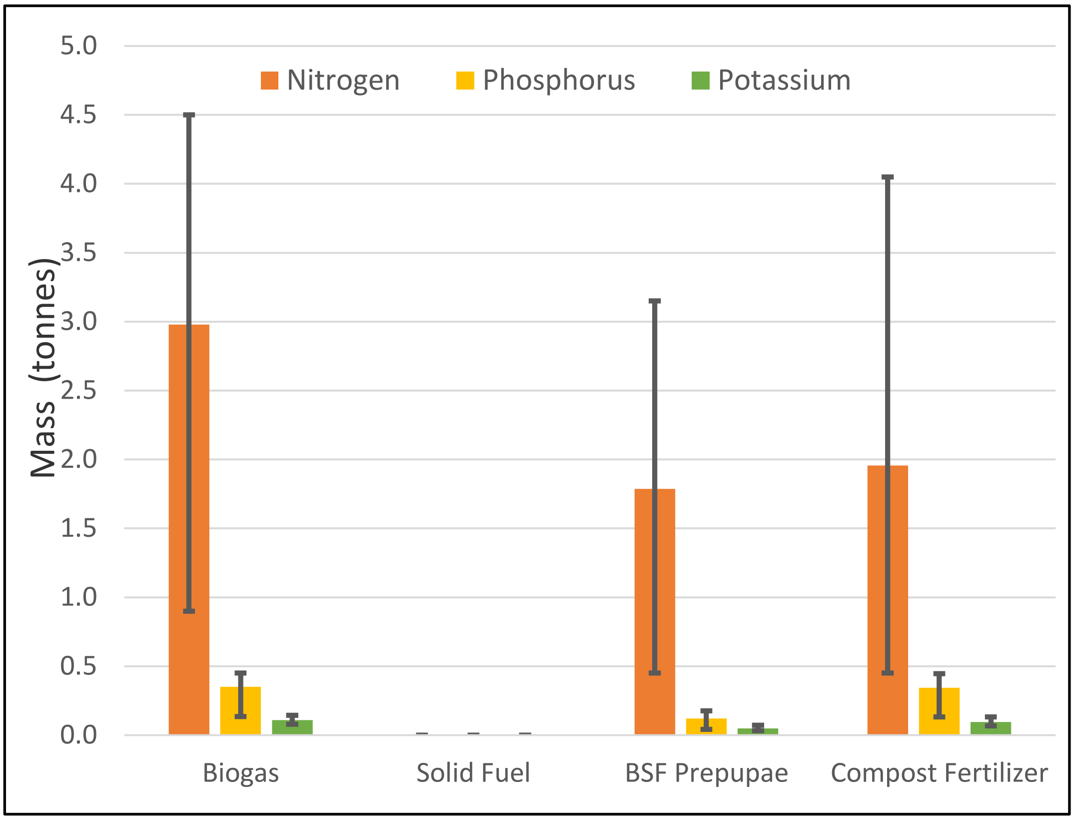

Figure 28: Potential nutrient content from resource recovery using the potential daily collection of faecal sludge (Scenario 2 – 900 m³)

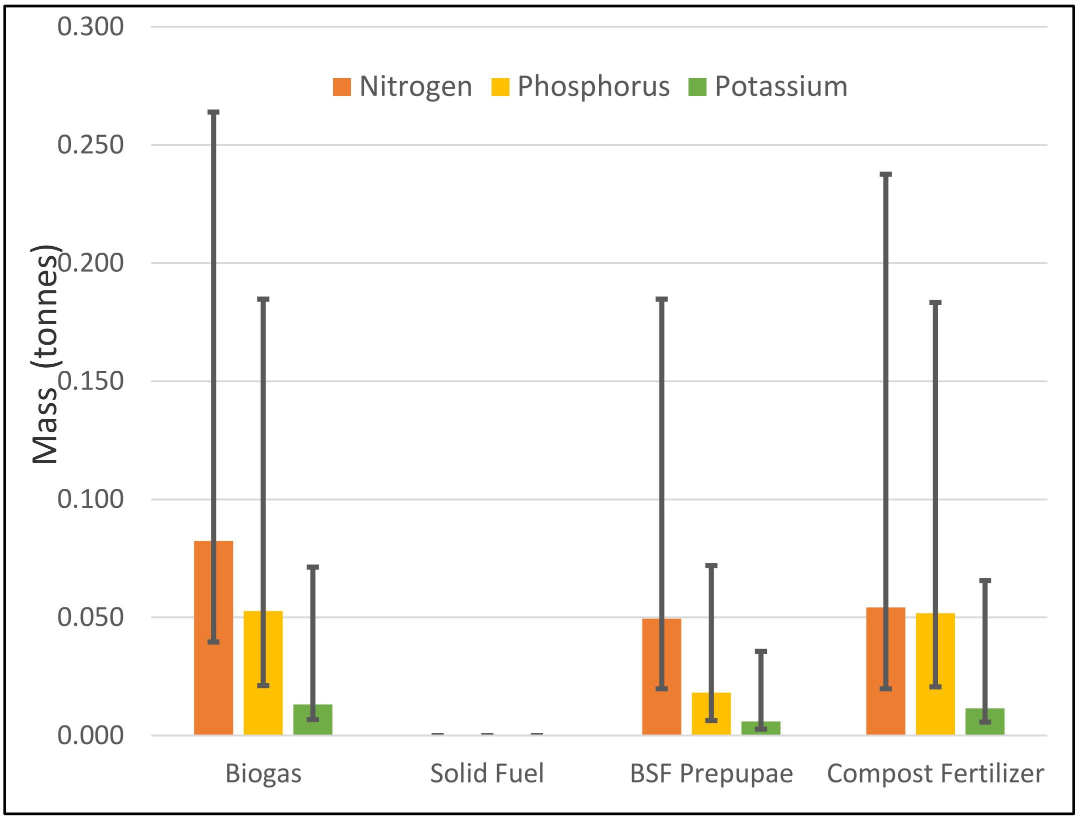

Figure 29: Potential nutrient content from resource recovery using the current daily generation of sewage sludge (Scenario 1 – 66 tonnes)

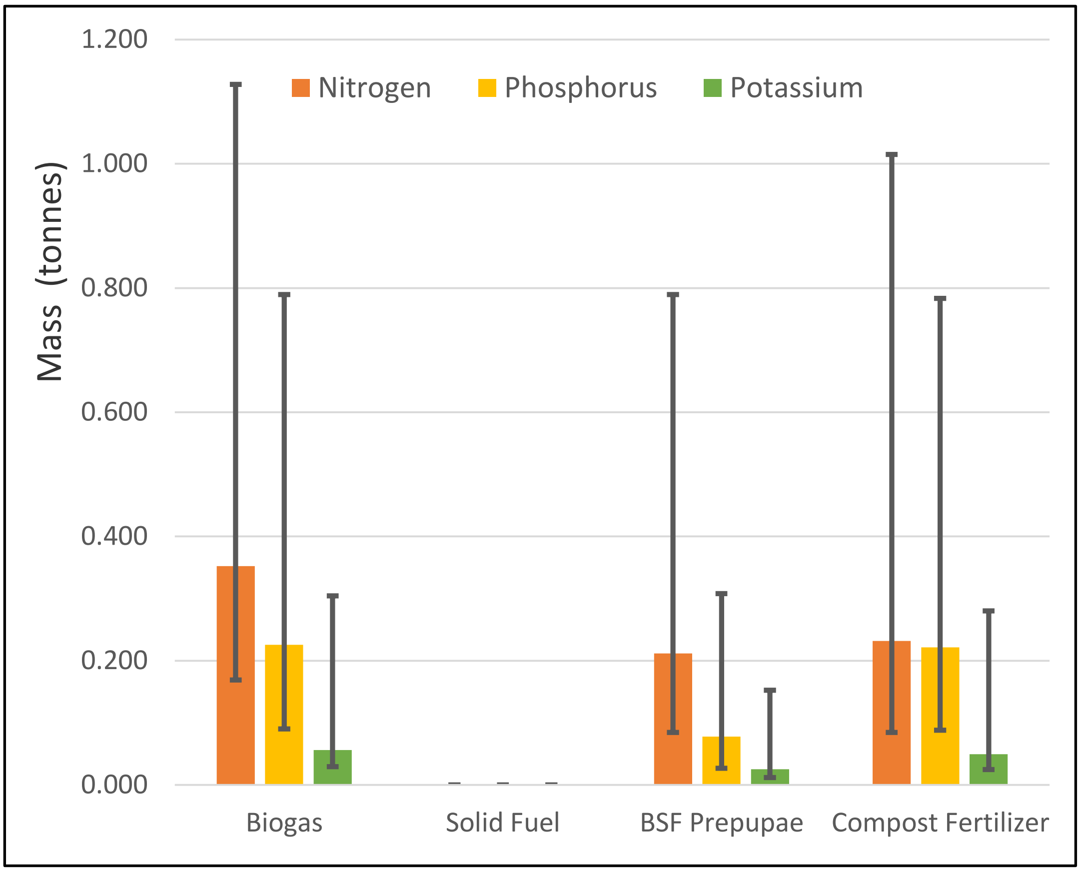

Figure 30: Potential nutrient content from resource recovery using the potential daily generation of sewage sludge (Scenario 2 – 282 tonnes)

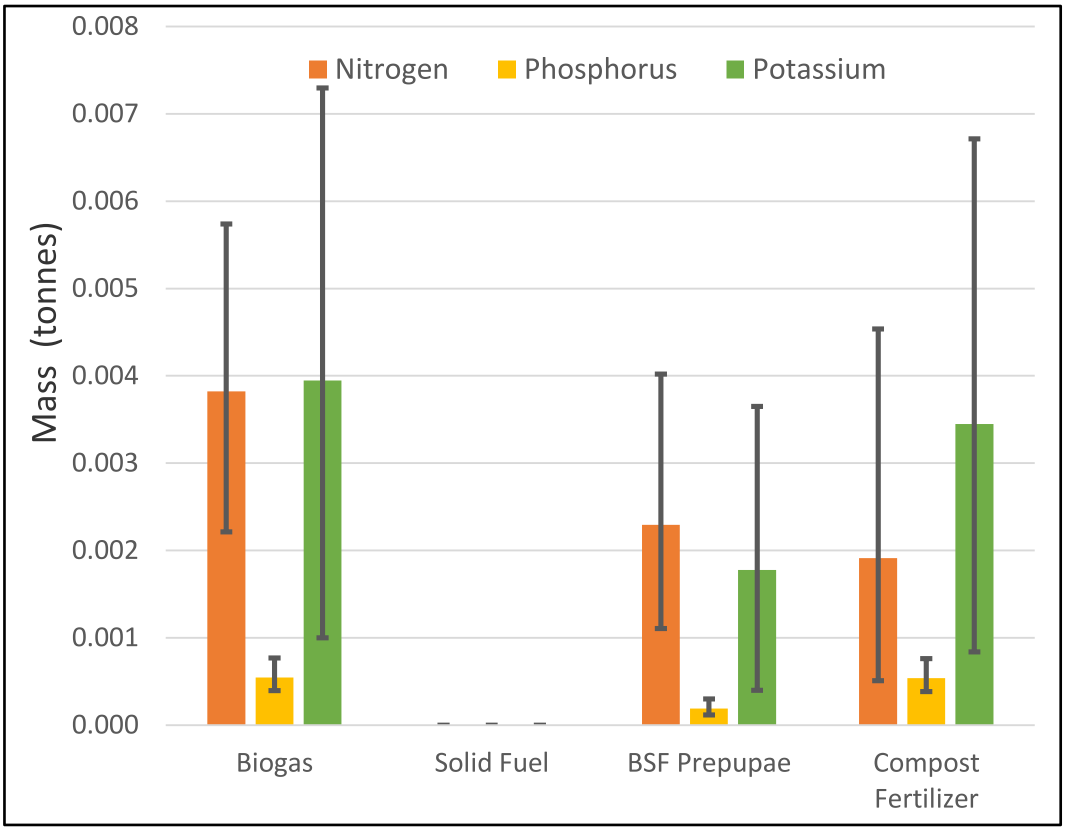

Figure 31: Potential nutrient content from resource recovery using the current daily collection of organic MSW (Scenario 1 – 700 tonnes)

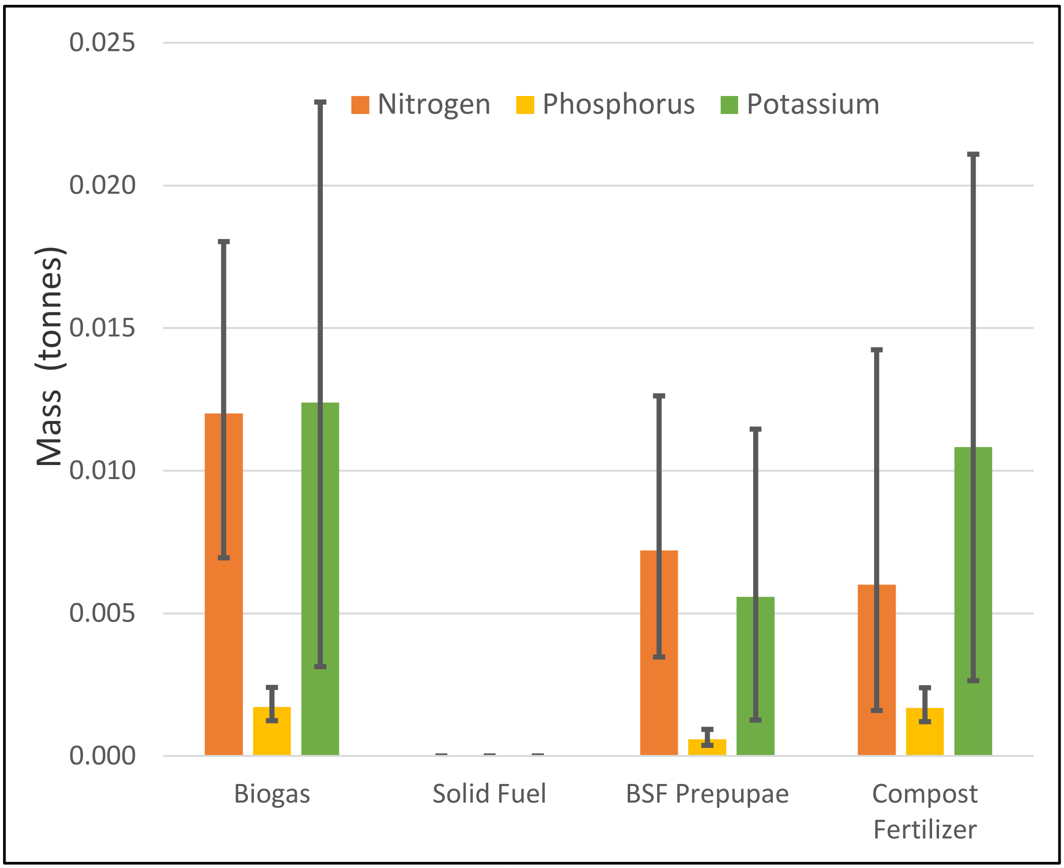

Figure 32: Potential nutrient content from resource recovery using the potential daily collection of organic MSW (Scenario 2 – 2199 tonnes)

4.1.7. ***Current resource recovery practices in Kampala***

To some extent, there a quite a number of efforts at resource recovery from sanitary and organic wastes being taken in Kampala at all levels of stakeholders. Currently, the effluent from the Lubigi and Bugolobi WWTPs ends up in Lake Victoria while the sludge is dried and sold at about US$ 5/tonne or more, to farmers who use it as soil conditioner. There are also private groups that use some of the sludge at the Lubigi plant to make briquettes. However, briquettes in the city are mostly made from a mixture of crop residues and charcoal dust and this is done by several upcoming small companies. In the Naalya area, farmers nowadays divert the effluent from the waste stabilization ponds into their nearby gardens for irrigation (Schöbitz et al., 2014).

As far as solid waste management is concerned, the city operates one major landfill at Kiteezi where all the solid waste that is collected is dumped. Solid waste collection is the mandate of KCCA but they are only able to collect about 40% of the total solid waste generated in the city. There are informal groups of waste pickers who go through the collected solid waste to salvage paper, plastics and metals which they deliver to private recycling plants in the city in exchange for cash. There is no centralised resource recovery from the organic waste portion of the solid waste which is about 93% of what is collected and delivered to the landfill every day.

There are some households that use their organic solid waste to make briquettes or to make compost for their gardens. Others use their organic waste together with animal manure to generate biogas for household lighting and cooking. There are also a number of schools that have started setting up biogas digesters connected to latrines (IWMI, 2012).

4.1.8. ***Implications of the model results for the city of Kampala***

From Table 5, it can be seen that there is great potential for resource recovery from the organic solid waste amounts in Kampala, especially for energy recovery. This is simply because the volumes of solid waste that are generated in the city are far greater than the volumes of the other two waste streams. It also implies that for efficient resource recovery, the majority of efforts at the moment have to be geared towards the organic solid waste fraction so as to have more efficient collection as well as separation already at the source to reduce the concentration of other contaminants or foreign objects in the waste stream. The potential for protein recovery for animal feeds using BSF larvae composting is also greatest from the organic MSW and this is mainly due to the volumes of waste that are available and can be processed.

As far as nutrients are concerned, the highest potential for resource recovery lies in the faecal and sewage sludge because of their high nutrient concentration. Where appropriate, co-composting with organic solid waste can be done to take advantage of the organic matter content therein. The results from the model could actually be an incentive for increased collection of solid waste in the city so as to facilitate resource recovery.

Unfortunately, it wasn't possible to compare all these results with actual data from existing resource recovery projects in Kampala because there is insufficient data on the scale of resource recovery at the moment (Appendix 1). In addition, there is no existing centralized resource recovery plant apart from the use of dried faecal sludge and sewage sludge at the existing wastewater treatment plants for soil conditioner. An extensive and comprehensive calibration for the model could therefore not be performed. While there are composting plants for organic solid waste in at least 17 other municipalities in Uganda, there is none in Kampala itself (IWMI, 2012). Most of the other resource recovery options are implemented at small scale within households or institutions like schools. This makes it hard to acquire exact data on the extent of resource recovery in the city but there are efforts being made to bridge this data gap according to information from KCCA (Appendix 1).

4.2. Discussion on the features of the Model

Looking at the model structure and the various features therein, a number of issues can be pointed out that affect the model output. These are discussed in the following sections.

4.2.1. *Uncertainty within the characterization data*

Since the results of the model depend a lot on the characterization of the various streams, it is crucial to examine the data that is fed into the model. Initially, it had been planned to have a set of data that could be as generic as possible to cover all possible urban areas to which the model could be applied. This however proved to be unfeasible due to the high variability of the data found in literature. For example, the concentration of total solids in faecal sludge could range from 7000mg/L as reported by Henze and Comeau (2008) to 52,500 mg/L as reported by Koné and Strauss (2004). These figures, when put into equations like 1 and 2 for calculating the potential amount of biogas would result into very wide ranges. For the end-user of the model, this would not make much sense in being used as a decision-support tool.

The variability of characterization of the waste streams has been acknowledged in literature like Strande et al. (2014) and Komakech (2014). For example, Komakech (2014) notes that solid waste characterization data for Kampala is radically different from that of other cities and therefore studies that assume average values end up being erroneous. For this reason, it is therefore better to have the actual characterization data that is specific to each city and use this in the model rather than have average values that try to cover a broad spectrum of cities in low and middle income countries. In cases where this data is not available for a particular city, data from cities with similar characteristics should be used. However, this could have significant effects on the overall results obtained.

While this model was specifically developed for the context of low and middle income countries, it may be possible to extend its validity to cover high income countries. Since the equations used in the calculations were based on literature that could be applied universally, all that would have to change is the characterization data so as to reflect cases from industrialized countries.

4.2.2. *Linearity of equations*

The underlying equations and assumptions in the model were based on the mathematical relationships between waste stream parameters and the amounts of recoverable resources. In most cases, these relationships turned out to be linear according to the literature reviewed. In actual practice, the validity of the linearity may be questionable since a number of factors related to climate, technology and user habits can end up influencing the actual amounts of resources obtained from a particular amount of a waste stream. However, it is safe to assume that since the model results depend entirely on the amount on input waste stream and its characterization, the linear behaviour holds if all other factors remain constant.

4.2.3. ***Variations due to external factors***

The fact that waste stream generation, treatment and resource recovery take place in a variety of contexts means that many external factors can influence the actual amount of recovered resources. The generic nature of this model implies that it cannot incorporate all these factors and therefore, the actual amounts of resources recovered in practice may differ from the results obtained in the model. Some of these factors include the following:

- Technology:

The sheer multiplicity of technologies for the collection, transportation, treatment and resource recovery of various waste streams implies that the outputs similarly vary a lot. The efficiencies of resource recovery in different treatment technologies also differs. For example, in continuous biogas digesters, the methane yields are lower compared to batch reactors due to lower degradation of organic matter (Karellas et al., 2010).

- Scale:

The size and scale of a resource recovery project may also have significant bearing on the differences between the actual resource amounts obtained and the results obtained from the model. For example, in most countries in Sub-Saharan Africa, large scale projects are quite prone to failure due to the bureaucracy and corruption that is often involved in implementation and operation as well as insufficient management capacity (Komakech, 2014). A number of large scale waste water treatment plants have also fallen into disrepair over time (Dodane et al., 2012) (Dodane et al., 2012). As such, it may be feasible to encourage several small scale projects that can be easily managed at a decentralized level rather than a few large scale projects. The proliferation of several small scale resource recovery projects, perhaps at the household level or self-help clubs for example, could indeed unlock the potential of organic waste reuse on a large scale. However, the choice of the scale of a resource recovery project should best be determined while considering the local context where it is going to be implemented. A number of factors can be important in this regard, not least of which is economic feasibility.

- User practices and motivations:

The motivations and practices of the users of the model can also cause further variations between the model results and actual practice. For example, Banks (2014) states that if the goal of a BSF bioreactor is to reduce the amount of organic waste available, then it is important to have a lower feeding rate for the BSF larvae while on the other hand, if the goal is to have maximum prepupae production, then the feeding rate should be increased. In this study, the goal is to have maximum prepupae production for maximum resource recovery and therefore, it was assumed that the parameters are attuned accordingly.

For compost fertilizers, a variety of dryness levels has been documented from research and practice: in Dakar, Senegal, FS is sold to farmers for use as soil conditioner at 60% TS (Diener et al., 2014), in Stockholm, digested sludge from the Bromma and Henriksdal WWTPs is released to farmers and also to mines for land reclamation at 24 – 33% TS (Stockholm Vatten, 2016) while the New York Organic Fertilizer Company (NYOFCo) treats biosolids to 90% dryness before selling them as fertilizer (Ekane, 2010). These differences ultimately determine the final amount of resources obtained.

- Climate:

The climatic conditions in a particular locality would definitely influence the variations between the model results and actual practice. For anaerobic digestion, the local temperatures highly influence the amount of biogas that can be obtained. Therefore, people in colder climates tend to invest in additional sources of heat to catalyze the biochemical processes in their digesters. For those treatment processes that involve drying, warm temperatures and windy conditions may come handy in reducing the energy dedicated towards drying.

It should be noted that the above mentioned factors not only influence the amounts of outputs from resource recovery but also the rates of output. While the waste stream data is used in terms of amount per day, the resource recovery products may all not be obtained at the same rate. This is because the different treatment technologies used, climatic conditions and user practices will make for different residence times. Therefore, the resources from a day's amount of faecal sludge for example may all be recovered within a few days in one case while in another case they might take much longer.

According to feedback from KCCA, the model was easy to navigate and it captured most of the relevant waste streams and resource recovery options as far as the Kampala context is concerned. At the moment, no suggestions were made regarding possible improvements on the model. However, the comment about the importance of the model's financial aspects in enabling cost recovery forecasts suggests that it would be worth-while to incorporate more aspects than just the potential revenues from the recovery products. Including aspects like possible investment and operational costs for the treatment technologies/systems per unit of waste stream or per unit of product would give a more holistic picture from the model. These aspects were not included in this phase due to time and budgetary constraints but further development on the model could incorporate them.

5. CONCLUSIONS AND OUTLOOK

In this study, the common waste streams emanating from sanitation systems in low and middle income countries were identified, the typical end-products that are currently recovered from these waste streams and the common treatment technologies resulting in those end-products. A generic mathematical model was developed for the purpose of estimating the amount of various end-products that can be recovered from each sanitary waste stream. The model was developed in MS Excel and its scope was limited to the three waste streams of faecal sludge, sewage sludge and organic municipal solid waste. The scope of resource recovery products was limited to biogas, solid combustion fuel, protein animal feed and soil conditioner (compost). The calculations in the model were based on the characterization and transformation data of the three waste streams into products and the available daily volumes of the waste streams.

The model was tested using data from the city of Kampala (Uganda) and the results obtained were shared with stakeholders from the Kampala

Capital City Authority (KCCA). The result showed that there is significant potential in utilizing the three waste streams in Kampala for resource recovery rather than just disposing them. The current daily collection of the three waste streams (390 m^3 of faecal sludge, 66 tonnes of sewage sludge and 700 tonnes of organic solid waste) could yield up to 115,495 Nm^3 of biogas or 241 tonnes of solid combustion fuel or 11 tonnes of Black Soldier Fly prepupae or 292 tonnes of soil conditioner/fertilizer. The potential amounts with increased collection efficiency and coverage (900 m^3 of faecal sludge, 282 tonnes of sewage sludge and 2199 tonnes of organic solid waste) could altogether yield up to 361,200 Nm^3 of biogas per day which could meet the daily energy needs of 824,000 people currently met by firewood daily. Alternatively, the three sources could produce, 752 tonnes of solid combustion fuel per day which could meet the daily energy needs of 1,108,700 people that are currently met by firewood. As a third alternative, the three sources could produce 198 tonnes of Black Soldier Fly prepupae per day which could substitute for 134 tonnes of dry fish per day that are currently used as a common animal feed ingredient and up to 909 tonnes of compost fertilizer per day which is enough to substitute two tonnes of urea used by farmers.

It also showed that organic solid waste has the highest potential for resource recovery across all the four end-product options, mainly because higher volumes of organic solid waste are collected daily compared to the other two waste streams. The model also showed clearly that production of solid fuel briquettes from these waste flows had significant potential socio-economic and environmental impact in substituting the use of firewood and charcoal. The model thus proved to be a simple way to provide decision support by making rapid estimations of the potential for resource recovery in urban areas, without the burden of having to do full scale feasibility studies.

Feedback from KCCA on the model indicates that the model is useful for their work, especially the financial aspect which would be crucial for making forecasts of the cost-recovery from investments made in sanitation infrastructure. There is need to test the model further with other stakeholders in different urban areas to obtain a wide range of feedback and make necessary improvements to it. This would help a lot in operationalizing it and making it appropriate for a varied range of users.

6. RECOMMENDATIONS AND FURTHER RESEARCH

Considering the global momentum towards achieving the sustainable development goals and the specific targets and indicators within SDG 6, it is obvious that a lot of money is going to be invested in sanitation infrastructure over the next two decades. There is a huge opportunity for these investments to not only solve the sanitation crisis but to also (partly) solve the resource crisis the world's growing cities. The model developed in this thesis could be useful in enabling city authorities and planners to carry out a paradigm shift towards resource-oriented sanitation systems, rather than systems that simply contain and dispose of excreta and other sanitary wastes. A look at current projects funded through the African Water Facility over the past 5 years shows that many are considering aspects of reuse but with scant information on how to go about it. This could imply that there is inadequate knowledge of the extent of the potential for resource recovery. This model could help in bridging this gap.

Considering the results that were obtained from testing the model for Kampala, it is clear that there is huge potential for resource recovery from the various waste streams available. City authorities and their respective governments need to put in place the necessary legal and regulatory framework as well as incentives that can create an enabling environment for a variety of public and private sector players to engage effectively in the resource recovery arena. This would also include implementing initiatives for source separation of the various waste streams for purposes of quality control and maximizing the recoverable resources.

There is need for further development of the model to incorporate more aspects like investment and operational costs associated with resource recovery, risk analysis, comparison of environmental impacts of the different resource recovery options and also comparison of various technology options that are available for the recovery of each resource. More waste streams, including those from source-separated sanitation technologies, and more resource recovery options could also be incorporated into the model.

A more extensive testing of the model in a range of varied towns and cities is necessary in order to validate its applicability in various cases. This would provide a lot of feedback that would enable improvements in the model. Further developments of the model could also include making an online version as well as integration with web-based networks, other existing models and decision support tools for sanitation & waste management in cities. Improvements to the user interface would also be necessary to make for a better user experience.

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APPENDIX

APPENDIX I: FEEDBACK FROM KCCA ENVIRONMENTAL SANITATION OFFICE

Estimating the potential for resource recovery from productive sanitation in urban areas

Name: *Joel Kagina Mwesigye* Date: *20th May 2016*

Your organization and your designation/position: *KCCA/Environmental Sanitation*

City/Municipality/Area of operation: *Kampala-Uganda*

Your assessment of the model

Please state your assessment of the model on the following areas:

Accuracy: How closely are the results in the model to the reality in your context? Do the results reflect anything from your own experience?

Currently, there is no accurate data on Resource Recovery & Reuse (3Rs) from Feacal -based products. However, an ongoing GIZ/SDC funded RRR aims at bridging this gap and providing sector with local research based data.

Were any of the results surprising? Which ones and why?

No.

Usefulness: How useful do you think the model would be in your city's sanitation planning context?)

The finances are important for policy formulation and enabling cost-recovery forecast for long sustainability of urban sanitation services.

Comprehensiveness: Does the model capture all the sanitary and organic waste types in your city? Does it reflect all the possible resource recovery options? What options do you think are important but were left out?

The model captures most important and known wastes and products.

Ease of use: Did you find the model easy to use or not? Did you find it easy to navigate? If any, what particular aspects in the model did you find confusing?

The model is user friendly, easy to navigate.

Improvements: What improvements do you think can be made to the model?

Your city's context

Population served in your city/municipality: *2.7 million day population*

Waste stream(s) available in the city: *Mixed faecal sludge (FS), sewage and municipal solid waste (MSW)*

Amounts of waste stream available per day: *390m^3 FS: 700tons MSW*

Do you have waste stream characterization data available? Did you feed it into the tool?

I have and fed in data for onsite sanitation systems and solid waste disposal

To what extent is resource recovery practiced in your city and what resourced are recovered in current practice? And at what scale (city, neighbourhood, household etc)?

Briquettes is common but done at insignificant scale given the waste streams volumes generated.

If resource recovery is currently done, are the resources sold on the open market or not? If yes, what are the price ranges used currently? If not, what do you think would be the likely price ranges? (Please mention for each different resource)

Yes.

Any contacts to other people/organizations:

1. *Najib Lukooya Bateganya, PhD*
Kampala Feacal Sludge Management Project - KCCA

nbateganya@kcca.go.ug

2. *Osbert Twijukye*
Sanitation Engineer - Water for People Uganda

oatwijukye@waterforpeople.org

APPENDIX II: INTRODUCTION AND INSTRUCTIONS PROVIDED IN THE MODEL FOR USERS

Estimating the potential for resource recovery from productive sanitation systems

Instructions

This Model consists of three Excel worksheets, all in this workbook. They are; *Model*, *Data* and *Graphs* and they are described below.

Model	This is the main interface of the tool where you will can in the amounts of each waste stream that you have available in your city and the tool will in turn give you figures of the potential amounts of recoverable resources you can get from those waste streams. In this worksheet, you should only change figures in the cells which are yellow in colour, as per the instructions you will see. Note that the figures you put in should be in the units specified in the tool. The Model worksheet comes with some default values of prices for the different products and these should only be changed if more relevant local values are available. It should also be noted that the amount of products given from each waste stream are mutually exclusive i.e. they indicate the amount of product that would be obtained if the entire amount of the waste stream available was used to generate that product alone.
Data	This is the sheet with characterization data on a range of physical and biochemical parameters for the different waste streams you have in your city. The calculations that the tool makes are based on this data. The tool comes with some default data, based on the references stated. Please look carefully at this data and assess how closely it is to the characterisation of the waste streams in your city. If you have characterisation data available for these waste streams in your city, you should replace the existing data with your own local data. However, you should maintain the same template and units as specified by the tool. If you don't have all the data, then you should only change those parameters for which you have available data and leave the rest unchanged. The tool will not work if any data field is empty.
Graphs	This worksheet contains bar graphs that you can use to compare the various resource recovery options on the basis of the financial value of the end-products, the amounts of nutrients that can be recovered and the energy amount that can be recovered. The graphs portray the typical values that can be obtained along with bars indicating the minimum and maximum values possible.

Waste Streams

Faecal Sludge	Faecal sludge comes from onsite sanitation technologies, i.e., it has not been transported through a sewer. It results from the collection and storage/treatment of excreta or blackwater, with or without greywater. Faecal sludge includes both sludge from pit latrines and that from septic tanks.
Sewage Sludge	Sewage sludge (also referred to as wastewater sludge) is sludge that originates from sewer-based wastewater collection and (semi-) centralized treatment processes.
Organic Municipal Solid Waste	This is the organic part of the urban solid waste and it includes items like food waste, market waste and crop residues

Resource Recovery Options

There are four resource recovery options that are included in this model as described below:

Biogas	This is a gas with about 60% methane content. It is generated from the process of anaerobic digestion and can be used for lighting, cooking and also for generating electricity and heat. The process of anaerobic digestion also generates a residue which can be used as soil conditioner or fertilizer in a farm to recover nutrients like nitrogen, phosphorus and potassium (Vögeli et al, 2014).
Solid Combustion Fuel	Excreta and organic waste streams have a high calorific value and can be turned into a solid dry fuel for combustion in briquette or powder form. This can be used either for cooking in households and institutional kitchens as well as for industrial applications like kilns and boilers (Diener et al, 2014)
Black soldier fly prepupae	Organic waste streams can can be treated using fly larvae composting, for example with the Black Soldier Fly, to produce valuable prepupae and a residue. The prepupae of the black soldier fly is 40% protein and 30% fat and can therefore make a protein-rich animal feed and/or be used to make biodiesel among other things (van Huis 2013). The residue from the fly larvae composting contains nutrients and can be applied to a garden as soil conditioner or fertilizer.
Soil conditioner	This would be the case when the entire waste stream is composted to make soil conditioner or fertilizer for applying on farms. The compost generated would be rich in nutrients and also rich in organic matter content.

The worksheets in this model are locked in order to protect the formulae, with the exception of the cells where the user has to make input. The sheets can be unlocked in case the user would like to have a closer look at the calculations behind the model.

APPENDIX III: MODEL RESULTS FOR THE CURRENT COLLECTION SCENARIO FOR FAECAL SLUDGE

Waste Streams >>>>	Faecal Sludge	
Amount available per day	390	m^3/day

Notes

Enter the amount of the waste stream into the yellow boxes in whole numbers,

in the units indicated. If the amount is not available, leave the yellow box blank

	Local Re-use Product Prices		**References**
Biogas	0.33	US$/Nm^3	Afrane & Ntiamoah (2012) and Vögeli et al. (2014)
Briquettes/solid combustion fuel	300	US$/ton	Ferguson (2012)
BSF prepupae	200	US$/ton	van Huis et al. (2013)
Compost fertilizer/soil conditioner	5	US$/ton	Diener et al. (2014)

In this section, enter the local price figures for each of the products in the stated units

and the source/reference for that figure. If a local price is not available,

leave the prices and references that are already indicated in the boxes

"Min" represent the lowest expected values while "Max" represents the highest ones

	Estimates	***Minimum***	***Typical***	***Maximum***		
					<<<	The "Min" and "Max" therefore indicate the range of values expected for each variable
Biogas from Anaerobic Digestion & Residue for fertilizer/soil conditioner	**Amount of Biogas in Nm^3**	1737.45	3378.96	6151.60		
	Energy Value (MJ)	37528.92	72985.54	132874.56		
	Potential revenue (US$)	573.36	1115.06	2030.03		
	Amount of AD Residue wet mass (tonnes)	3.58	6.34	10.40		
	Potential revenue (US$)	17.88	31.69	52.00		
Nutrients in the Residue	**N% of wet mass**	10.91%	20.37%	18.75%		
	N by mass (tonnes)	0.39	1.29	1.95		
	P% of wet mass	1.64%	2.40%	1.88%		
	P by mass (tonnes)	0.06	0.15	0.20		
	K% of wet mass	0.96%	0.74%	0.60%		
	K by mass (tonnes)	0.03	0.05	0.06		
	Total potential revenue (US$)	591.23	1146.74	2082.03		
Solid Combustion Fuel	**Amount at 90% TS (tonnes)**	9.53	13.00	17.33	<<<	Using sanitary wastes to make solid fuels requires sufficient drying and some companies
	Energy value (MJ)	126984.00	189540.00	285480.00		require a dryness level of 90% before they can use briquettes or fuel powder
	Potential revenue (US$)	2860.00	3900.00	5200.00		derived from sanitary wastes (Diener et al, 2014)
Black Soldier Fly Prepupae & Residue for fertilizer/soil conditioner	**Amount of BSF Prepupae (tonnes)**	0.34	2.93	8.93		
	Amount of Protein (40%) in tonnes	0.14	1.17	3.57	<<<	BSF prepupae typically contain 40% protein by weight (Diener, 2010)
	Amount of Fat (30%) in tonnes	0.10	0.88	2.68	<<<	BSF prepupae typically contain 30% fat by weight (Diener, 2010)
	Energy value (MJ) if used for biodiesel	2000.00	17045.44	52045.40		
	Potential revenue (US$)	68.64	585.00	1786.20		
	Amount of Residue wet mass (tonnes)	7.51	14.08	23.91		
	Potential revenue (US$)	37.54	70.42	119.54		
Nutrients in the Residue	**N% of wet mass**	2.60%	5.50%	5.71%		
	N by mass (tonnes)	0.20	0.77	1.37		
	P% of wet mass	0.23%	0.37%	0.32%		
	P by mass (tonnes)	0.02	0.05	0.08		
	K% of wet mass	0.18%	0.15%	0.13%		

Abbreviations

m3	Cubic metre
Nm3	Normal cubic metre (at a temperature of 0 °C and pressure of 1.01 bar)
US$	United States Dollars
MJ	Mega Joules (unit of energy)
AD	Anaerobic digestion
N	Nitrogen
P	Phosphorus
K	Potassium
BSF	Black Soldier Fly
WW	Wet weight
TS	Total Solids

	K by mass (tonnes)	0.01	0.02	0.03		
	Total potential revenue (US$)	106.18	655.42	1905.74		
Fertilizer/Soil conditioner from composting	**Amount at 60% TS (tonnes)**	9.81	15.72	23.01	**<<<**	Soil conditioner is commonly applied when it has a moisture content of about 40% according to Diener et al. (2014)
	Potential revenue (US$)	49.05	78.59	115.05		
	N% of wet mass	2.73%	6.62%	7.50%		
	N by mass (tonnes)	0.20	0.85	1.76		
	P% of wet mass	0.41%	0.78%	0.75%		
	P by mass (tonnes)	0.06	0.15	0.19		
	K% of wet mass	0.24%	0.24%	0.24%		
	K by mass (tonnes)	0.03	0.04	0.06		

APPENDIX IV: MODEL RESULTS FOR THE CURRENT COLLECTION SCENARIO FOR SEWAGE SLUDGE

Waste Streams >>>>	Sewage Sludge	
Amount available per day	66	tonnes/day

Notes

Enter the amount of the waste stream into the yellow boxes in whole numbers,

in the units indicated. If the amount is not available, leave the yellow box blank

	Local Re-use Product Prices		References
Biogas	0.33	US$/$Nm^3$	Afrane & Ntiamoah (2012) and Vögeli et al. (2014)
Briquettes/solid combustion fuel	300	US$/ton	Ferguson (2012)
BSF prepupae	200	US$/ton	van Huis et al. (2013)
Compost fertilizer/soil conditioner	5	US$/ton	Diener et al. (2014)

In this section, enter the local price figures for each of the products in the stated units

and the source/reference for that figure. If a local price is not available,

leave the prices and references that are already indicated in the boxes

"Min" represent the lowest expected values while "Max" represents the highest ones

	Estimates	*Minimum*	*Typical*	*Maximum*
Biogas from Anaerobic Digestion & Residue for fertilizer/soil conditioner	**Amount of Biogas in Nm^3**	712.80	1086.80	2974.40
	Energy Value (MJ)	15396.48	23474.88	64247.04
	Potential revenue (US$)	235.22	358.64	981.55
	Amount of AD Residue wet mass (tonnes)	1.10	1.79	4.40
	Potential revenue (US$)	5.50	8.94	22.00
Nutrients in the Residue	**N% of wet mass**	3.60%	4.62%	6.00%
	N by mass (tonnes)	0.04	0.08	0.26
	P% of wet mass	1.92%	2.95%	4.20%
	P by mass (tonnes)	0.02	0.05	0.18
	K% of wet mass	0.62%	0.74%	1.62%
	K by mass (tonnes)	0.01	0.01	0.07
	Total potential revenue (US$)	240.72	367.58	1003.55
Solid Combustion Fuel	**Amount at 90% TS (tonnes)**	2.93	3.67	7.33
	Energy value (MJ)	26400.00	52800.00	145200.00
	Potential revenue (US$)	880.00	1100.00	2200.00
Black Soldier Fly Prepupae & Residue for fertilizer/soil conditioner	**Amount of BSF Prepupae (tonnes)**	0.11	0.83	3.78
	Amount of Protein (40%) in tonnes	0.04	0.33	1.51
	Amount of Fat (30%) in tonnes	0.03	0.25	1.13
	Energy value (MJ) if used for biodiesel	615.38	4807.69	22019.21
	Potential revenue (US$)	21.12	165.00	755.70
	Amount of Residue wet mass (tonnes)	2.31	3.97	10.11
	Potential revenue (US$)	11.55	19.86	50.57
Nutrients in the Residue	**N% of wet mass**	0.86%	1.25%	1.83%
	N by mass (tonnes)	0.02	0.05	0.18
	P% of wet mass	0.27%	0.46%	0.71%
	P by mass (tonnes)	0.01	0.02	0.07
	K% of wet mass	0.12%	0.15%	0.35%

<<< The "Min" and "Max" therefore indicate the range of values expected for each variable

Abbreviations

m3	Cubic metre
Nm3	Normal cubic metre (at a temperature of 0 °C and pressure of 1.01 bar)
US$	United States Dollars
MJ	Mega Joules (unit of energy)
AD	Anaerobic digestion
N	Nitrogen
P	Phosphorus
K	Potassium
BSF	Black Soldier Fly
WW	Wet weight
TS	Total Solids

<<< Using sanitary wastes to make solid fuels requires sufficient drying and some companies require a dryness level of 90% before they can use briquettes or fuel powder derived from sanitary wastes (Diener et al, 2014)

<<< BSF prepupae typically contain 40% protein by weight (Diener, 2010)

<<< BSF prepupae typically contain 30% fat by weight (Diener, 2010)

	K by mass (tonnes)	0.00	0.01	0.04		
	Total potential revenue (US$)	32.67	184.86	806.27		
Fertilizer/Soil conditioner from composting	**Amount at 60% TS (tonnes)**	3.02	4.43	9.74	**<<<**	Soil conditioner is commonly applied when it has a moisture content of about 40% according to Diener et al. (2014)
	Potential revenue (US$)	15.09	22.17	48.68		
	N% of wet mass	0.90%	1.50%	2.40%		
	N by mass (tonnes)	0.02	0.05	0.24		
	P% of wet mass	0.48%	0.96%	1.68%		
	P by mass (tonnes)	0.02	0.05	0.18		
	K% of wet mass	0.16%	0.24%	0.65%		
	K by mass (tonnes)	0.01	0.01	0.07		

APPENDIX V: MODEL RESULTS FOR THE CURRENT COLLECTION SCENARIO FOR ORGANIC MUNICIPAL SOLID WASTE

Waste Streams >>>>	Organic Municipal Solid Waste	
Amount available per day	700	tonnes/day

Local Re-use Product Prices

			References
Biogas	0.33	US$/Nm^3	Afrane & Ntiamoah (2012) and Vögeli et al. (2014)
Briquettes/solid combustion fuel	300	US$/ton	Ferguson (2012)
BSF prepupae	200	US$/ton	van Huis et al. (2013)
Compost fertilizer/soil conditioner	5	US$/ton	Diener et al. (2014)

	Estimates	***Minimum***	***Typical***	***Maximum***
Biogas from Anaerobic Digestion & Residue for fertilizer/soil conditioner	**Amount of Biogas in Nm^3**	49140.00	111028.98	201180.93
	Energy Value (MJ)	1061424.00	2398226.04	4345508.16
	Potential revenue (US$)	16216.20	36639.56	66389.71
	Amount of AD Residue wet mass (tonnes)	68.25	109.58	154.93
	Potential revenue (US$)	341.25	547.90	774.67
Nutrients in the Residue	**N% of wet mass**	0.00%	0.00%	0.00%
	N by mass (tonnes)	0.00	0.00	0.01
	P% of wet mass	0.00%	0.00%	0.00%
	P by mass (tonnes)	0.00	0.00	0.00
	K% of wet mass	0.00%	0.00%	0.00%
	K by mass (tonnes)	0.00	0.00	0.01
	Total potential revenue (US$)	16557.45	37187.46	67164.37
Solid Combustion Fuel	**Amount at 90% TS (tonnes)**	182.00	224.78	258.22
	Energy value (MJ)	2555280.00	3499790.00	4462080.00
	Potential revenue (US$)	54600.00	67433.33	77466.67
Black Soldier Fly Prepupae & Residue for fertilizer/soil conditioner	**Amount of BSF Prepupae (tonnes)**	16.26	59.68	84.25
	Amount of Protein (40%) in tonnes	6.50	23.87	33.70
	Amount of Fat (30%) in tonnes	4.88	17.90	25.27
	Energy value (MJ) if used for biodiesel	94738.54	347776.46	490937.74
	Potential revenue (US$)	3251.43	11935.70	16849.00
	Amount of Residue wet mass (tonnes)	102.38	151.73	203.35
	Potential revenue (US$)	511.88	758.63	1016.75
Nutrients in the Residue	**N% of wet mass**	0.00%	0.00%	0.00%
	N by mass (tonnes)	0.00	0.00	0.00
	P% of wet mass	0.00%	0.00%	0.00%
	P by mass (tonnes)	0.00	0.00	0.00

Notes

Enter the amount of the waste stream into the yellow boxes in whole numbers, in the units indicated. If the amount is not available, leave the yellow box blank

In this section, enter the local price figures for each of the products in the stated units and the source/reference for that figure. If a local price is not available, leave the prices and references that are already indicated in the boxes

"Min" represent the lowest expected values while "Max" represents the highest ones

<<< The "Min" and "Max" therefore indicate the range of values expected for each variable

Abbreviations

m3	Cubic metre
Nm3	Normal cubic metre (at a temperature of 0 °C and pressure of 1.01 bar)
US$	United States Dollars
MJ	Mega Joules (unit of energy)
AD	Anaerobic digestion
N	Nitrogen
P	Phosphorus
K	Potassium
BSF	Black Soldier Fly
WW	Wet weight
TS	Total Solids

<<< Using sanitary wastes to make solid fuels requires sufficient drying and some companies require a dryness level of 90% before they can use briquettes or fuel powder derived from sanitary wastes (Diener et al, 2014)

<<< BSF prepupae typically contain 40% protein by weight (Diener, 2010)

<<< BSF prepupae typically contain 30% fat by weight (Diener, 2010)

	K% of wet mass	0.00%	0.00%	0.00%		
	K by mass (tonnes)	0.00	0.00	0.00		
	Total potential revenue (US$)	3763.31	12694.33	17865.75		
Fertilizer/Soil conditioner from composting	**Amount at 60% TS (tonnes)**	187.28	271.76	342.79	<<<	Soil conditioner is commonly applied when it has a moisture content of about 40%
	Potential revenue (US$)	936.39	1358.78	1713.95		according to Diener et al. (2014)
	N% of wet mass	0.00%	0.00%	0.00%		
	N by mass (tonnes)	0.00	0.00	0.00		
	P% of wet mass	0.00%	0.00%	0.00%		
	P by mass (tonnes)	0.00	0.00	0.00		
	K% of wet mass	0.00%	0.00%	0.00%		
	K by mass (tonnes)	0.00	0.00	0.01		

APPENDIX VI: CHARACTERIZATION DATA FOR KAMPALA'S FAECAL SLUDGE FROM THE *DATA* MODEL WORKSHEET

Parameter	Units	Faecal Sludge			Reference(s)
	Range>>>>	Minimum	Typical	Maximum	
Total solids, TS	**%**	2.20	3.00	4.00	Schöbitz et al. (2014)
Total solids, TS	**mg/L**	22,000.00	30,000.00	40,000.00	Schöbitz et al. (2014)
Total volatile solids, TVS	**% TS**	45.00	57.00	70.00	Schöbitz et al. (2014)
Total volatile solids, TVS	**mg/L**	9,900.00	18,000.00	24,500.00	Schöbitz et al. (2014)
COD	**mg/L**	10,000.00	30,000.00	35,000.00	NWSC (2008) and Schöbitz et al. (2014)
Total Nitrogen, TN	**mg N/L**	1,000.00	3,310.00	5,000.00	Assumed values based on TKN in Schöbitz et al. (2014)
Total Phosphorus, TP	**mg P/L**	150.00	390.00	500.00	Schöbitz et al. (2014)
Total Potassium, TK	**mg K/L**	88.00	120.00	160.00	Based on K_2O figures for primary sludge from Tchobanoglous et al. (2003)
Calorific Value, CV	**MJ/Kg TS**	14.80	16.20	18.30	Muspratt et al. (2014)
Biomethane Potential, BMP	**Nm^3 CH_4/ton VS_{added}**	270.00	304.00	338.00	Davidsson et al. (2007) and Kjerstadius et al. (2015)
Dry Matter Reduction rate for AD/Biogas	**%**	60.00	67.50	75.00	Alfa et al. (2014)
Total solids in AD residue, AD.TS	**%**	60.00	60.00	60.00	Based on Diener et al. (2014)
Biomass conversion rate for BSF prepupae, BCR	**%**	1.60	10.00	22.90	Banks (2014)
Wet Mass Reduction rate for BSF, WMR	**%**	38.70	51.85	65.00	Banks (2014)
Total solids in BSF residue, BSF.TS	**%**	57.00	62.00	67.00	Banks (2014)
Total N reduction in BSF residue, BSF.TNR	**% of initial TN**	30.00	40.00	50.00	van Huis et al. (2013)
Total P reduction in BSF residue, BSF.TPR	**% of initial TP**	61.00	65.50	70.00	van Huis et al. (2013)
Total K reduction in BSF residue, BSF.TKR	**% of initial TK**	50.00	55.00	60.00	van Huis et al. (2013)
Mass Reduction in compost, CMR	**% of initial mass**	11.50	19.40	31.40	Averages based on Breitenbeck & Schellinger (2004)
Nitrogen Losses during composting, TNL	**% of initial TN**	10.00	34.30	50.00	Based on figures in Galvin (2013)
Phosphorus losses during composting, TPL	**% of initial TP**	0.80	1.77	2.40	Eghball et al. (1997) & Sommer et al. (2001)
Potassium losses during composting, TKL	**% of initial TK**	8.00	12.63	16.00	Eghball et al. (1997) and Sommer et al. (2001)

Note: Cells highlighted in the ORANGE colour indicate averages calculated from the minimum and maximum values. All the other values are obtained from the cited literature

APPENDIX VII: CHARACTERIZATION DATA FOR KAMPALA'S SEWAGE SLUDGE FROM THE DATA MODEL WORKSHEET

Parameter	Units	Sewage sludge			Reference(s)
	Range>>>>	Minimum	Typical	Maximum	
Total solids, TS	%	4.00	5.00	10.00	Tchobanoglous et al. (2003)
Total volatile solids, TVS	% TS	60.00	65.00	80.00	Semiyaga et al. (2015) & Tchobanoglous et al. (2003)
COD	mg/L	47.00		608.00	NWSC (2008)
Total Nitrogen, TN	mg N/L	32.00		250.00	NWSC (2008)
Total Nitrogen, TN	mg N/kg TS	15,000.00	25,000.00	40,000.00	Tchobanoglous et al. (2003)
Total Phosphorus, TP	mg P/L	9.00		63.00	NWSC (2008)
Total Phosphorus, TP	mg P/kg TS	8,000.00	16,000.00	28,000.00	Assumed based on P_2O_5 from Tchobanoglous et al. (2003)
Total Potassium, TK	mg K/kg TS	2,600.00	4,000.00	10,800.00	Assumed based on K2O from Johannesson 1999, Tchobanoglous
Calorific Value, CV	MJ/Kg TS	10.00	16.00	22.00	Muspratt et al. (2014)
Biomethane Potential, BMP	Nm^3 CH_4/ton VS_{added}	270.00	304.00	338.00	Davidsson et al. (2007) and Kjerstadius et al. (2015)
Dry Matter Reduction rate for AD/Biogas	%	60.00	67.50	75.00	Alfa et al. (2014)
Total solids in AD residue, AD.TS	%	60.00	60.00	60.00	Based on Diener et al. (2014)
Biomass conversion rate for BSF prepupae, BCR	%	1.60	10.00	22.90	Banks (2014)
Wet Mass Reduction rate for BSF, WMR	%	38.70	51.85	65.00	Banks (2014)
Total solids in BSF residue, BSF.TS	%	57.00	62.00	67.00	Banks (2014)
Total N reduction in BSF residue, BSF.TNR	% of initial TN	30.00	40.00	50.00	van Huis et al. (2013)
Total P reduction in BSF residue, BSF.TPR	% of initial TP	61.00	65.50	70.00	van Huis et al. (2013)
Total K reduction in BSF residue, BSF.TKR	% of initial TK	50.00	55.00	60.00	van Huis et al. (2013)
Mass Reduction in compost, CMR	% of initial mass	11.50	19.40	31.40	Average values based on Breitenbeck & Schellinger (2004)
Nitrogen Losses during composting, TNL	% of initial TN	10.00	34.30	50.00	Based on figures in Galvin (2013)
Phosphorus losses during composting, TPL	% of initial TP	0.80	1.77	2.40	Average values from Eghball et al. (1997) and Sommer et al. (2001)
Potassium losses during composting, TKL	% of initial TK	8.00	12.63	16.00	Average values from Eghball et al. (1997) and Sommer et al. (2001)

Note: Cells highlighted in the ORANGE colour indicate averages calculated from the minimum and maximum values. All the other values are obtained from the cited literature

APPENDIX VIII: CHARACTERIZATION DATA FOR KAMPALA'S ORGANIC MUNICIPAL SOLID WASTE FROM THE *DATA* MODEL WORKSHEET

Parameter	Units	Organic Municipal Solid Waste			Reference(s)
	Range>>>>	Minimum	Typical	Maximum	
Total solids, TS	**%**	23.40	28.90	33.20	Komakech 2014
Total volatile solids, TVS	**% TS**	50.00	74.00	98.00	Vogeli et al 2014 Eawag
Total Nitrogen, TN	**mg N/kg TS**	13.50	18.90	24.70	Komakech (2014)
Total Phosphorus, TP	**mg P/kg TS**	2.40	2.70	3.30	Komakech (2014)
Total Potassium, TK	**mg K/kg TS**	6.10	19.50	31.40	Komakech (2014)
Calorific Value, CV	**MJ/Kg TS**	15.60	17.30	19.20	Komakech (2014)
Biomethane Potential, BMP	**Nm^3 CH_4/ton VS_{added}**	360.00	445.00	530.00	Vögeli et al. (2014)
Dry Matter Reduction rate for AD/Biogas	**%**	60.00	67.50	75.00	Alfa et al. (2014)
Total solids in AD residue, AD.TS	**%**	60.00	60.00	60.00	Based on Diener et al. (2014)
Biomass conversion rate for BSF prepupae, BCR	**%**	3.97	11.80	14.50	Mutafela (2015), Lalander et al. (2015), Diener et al. (2011)
Wet Mass Reduction rate for BSF, WMR	**%**	65.00	70.00	75.00	Diener (2010)
Total solids in BSF residue, BSF.TS	**%**	40.20	48.85	57.50	Dortmans (2015)
Total N reduction in BSF residue, BSF.TNR	**% of initial TN**	30.00	40.00	50.00	van Huis et al. (2013)
Total P reduction in BSF residue, BSF.TPR	**% of initial TP**	61.00	65.50	70.00	van Huis et al. (2013)
Total K reduction in BSF residue, BSF.TKR	**% of initial TK**	50.00	55.00	60.00	van Huis et al. (2013)
Mass Reduction in compost, CMR	**% of initial mass**	11.50	19.40	31.40	Averages based on Breitenbeck & Schellinger (2004)
Nitrogen Losses during composting, TNL	**% of initial TN**	21.00	50.00	77.00	Tiquia et al. (2002), Anwar et al. (2015) and Strauss et al. (2003)
Phosphorus losses during composting, TPL	**% of initial TP**	0.80	1.77	2.40	Average values from Eghball et al. (1997) and Sommer et al. (2001)
Potassium losses during composting, TKL	**% of initial TK**	8.00	12.63	16.00	Average values from Eghball et al. (1997) and Sommer et al. (2001)

Note: Cells highlighted in the ORANGE colour indicate averages calculated from the minimum and maximum values. All the other values are obtained from the cited literature