Urban waste management and the environmental impact of organic waste treatment systems in Kampala, Uganda

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Abstract

In Kampala, Uganda, about 28,000 tonnes of waste are collected and delivered to landfill every month. Kampala Capital City Authority records show that this represents approximately 40 % of the waste generated in the city. The remaining uncollected waste is normally burnt and/or dumped in unauthorised sites, causing health and environmental problems. However, the organic fraction of domestic waste can provide an opportunity to improve livelihoods and incomes through fertiliser and energy production. This study employed environmental systems analysis to identify the most environmentally efficient technologies for treating the organic waste generated. The work was undertaken through interrelated studies. These were a literature review of waste hierarchy practices suitable to the development of a sub-Saharan African city using Kampala as a case study; a physical and chemical characterisation of municipal waste collected and delivered to Kampala's landfill over the span of a year to cover both dry and wet seasons; a mapping of the location of animal farms and the establishment of animal feeding and waste management practices on animal farms in Kampala; treatment of Kampala's organic waste by means of the vermicompost method and finally using life cycle analysis to identify the best waste treatment method for organic waste generated out of anaerobic digestion, compost, vermicompost and fly larvae waste treatment technologies. The impact categories assessed were energy use, global warming and eutrophication potentials. Generally, the results showed that re-use and waste prevention waste hierarchy methods are the most feasible for the development of waste management in Kampala: over 92 % of the waste generated is organic in nature, containing on average a moisture content of 71.1 %, 1.65 % nitrogen, 0.28 % phosphorus, 2.38 % potassium and a gross energy content of 17 MJ/kg; most animal farms are located on the periphery of the city, and the most popular animal feeds are peelings and pasture; 60 % of the animal manure generated is discarded and 32 % used as fertiliser; a 60.3% material degradation was achieved in the vermicompost process while the feed-to-biomass conversion rate was 3.6 % on a dry matter basis; and finally anaerobic digestion performs best in terms of energy use, global warming potential and eutrophication potential. However the study concluded that poorly managed anaerobic digestion technology with extensive methane leakages will make a considerable contribution to global warming. Further research is needed to establish the viability of fly larvae waste composting in sub-Saharan Africa and to measure direct emissions from the different organic waste treatment technologies in a sub-Sahara African city setting.

Keywords: Kampala, life cycle assessment, organic waste, sub-Saharan Africa, waste characterisation, waste treatment

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Dedication

To my wife Klaire and children Abigail, Aaron, Angel and Andrew for always being there for me.

The biggest reward for a thing well done is to have done it.
Voltaire

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List of publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I Komakech A.J., Banadda N.E., Kinobe J.R., Kasisira L., Sundberg C., Gebresenbet G. and Vinnerås B. (2014). Characterisation of municipal waste in Kampala, Uganda. *Journal of the Air & Waste Management Association* 64(3), 1-9. DOI: 10.1080/10962247.2013.861373.

II Komakech A.J., Banadda N.E., Gebresenbet G. and Vinnerås B. (2014). Maps of animal urban agriculture in Kampala City. *Agronomy for Sustainable Development* 34(2), 493-500. DOI 10.1007/s13593-013-0164-7

III Lalander C.H., Komakech A.J., and Vinnerås B. Production of vermicompost and protein from manure and food waste – A case study from Kampala (manuscript).

IV Komakech A.J., Vinnerås B., Jönsson H. and Sundberg C. Comparison of different biodegradable waste treatment technologies in SSA cities using life cycle assessment – A case study of Kampala (manuscript).

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The contribution of Allan John Komakech to the papers included in this thesis was as follows:

I Participated in planning the experiment and conducted both field and laboratory work. Analysed and interpreted the data with co-authors. Had the main responsibility for writing the manuscript as well as incorporating reviewers' comments, including the production of illustrations.

II Participated in planning the study and conducted the data collection. Analysed and interpreted the data with co-authors. Had the main responsibility for writing the manuscript as well as incorporating reviewers' comments, including the production of maps using GIS software.

III Participated in planning the experiment and conducted both field and some laboratory work. Participated in the analysis, interpretation of the data and writing of manuscript with co-authors.

IV Participated in planning the experiment and conducted the data collection. Analysed and interpreted the data with co-authors. Had the main responsibility for writing the manuscript, including the production of illustrations, as well as incorporating reviewers' comments.

Abbreviations

AD	Anaerobic digestion
BCR	Biomass conversion rate
BSF	Black soldier fly
CHP	Combined heat and power
DM	Dry matter
EP	Eutrophication potential
EPR	Extended producer responsibility
GHG	Greenhouse gas
GWP	Global warming potential
IPCC	Intergovernmental Panel on Climate Change
KCCA	Kampala Capital City Authority
LCA	Life cycle assessment
LMI	Low to middle income
MIS	Manufacturers, importers and sellers
MSW	Municipal solid waste
MUARIK	Makerere University Agricultural Research Institute Kabanyolo
NARL	National Agricultural Research Laboratories
PRO	Producer responsibility organisation
PRRS	Producer responsibility recycling system
SSA	Sub-Saharan Africa
TC	Total coliforms
TS	Total solids
TTC	Thermo tolerant coliforms
UA	Urban agriculture
VCR	Vermicompost reactor
VS	Volatile solids

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1. Introduction and outline

Cities around the world currently generate around 1.3 billion tonnes of waste annually and this value is expected to increase to 2.2 billion by 2025 (Hoornweg & Bhada-Tata, 2012). The increase is anticipated to be greatest in lower-income countries. Related to this is the annual global waste management cost which is expected to increase from $ 205 billion to about $ 376 billion in 2025, again with cost increases being most severe in low-income countries. In addition to costs increases, other global negative impacts of solid waste include it being a large source of emissions of methane, a particularly potent greenhouse gas, from the organic fraction of the waste stream. This impact is exacerbated by the fact that over 75 % of the waste generated globally is landfilled. The leachate generated from landfills is also a contaminant to surface and groundwater sources. Landfills are also sources of fires and explosions, unpleasant odours, vermin, mosquitoes, flies, scattering of garbage by scavenger birds and air pollution (Mwiganga & Kansiime, 2005). Uncollected solid waste also contributes to flooding, air pollution and public health impacts such as respiratory ailments, diarrhoea and dengue fever. In cities in lower-income countries, solid waste management is usually a city's single largest budgetary item (Hoornweg & Bhada-Tata, 2012).

In the case of Kampala, Uganda, Kampala Capital City Authority (KCCA) is mandated by the Local Government Act 1997 to provide solid waste management services to all five divisions of Kampala City (KCCA, 2012; Banadda *et al.*, 2009). However, efforts to manage garbage in the city are continuously being overwhelmed and frustrated by the ever-increasing population of city residents, increased levels of economic activity and reduced funding from central government. In an effort to alleviate this situation, KCCA has contracted private companies to assist it with the management of solid waste collection so as to improve the city's cleanliness. However, in spite of this, less than half of the total waste generated, estimated to be 1,500 tonnes daily, is collected (OAG, 2010). The uncollected waste is normally dumped in open areas, streams, open drainage channels and other areas inaccessible to waste collection vehicles, thus creating both an environmental and public health disaster for the inhabitants of Kampala (OAG, 2010), a fact that is made worse by the fact that over 80 % of the waste being generated is organic (Paper I).

It should also be noted that the domestic waste generated is a vital resource that, if exploited well, can go a long way towards improving the livelihoods of the city's inhabitants. This is evident from the large number of scavengers retrieving material from the waste that can be re-used/recycled. However they normally leave behind organic waste, which they regard as being of low value (Dangi *et al*., 2011). In addition, most animal farmers seem not to appreciate the value of animal waste, as noted by the poor animal waste management on Kampala's animal farms. Nevertheless, organic waste is an extremely useful resource. According to Nzila *et al*. (2010) this waste could play a phenomenal role in future energy supply, mainly through thermochemical, physicochemical, and biochemical transformations as well as conventional combustion. Cofie *et al*. (2009) report that the organic fraction of domestic waste generated can provide an opportunity for exploitation through the process of composting, thus releasing vital nutrients to the soil. Amoding (2007) adds that about 50, 10 and 130 metric tonnes per year of N, P and K respectively are bound up in market crop wastes in Kampala City alone. Organic waste is therefore a substantial potential source for nutrient recycling, especially for urban farming which often requires a considerable amount of nutrients to replace losses from intensive farming. The main challenge is to make residents in SSA cities appreciate organic waste as a high value resource.

Worldwide, several efforts have been undertaken to add value to organic waste. Some of these efforts include anaerobic digestion (AD), compost, vermicompost, fly larvae compost (FLC) and incineration with energy production. The main efforts introduced in many low-income countries have been around composting organic waste (Hoornweg & Bhada-Tata, 2012; Zurbrügg *et al*., 2005). However this and other efforts that add value to organic waste have not been particularly successful (Oteng-Ababio *et al*., 2013; Parawira, 2009). In the case of composting, for instance, one of the major reasons for its failure is the lack of a ready market for the fertiliser produced (Ngoc & Schnitzer, 2009), thus showing how unappreciative farmers are of this organic waste value chain. There is therefore an urgent need to investigate the attractiveness of other organic waste value chains.

1.1 Objectives

The main research objective was to investigate ways of making organic waste attractive as a valuable resource in urban agriculture, using Kampala, Uganda as a case study, with the aim of contributing towards alleviating the perennial challenge faced by SSA cities in managing urban waste. It would also facilitate a more comprehensive understanding of the aspects affecting the environmental performance of the different organic waste value chains with a view to developing strategies to optimise them. The specific objectives were:

- to assess waste management practices in SSA cities based on waste hierarchy case studies from other parts of the world in order to draw valuable lessons that can then be scaled out (stage setting - literature study)
- to investigate the mass and composition of waste generated in Kampala city in order to determine the potential for recycling organic matter and plant nutrients contained in the waste (Paper I)
- to map animal urban agriculture in Kampala city taking into account animal numbers and types, feeds and their sources, and manure generation and use (Paper II)
- to evaluate the effectiveness of a small-scale, low cost and simple technology vermicomposting reactor that introduces a new value chain with the degradation of organic waste and the production of biomass to be used as a fertiliser and animal feed (Paper III)
- to evaluate and compare the different biological/recycling/fertiliser-producing organic waste treatment technologies using the life cycle assessment (LCA) methodology so as to determine the most suitable technology for SSA cities (Paper IV).

Details on the methodology employed to achieve these specific objectives is reported in Papers I – IV and the results are combined and discussed in this thesis in chapters 2 to 4. General discussions and conclusions are presented in chapters 5 and 6 respectively.

1.2 Conceptual framework

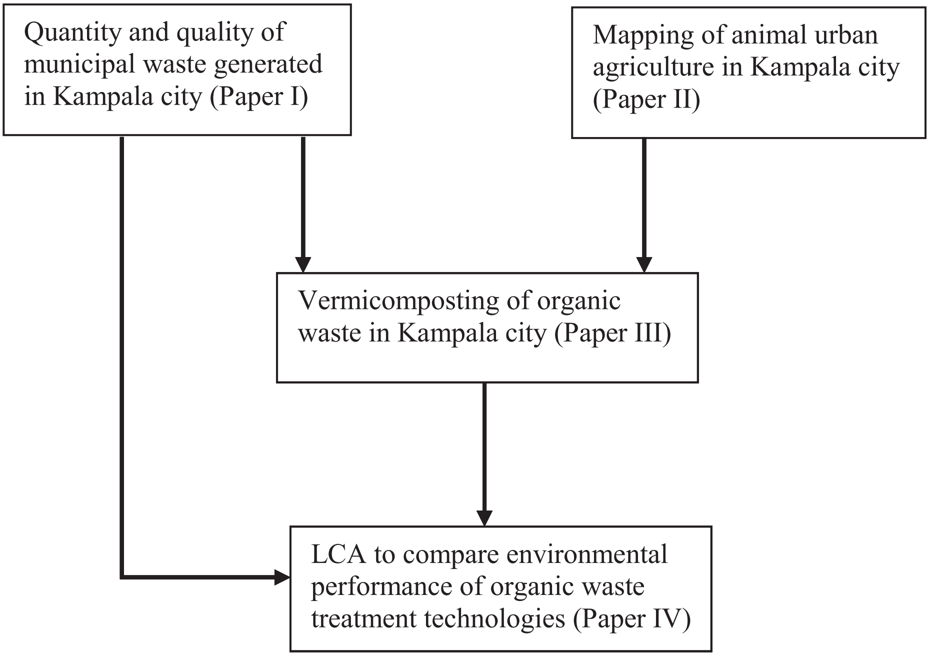

Figure 1: Conceptual framework of this Ph.D. thesis

Figure 1 shows the conceptual framework that was followed in developing this Ph.D. thesis. The first step was to undertake a literature review study of the waste management challenges faced by cities in SSA before investigating how similar challenges have been addressed in other parts of the world using the waste management hierarchy and identifying the lessons that SSA cities could learn. According to Sakai *et al.* (1996), before any suitable waste management strategy can be developed/recommended, there is a need to characterise the volume and composition of waste stream within a given region. Based on this, as well as on the findings obtained from the literature review, further studies were performed to determine the quality and quantity of waste generated in SSA cities using Kampala as a case study (Papers I and II). In Paper I, the quantities and types of household waste collected and landfilled were established, as well as their seasonal variation. In addition, the nutrients contained in the organic waste and its energy content were determined using both a physical and chemical characterisation of the waste. A similar study was undertaken for Kampala city in 1989 (MLHUD, 1993). Since then, conditions in Kampala have changed significantly due to rapid population growth, urbanisation and increased levels of economic activity, thus necessitating a repeat of the study to establish current conditions. In Paper II, the main type of agricultural waste generated in Kampala was identified as animal manure, fruit peelings and crop residues. Although similar studies have been undertaken for Kampala (Katongole *et al.*, 2011; Prain *et al.*, 2010; UBOS, 2008), they have been based on smaller samples of farms, thus affecting their accuracy and reliability. However the present study considered 1,300 animal farms in Kampala, with the intention of considering all the animal farms in the city so as to obtain more accurate and reliable results. Having determined the attributes of the waste generated in Kampala city, then according to the literature review on the waste management hierarchy, the management of this waste can be moved from disposal to higher up the waste management hierarchy, *i.e.* to energy recovery (anaerobic digestion) or recycling (vermicompost, compost and fly larvae compost). However, which of these methods is most environmentally sound for a city such as Kampala in a low-income country? To answer this question, different waste treatment methods were compared using the life cycle analysis method (Paper IV), a study that had never been carried out for Kampala before. However, since data on vermicomposting for small-scale protein production were not readily available, a vermicompost experiment in Kampala was performed (Paper III) using indigenous earthworm (*Eudrilus eugeniae*), which was fed a mixture of cow dung (80 %) and food waste (20 %). Data on the other organic waste treatment methods were obtained from a plant in Fort Portal Uganda (compost), Intergovernmental Panel on Climate Change (IPCC) databases and journal publications (anaerobic digestion and fly larvae compost).

2. Waste management hierarchy practices applicable to the development of SSA cities

Solid waste management is one of the basic services attracting widespread attention on the urban agenda of a number of SSA countries (Kaseva & Mbuligwe, 2005). In many SSA countries, considerable effort is being directed towards the collection and disposal of waste, while other aspects of an effective waste management system are being ignored. The organisation and planning of public waste collection and disposal services are still rudimentary, resulting in limited amounts of municipal solid waste being recycled and recovered (Matete & Trois, 2008), resulting in recycling essentially remaining an informal activity (Agarwal *et al.*, 2005). In high-income countries, the waste management hierarchy has been successfully used to manage the waste produced. Is it possible that the waste management hierarchy can be helpful in alleviating some of the challenges currently being faced in the management of waste in SSA cities? This chapter contains an analysis of the situation in SSA cities based on the waste hierarchy and findings from case studies in other parts of the world in order to see what lessons can be learnt.

2.1 Waste management hierarchy

The waste management hierarchy can be defined as a concept that promotes waste avoidance ahead of recycling and disposal. It has its origins in the 1970s when environmentalists started to criticise the dominant disposal-based waste management, reasoning that waste was not a homogenous mass that should be buried, but rather that it was made up of different materials that required unique treatment methods (Gertsakis & Lewis, 2003). In developed countries, the waste management hierarchy is being employed as a guiding framework in the formulation of waste-related policies and programmes and regulations (Gertsakis & Lewis, 2003; Sakai *et al.*, 1996) as well as the minimisation of waste (Table 1). The guiding principle of the waste management hierarchy is that actions at the top of the hierarchy are preferable to those lower down (Seadon, 2010). This is because actions at the top have a smaller impact on the environment than those at the bottom, *i.e.* preventing waste is more environmentally beneficial than re-use, re-use is better than recycling which in turn is better than incineration or land filling (Fishbein *et al*., 2000).

Table 1: Different variants of the waste management hierarchy (adapted from Seadon (2010))

Outcomes	EU	USA	Australia	Japan
Most desirable	Prevention or reduction	Reduction & re-use	Avoidance	Reduction
↑	Re-use	Recycling/ composting	Reduction	Re-use
	Recycling	Energy recovery	Re-use	Recycling
	Recovery	Landfill & incineration no energy recovery	Recycling	
↓	Disposal		Recovery	
Least desirable			Treatment	
			Disposal	

For this discussion, the European Union's waste management hierarchy (Table 1) was used. The definitions of the various parts of the waste management hierarchy are as follows:

- according to Cox *et al*. (2010), who quote the waste management framework directive (EU Directive 2008), waste prevention refers to measures taken before a substance, material or a product has become waste and that reduce the quantity of waste, the adverse impacts of the waste on the environment and human health, and the content of harmful substances in the waste. Waste prevention is a long-term process requiring a behaviour change by households, manufacturers and other stakeholders in the economy, in addition to the authorities providing an enabling environment for this to happen (Salhofer *et al.*, 2008)
- re-use is "the reapplication of a package, used product or material that retains its original form or identity" (Fishbein *et al.*, 2000)
- recycling is "a series of activities whereby discarded materials are collected, sorted, processed, converted into raw materials, and used in the production of new products. Recycling does not include the use of these materials as a fuel substitute for energy production" (Fishbein *et al.*, 2000)
- recovery is the recovery of value or energy from the waste material (Bates & Phillips, 1999). In this context, recovery will be regarded as the recovery of energy from waste material, while the recovery of material is treated under recycling. The two popular energy recovery methods are energy recovery from the combustion of waste materials and anaerobic digestion

- disposal refers to the disposal of waste, usually in landfill. It is the least desirable waste management option (Bates & Phillips, 1999).

Actions at the top of the hierarchy can be achieved if central government provides leadership in the form of setting the direction and encouraging the commitment necessary to change behaviour. On the other hand, actions that are lower down the hierarchy, such as recycling and recovery, depend on the adequacy of resources at a local level, *i.e.* collection of waste (Seadon, 2010). Waste that cannot be re-used, recycled or composted needs to be landfilled, with or without prior incineration (Giusti, 2009).

According to Gertsakis and Lewis (2003), a hierarchy of prevention necessarily requires upheaval and organisational change that is not always desirable or appealing to companies that have invested heavily in conventional environmental management systems and other end-of-pipe strategies. Another shortcoming in the implementation of the waste hierarchy is the fact that solid waste managers have very little control over the generation of waste and therefore have a limited capacity to achieve source reduction. Designers, engineers and managers in industry make decisions about what is manufactured, processed or constructed and how this is done, and therefore the amount and type of waste generated. In order to be effective, therefore, the waste hierarchy needs to be tackled by working in two different systems: the waste management system and the production system.

2.2 Waste management hierarchy: the existing situation in SSA cities

In many countries in SSA, no deliberate policy has been developed by municipal authorities to implement the waste management hierarchy. As such, municipal authorities have done very little to enable this to happen. For example, many SSA authorities do not prioritise the sorting of municipal waste (Ofori-Boateng *et al.*, 2013; Okot-Okumu & Nyenje, 2011), a key factor in the successful implementation of the waste management hierarchy. Furthermore, for the waste management hierarchy to be successful, enabling environmental policies should be in place and these should be enforced. In many SSA cities, however, although such policies do exist, they are not enforced by the authorities, leaving citizens to manage waste according to their own convenience (Ofori-Boateng *et al.*, 2013). As a result, there is a suggestion that low-income cities are better off trying to collect all the municipal waste generated rather than trying to implement the waste management hierarchy (Brunner & Fellner, 2007). Nevertheless, this section discusses how different aspects of the waste management hierarchy are being employed in SSA.

2.2.1 Waste prevention

Although waste prevention would appear to be a long way off for many SSA countries, a few of them have nevertheless passed legislation to promote it. These include South Africa with its Polokwane declaration in 2001, which set the target of a 50 % reduction in waste to landfill by 2012 (Couth & Trois, 2010), and Botswana with the Botswana strategy for waste management in 1998 (Ketlogetswe & Mothudi, 2005). However in both cases, as in other SSA countries that have passed legislation to promote waste prevention, not much progress has been made in implementing the initiatives. According to Couth and Trois (2010), this is because the targets set are too ambitious and insignificant resources have been set aside for this purpose. However, some success has been noted in South Africa. According to (Nahman, 2010), by the late 1990s plastic bag litter in South Africa was so common across the country that it was nicknamed the new national flower. Bags were distributed free of charge, encouraging excess consumption and litter. In May 2003 a law regarding the manufacture/import of these bags was introduced. Among other things, this legislation imposed a levy of 3 South African cents (0.004 USD) per bag to reduce customer demand and encourage re-use. The levy was imposed on bag manufacturers and importers and passed on to end consumers. This legislation proved effective at reducing plastic bag production and waste.

2.2.2 Re-use and recycling

Recycling in low-to-middle income (LMI) countries is mainly an economic activity of commodity extraction, upgrading and trading (Scheinberg *et al.*, 2011). Re-use and recycling of waste in many SSA cities is performed by a variety of groups as in most cases there is no central organised recycling scheme (Ketlogetswe & Mothudi, 2005). This is mainly because many authorities do not give it the attention it deserves (Ofori-Boateng *et al.*, 2013; Kofoworola, 2007). As such the informal sector, represented mainly by scavengers, is the main recycler in many cities in developing countries (Wilson *et al.*, 2006), separating the waste into high-value items such as metal, plastic, cardboard, glass and hard paper (Kofoworola, 2007; Mugagga, 2006). Such recycling forms the livelihood of hundreds, sometimes thousands of scavengers in these cities (Scheinberg *et al.*, 2011).

In Kampala, metallic food containers fond in waste are sold to individual metal workers/artisans (junk shops) for manufacturing into new products, *e.g.* toys, cooking stoves, kitchen utensils *etc*. Plastic, cardboard and hard paper are mainly sold to agents who sell them on, *e.g.* to paper recycling industries in Nairobi, Kenya (Mugagga, 2006). Ketlogetswe and Mothudi (2005) report something similar for Botswana where local recycling companies are only involved in the collection of recycling materials that they then export to other countries, mainly South Africa. However, according to Scheinberg *et al.*

(2011), other than in the metal sector in Lusaka, there are minimal recycling opportunities in other SSA cities.

Even if some plastic and glass in Kampala is recycled, the majority is not, mainly due to the city not having the necessary technology. As a result, most of it is landfilled (Mugagga, 2006). However there are some itinerant waste traders who buy recyclable materials, such as drinks bottles, from households, which they later sell to manufacturing companies. In addition, some local breweries encourage the use of refillable bottles. A deposit is held on a bottle that is returned when the empty bottle is brought back to the brewery's agent (Mugagga, 2006).

Although the quantity of generated waste that is re-used/recycled in Kampala is not known, it is more likely to be close to the 11 % value that Kaseva and Mbuligwe (2005) state for Dar es Salaam city. Even though Scheinberg *et al.* (2011) report that between 15-35 % of MSW waste generated in cities of LMI countries is informally recycled, that figure is only 2 % in Ghana. Ofori-Boateng *et al.* (2013) report that MSW recycling in Ghana is hindered by the costly and inappropriate technology for source sorting, given that waste is not sorted at source. However, there are ongoing programmes to encourage waste sorting through the provision of different containers to homes for collecting different types of waste and public education on the benefits of doing so. Furthermore, plans are in the advanced stages for installing a 2000 Mt/day recycling plant to recycle MSW in Accra (Ofori-Boateng *et al.*, 2013).

As already noted, over 70 % of Kampala's urban waste is organic in nature. This therefore presents a great opportunity for the waste to be used to support urban agriculture in the form of compost, while at the same time extending the lifespan of the landfill. Compost from biodegradable waste supports agriculture in a few areas in Kampala (Mugagga, 2006), as has been reported for Ghana (Ofori-Boateng *et al.*, 2013). People with reasonable plot sizes use the organic waste as fertiliser in their own gardens. A large proportion of the waste from households, restaurants/hotels and markets is re-used as animal feed (Paper II). However the city does not have a large-scale compost plant, even though KCCA policy encourages composting as a waste management method (WMW, 2013). Unfortunately, in many other SSA cities there is no clear policy on the composting of waste, resulting in the negligible use of this method in waste management (Parrot *et al.*, 2009; Imam *et al.*, 2008; Kaseva & Mbuligwe, 2005). In Accra, on the other hand, even though a large compost plant was constructed in the late 1970s to produce compost fertiliser from household organic waste, this plant has not performed as expected. It operates far below its designed capacity owing to inadequate management (Oteng-Ababio *et al.*, 2013). Also, according to Ngoc and Schnitzer (2009), the success of composting programmes is hindered by their high operation and maintenance costs, the high cost of compost compared to commercial fertilisers, and the absence of a readily available market.

2.2.3 Energy recovery

Some SSA cities either have plans to install or have already installed anaerobic digesters to treat their organic municipal waste for energy recovery in the form of biogas. For example in Dar es Salaam city, Mbuligwe and Kassenga (2004) report on plans that are underway to construct an anaerobic digestion plant under a project called the taka gas project. The plant was expected to generate biogas that could be used in electricity generation, with its total electricity generation capacity expected to be 5.18 Mwh/day. However, Parawira (2009) reports that this project failed to take off due to bureaucracy, highlighting one of the challenges faced in introducing large-scale anaerobic digestion (AD) in SSA.

In spite of this, efforts have been made to enhance AD technology through the various promotional efforts of international organisations and foreign agencies in publications, meetings and visits (Omer & Fadalla, 2003). As such, AD digesters, mainly of them of the small-scale type, have been installed in many SSA countries, although few of them are operational and most use animal and human excreta as their major substrate (Parawira, 2009). Furthermore, according to Parawira (2009), most of the digesters used are the Chinese fixed dome and Indian floating cover digesters, which are not reliable and do not perform well. They therefore only operate for a short time because of their poor technical quality. However, the development of large-scale AD technology, the kind needed to treat municipal waste, is still at an embryonic stage in many SSA cities, although the potential is there, with economic, political and technical factors presenting the major challenges to its development (Parawira, 2009).

Incineration with energy recovery is a method that can be used to recover energy and there have been attempts to popularise it in SSA cities such as Lagos, where Kofoworola (2007) reports that two waste incineration plants have been installed, although they have never been used.

It should be noted, however, that incineration as a technology in waste management is not suitable for low-income countries for a number of reasons. These include the fact that waste in these countries is largely organic, with a low calorific value and high moisture content (Giusti, 2009; Narayana, 2009; Shekdar, 2009), making such waste unviable for incineration; air emissions from incinerators contain several carcinogens and soil, water and food pollutants such as dioxins, heavy metals and other volatile organic compounds; and they require a large capital investment with little economic return, as well as a constant supply of waste, rendering useless any innovative techniques undertaken to reduce the quantity of waste. In addition, the incinerators require landfills for their inert by-products, a factor that increases further the capital cost of the incinerator (Narayana, 2009). However, some researchers report that incinerators suitable for waste generated in SSA cities have been designed (Ayaa *et al.*, 2014). More tests are needed to confirm this claim.

2.2.4 Disposal

The largest fraction of the waste generated in SSA cities, as discussed in chapter 1, is organic waste. At present, most of this waste is dumped in sanitary landfills (Ofori-Boateng *et al.*, 2013; NEMA, 2007; Mwiganga & Kansiime, 2005), open dumps (Ofori-Boateng *et al.*, 2013; Kofoworola, 2007; Mugagga, 2006)Ofori-Boateng *et al.*, 2013), open pits from which soil has been mined (Ketlogetswe & Mothudi, 2005) or other open areas, streams and drainage channels, creating both environmental and public health issues for the cities' inhabitants (OAG, 2010). Although landfill gas has been harnessed from sanitary landfills in high-income countries (Themelis & Ulloa, 2007; Spokas *et al.*, 2006), this is not the case in many landfills in SSA cities (Kofoworola, 2007; MEMD, 2006) where the landfill gas is allowed to escape into the atmosphere, thus contributing significantly to global warming. In addition, a great quantity of the waste dumped in the landfill could be recycled, but this is does not happen due to the lack of efficient technologies and capital for recycling (Ofori-Boateng *et al.*, 2013; Mugagga, 2006).

Incineration without energy recovery is a disposal method that has been used in some SSA countries to manage the waste generated. Incineration is a thermal processing method in which the combustible fractions of solid waste are incinerated to reduce their volume before final disposal, and in some cases to recover the heat released (Shekdar, 2009). In Ghana, there are over 12 major incineration plants without energy recovery (Ofori-Boateng *et al.*, 2013).

2.3 Waste management hierarchy: practices in other parts of the world

This subsection reviews the waste management hierarchy practices in other parts of the world with the intention of identifying practices that can be adopted by the authorities in SSA cities to stimulate movement up the waste management hierarchy. The methodology used was to review what is happening in each of the different parts of the waste management hierarchy and learn important lessons that could be adopted to improve waste management in SSA cities.

2.3.1 Waste prevention

One of the most important factors when planning waste prevention interventions in high-income countries is behaviour change among consumers. Actions, also known as the 4Es, are necessary to induce behaviour change. According to Cox *et al.* (2010) these are:

- Enable – actions that make it easier for people to make responsible choices, for example provision of the necessary infrastructure and facilities, support, guidance, education, skills, alternatives and information
- Engage – actions that involve people early on in order for them to understand and take personal responsibility. The use of initiatives such as community action, media campaigns/opinion formers and networks can encourage people to become more actively involved in waste prevention
- Encourage – actions that send the right signals for people to get involved in waste prevention. Examples of such actions include grants, reward schemes, recognition, tax system, penalties, fines and enforcement action
- Exemplify – lead by example and achieve consistency.

Examples of how the 4Es have been applied in different countries are presented in the following paragraphs.

In Taipei, Taiwan there are various programmes to reduce the use of plastic shopping bags and plastic disposal dishes by providing incentives and subsidies to various businesses in an effort to motivate them to introduce re-usable shopping bags and dishes. There is also another programme to encourage the re-use of food and garden waste for animal feed and composting (Lu *et al.*, 2006).

In Singapore, some of the waste prevention measures implemented include the promotion of minimal packaging for consumer products and the development of biodegradable plastics to replace the conventional plastics that have several disadvantages, such as being slow to decay and releasing toxic chemicals when incinerated (Bai & Sutanto, 2002).

In the UK, amendments to the 1997 UK regulations included proposals that made more information available to consumers, for example labelling on packages to inform consumers whether they could be re-used or recycled. In addition, the government clearly pointed out the role that households had to play in responsible waste management by advising them on what they had to buy and what they had to throw away. To stimulate the former, the government encouraged the production/consumption of products that contained fewer hazardous materials, consisted of recycled materials, had a longer life, were repairable, could be leased or hired out, could be refilled, had less packaging and were not disposable (*e.g.* disposable nappies, razors, plastic cups, disposable cameras). In addition, the government encouraged the setting up of repair centres and places where unwanted products could be taken, *e.g.* charity shops, scrap shops, exchange centres, civic amenity sites *etc.*, participation in recycling activities and home composting, and the correct and safe disposal of hazardous household materials. The government also encouraged the use of electronic information sources and the rejection of junk mail.

The UK government also realised the importance of consumer awareness in the success of any waste prevention measures. To stimulate this, the UK National Awareness Initiative was launched in November 2000, stressing the importance of recycling, composting and smart shopping. Another national campaign entitled ‘Are you doing your bit?’ was also introduced to promote the going green initiative (Coggins, 2001). Also in the UK, customers and households were encouraged to rethink their behaviours in a bid to stimulate waste prevention. Examples of these included re-using food leftovers (commitment to preventing food waste), home composting, buying second-hand clothes and using their own shopping bags (Cox *et al.*, 2010).

The cost of waste reduction measures that are put in place always ends up being passed to consumers. How the consumer pays will determine the incentive for consumers and industry, *e.g.* in the USA, waste management is tax funded, meaning that neither the consumer nor industry has an incentive to reduce waste. Instead, if households are charged by the amount of waste they put out for disposal, it encourages households to reduce the waste generated, *e.g.* by purchasing less wasteful and more recyclable products (Fishbein *et al.*, 2000).

2.3.2 Re-use and recycling

In recognition of the great importance of recycling in waste management, numerous initiatives have been introduced to promote it in a variety of countries. One of these initiatives that has attracted great attention in recent years is the extended producer responsibility (EPR) (Nahman, 2010). EPR is defined as “the extension of the responsibility of producers for the environmental impacts of their products to the entire product life cycle, and especially for their take-back, recycling, and disposal.” Through EPR, the responsibility of managing waste products is assigned to private industry instead of government/municipal authorities, and the cost of its management is assigned to the product. EPR was first applied to packaging in Germany in 1991. At present it is being applied to several product sectors in most countries in the developed world. Under EPR, the producer either takes back its products directly or via a communal organisation, also known as a producer responsibility organisation (PRO). PROs usually manage the take-back programme for a particular product collectively for all producers. The PRO is financed by a fee per product. The fees are most often connected to product weight, as well as to the ease of recycling the product. This encourages producers to design products that are easier to recycle and use minimal packaging (Fishbein *et al.*, 2000).

EPR forces producers to manufacture less wasteful and more economically recyclable products. EPR can be implemented voluntarily, often based on a memorandum of understanding between industry and government. If implementation is based on mandatory product take-back schemes, it is connected to legislation and recovery/recycling goals (Nahman, 2010).

EPR has been implemented in Taiwan, with the programme known as the producer responsibility recycling system (PRRS). PRRS specifies that the manufacturers, importers and sellers (MIS) of particular products (waste containers, used tyres, used agricultural containers, scrap batteries, waste lubricant oils, scrap vehicles and electrical appliances) are responsible for the proper recovery and recycling of their post-consumer products. The penalty for failure to comply with PRRS regulations is hefty fines or having the business shut down. Owing to these stringent penalties, most MIS have taken steps to abide by PRRS regulations. For example, manufacturers whose products are packaged in PET bottles (soft drinks, soy sauce *etc.*) introduced a deposit fee per PET bottle. This had an effect of increasing the recycling rate from 41.04 % to 80.47 % in 1992, the year in which the deposit fee was implemented (Lee *et al.*, 1998). The EPR system has since been modified and MIS are no longer directly involved in recycling. Instead they are required to pay disposal fees, the rates of which are set by the Taiwan Environmental Protection Administration (a governmental body that combines the recycling organisations originally established by MIS). These funds meant that the governmental body was able to conduct waste recycling activities (Lu *et al.*, 2006).

In the EU, incineration plants also contribute to material recovery, as the ash left after the separation of scrap metal and bulky material can, after pre-treatment, be utilised in the building sector. In the Netherlands, for example, 100 % of this ash is used in road construction. Other EU countries apply the same strategy, but to a lesser extent (Vehlow *et al.*, 2007).

In Germany, a mandatory deposit on non-refillable containers was introduced in 2003 in a bid to increase the market share of refillable containers. In addition, stores selling drinks in cans, plastic and glass are required to take back not only the packaging from the drinks they sell, but from manufacturers of similar drinks. As a result, the shares of drinks in refillable packaging rose from 56 % in 2002 to 63 % in 2003. The challenge with this, however, is that it is quite costly to change the production system from single use to refillable packaging (Salhofer *et al.*, 2008).

According to Barr *et al.* (2005), in a bid to stimulate re-use and recycling, the UK government contemplated introducing measures to punish households that produce too much waste. Some of the measures included the introduction of variable charging of households that put out extra bags of refuse for collection over and above the stipulated limit.

In Japanese cities, waste such as cans, glass bottles, PET and metals are collected, stored and recycled by the municipal authorities. The authorities also operate MSW collection centres where waste is separated. Other stakeholders, such as non-governmental organisations (NGOs), complement the efforts of municipal authorities in promoting environmental friendly practices such as proposals to reduce household waste, encouragement of composting of raw waste *etc.* (Geng *et al.*, 2010).

In order to improve waste management in Japanese cities, several ordinances have been issued. With the enforcement of these ordinances, cities have made great strides towards reducing the total amount of MSW (Geng *et al.*, 2010). For instance, in 2001 the food recycling law was established in Japan. The law required food waste emitters to reduce their waste by recycling their food waste into compost or animal feed/biogas. Although the latter was the main recycling method employed, there was limited demand for the compost produced due to increased competition from chemical fertilisers. This law was therefore revised in 2007 to include, among other things, a requirement that food waste emitters report the amount of food waste recycled and purchase food from farms that use food waste-derived products such as compost and animal feeds. This law is credited with bringing about a significant increase in food waste recycling. Moreover, MSW such as cans, glass bottles, PET and metals in Japanese cities such as Kawasaki are collected, stored and recycled by municipal authorities (Takata *et al.*, 2012).

Furthermore, according to Shekdar (2009) who quotes Sakai (2002), the concept of shared responsibility has been used effectively in Japan. Under this, it is mandatory for citizens to separate their waste into combustibles, non-combustibles and recyclables and to deposit the sorted waste fractions at collection centres. Municipalities collect waste paper, glass, metal *etc.* as recyclables that are separated at source for transfer to appropriate recycling facilities, while bulky waste containing plastics, glass, metal *etc.* is crushed before recycling. Manufacturers are responsible for material recycling.

In 1995, a volume-based waste fee system (unit pricing system) was introduced by the government in Korea to reduce waste at source and stimulate recycling. The pricing system required every household to purchase certified plastic bags for waste disposal, while the disposal of separated recyclables was performed free of charge. All recyclable packaging materials had to be marked clearly and recyclable waste separated into paper, plastic, metal and glass before disposal. Food waste was also separated from other household solid waste and disposed in separate plastic bags at no cost. The unit pricing system is credited with the increment of recycling values from 15 % in 1994 to 60 % by 2008. During the same period, the values of landfilled waste declined from 81 % in 1994 to 20 % by 2008 (Lee & Paik, 2011). This therefore makes the unit pricing system an effective tool for promoting the recycling of waste generated in a city.

A similar system to the unit price system in Korea was introduced for Taipei, Taiwan. That system, together with mandatory waste recycling bylaw, is credited with the recycling rate increasing from 2.3 % to 23 %. The bylaw required the public to take recyclable waste to waste collection crews or scrap processors. People who threw out recyclable waste with the other waste would be heavily fined, in addition to the waste collection crew refusing to accept the mixed waste. In addition, the bylaw made it mandatory for waste crews to recycle waste (Lu *et al.*, 2006).

In Dhaka city, Bangladesh, a non-governmental organisation called Waste Concern (WC) collects mixed solid waste from households for a fee. WC then sorts the waste into different fractions. It converts the organic fraction obtained into compost while the inorganic fraction is given to the municipal authorities (Zurbrügg *et al.*, 2005). In many cases over 80 % of the waste is organic, making composting a suitable MSW management method in urban areas of low-income countries (Narayana, 2009). Most of the compost obtained is sold as fertiliser. The remaining compost obtained is used directly by WC in their nurseries and farm demonstration plots (Zurbrügg *et al.*, 2005). However, there is a quality risk with the compost as mixed solid waste can be highly contaminated by inorganic substances, *e.g.* batteries and other heavy metal-containing products (Narayana, 2009).

2.3.3 Recovery

Energy recovery technologies used in high-income countries include combustion of waste with energy recovery and anaerobic digestion (AD) technology.

In the EU, MSW is burnt in mass burners based on grate technology. In some countries such as Germany, co-combustion of MSW in utility boilers and industrial furnaces is playing an increasingly important role. Modern incinerators have considerable potential for energy recovery, with power efficiency values of between 20 – 25 % being achieved (Vehlow *et al.*, 2007). If the boilers used are made from high corrosion-resistant alloys, power efficiency values of over 30 % can be achieved. However, the best configuration for energy recovery is combined heat and power (CHP) in which energy efficiencies of over 60 % can be attained (Vehlow *et al.*, 2007).

AD technology currently plays a small, but steadily increasingly role in the renewable energy mix in many European countries, especially in Germany, Denmark, Austria and Sweden (Wilkinson, 2011), with the most important drivers for this being economic growth and regional employment (Domac *et al.*, 2005). When AD was first promoted in these countries in the 1970s and 1980s following the energy crisis, failure rates were very high (Raven & Gregersen, 2007). This was mainly due to poor design, inadequate operator training and unfavourable economics. However these initial challenges have been overcome through better reactor design and favourable economic incentives for biogas utilisation (Wilkinson, 2011).

The biogas produced from AD plants is mainly used for combined heat and power (CHP) generation, with the heat being used locally for district heating. Sometimes, the biogas is upgraded by removing carbon dioxide and hydrogen sulphide for use as a vehicle fuel, a practice that started gaining popularity in countries such as Sweden during the early 2000s (Lantz *et al.*, 2007). In addition to biogas, the added material is transformed in the AD system to produce digestate that can be used as a fertiliser in crop production, thus presenting a sustainable way to control and direct nutrients in society (Lantz *et al.*, 2007). In other countries such as Denmark, the AD-production system represents an integrated system of renewable energy production, resource utilisation, organic waste treatment and nutrient recycling and redistribution (Holm-Nielsen *et al.*, 2009).

AD plants used in the EU are either large-scale centralised or community plants or smaller farm-scale plants. The former are dominant in Denmark, while Germany is the leading country in the latter with over 4,000 such plants.

The generous feed-in tariff for renewable energy in Germany is credited with the tremendous growth in farm-scale AD plants (Wilkinson, 2011). This feed-in tariff, which was introduced in 1991, compels utility companies to buy electricity from producers of renewable energy at a premium price. Since then the feed-in tariff law has continually been revised and expanded (Wilkinson, 2011). In the case of Denmark, some of the factors responsible for the success of the AD system are the authorities' employment of a bottom-up approach, which stimulated interaction and exchange of experiences between farmers, researchers, biogas operators, biogas companies and public authorities. Furthermore, biogas plants combined the digestion of manure with organic waste – a factor that significantly contributed to the increment in biogas yields (Raven & Gregersen, 2007).

2.3.4 Disposal

As already discussed, many high-income countries follow the waste management hierarchy. As such, disposal in landfill is the least desirable waste management option. In Japan, for instance, only inert waste is accepted in landfills. Other waste is subjected to different waste treatment methods, such as composting, recycling and incineration with energy recovery (Geng *et al.*, 2010).

According to Shekdar (2009), of the total waste managed in Japan during 2005, only 13 % was landfilled, while 68 % underwent intermediate processing, mainly by incineration. This is quite different from what happens in SSA cities, where 100 % of waste collected is landfilled (OAG, 2010; Henry *et al.*, 2006). Waste incinerated in Japan includes, but is not limited to, general and bulky waste from households and businesses, waste paper, plastics and food waste from the commercial sector such as shops and restaurants. During incineration, oil is added to ensure a high burning temperature and avoid the emission of hazardous gases such as dioxins (Geng *et al.*, 2010). The advanced incinerators used achieve up to 98 % volume reduction, with plasma technology being used for ash processing. Another reason for the minimisation of the landfill method is the difficulty of acquiring land due to public opposition and a shortage of land (Shekdar, 2009). During the same period, 78.7 % of waste generated in Taiwan was incinerated and the rest landfilled (Lu *et al.*, 2006), while in Hong Kong 43 % was recovered while the rest was landfilled. In other Asian countries such as Malaysia, Thailand and Indonesia, although there are no specific regulations regarding solid waste management and open dumping is still the norm, attempts are being made to shift towards sanitary landfills (Shekdar, 2009) and incinerators for waste management (Kathirvale *et al.*, 2004). Solid waste management in these countries is similar to what is found in SSA.

Waste management in the European Union (EU) is almost completely regulated by EU directives issued by the European Council/European Parliament that have to be adopted by all the member states. Although the first directive was issued in 1975, there have been several amendments since. They generally give advice on waste management and disposal (Vehlow *et al.*, 2007). An important directive for MSW disposal is the Landfill Directive 1999/31/EC which stipulates a system of operating permits for landfill sites (Vehlow *et al.*, 2007). It also requires the reduction of biodegradable municipal waste being sent to landfill to 35 % of 1995 levels by 2016 (Price, 2001). This directive promotes not only recycling, biogas production and composting, but also greatly encourages waste incineration (Vehlow *et al.*, 2007). The landfill tax is also a measure that has been used to divert biogenic waste from landfill, whereby untreated biogenic waste going to landfill is subjected to this tax (Vehlow *et al.*, 2007). The landfill tax has been found to be very effective in reducing the waste that is landfilled. For instance since its introduction, waste landfilled in the UK has reduced from 85 % in 2001 (Price, 2001) to 34 % by 2012/2013 (DEFRA, 2013).

2.4 Lessons for SSA cities

There are several lessons that SSA cities can learn from transition economies and/or high-income countries with regard to the waste management hierarchy. These include:

- encouraging behaviour change in citizens, using the 4Es reported by Cox *et al.* (2010), to reduce the waste generated
- passing and enforcing suitable legislation on waste management. As reported by Couth and Trois (2010), legislation should not be overly ambitious, but rather should be set towards meeting achievable targets. When these targets are achieved the legislation may then be revised with higher targets set, as happens in countries in the EU. In addition, municipal authorities/central governments should be encouraged to allocate significant resources for this purpose. Some suitable legislation to reduce waste at source and stimulate recycling includes the volume-based waste fee system (together with household waste sorting) which is working well in Korea and Taiwan. It should be noted, however, that this system works well when all generated waste is collected. Therefore SSA authorities should first ensure that all generated waste is collected before applying the volume-based waste fee system
- formalising re-use and recycling. In many SSA cities at present, re-use and recycling is being undertaken by informal groups, such as 'scavengers' or waste pickers, with little organisation in some cities such as Kampala (Mugagga, 2006). It is likely if authorities, both municipal and central government, were more directly involved in this process, as is the case with their counterparts in high-income countries, it could have a greater impact on waste management in SSA cities. Other stakeholders such as NGOs should be encouraged to intervene and complement the waste management efforts of the authorities, as is the case in Japan (Geng *et al.*, 2010)
- introducing EPR. As noted earlier in section 2.2.3, implementation of EPR, where the manufacturers of goods are responsible for the recycling of their products, has contributed significantly to recycling efforts elsewhere. Even though most of the goods used in SSA cities are imported from elsewhere, EPR could nevertheless still be implemented in these cities. In this case, the producer's responsibility would be passed on to the supplier/agent of the goods in question. However, as pointed out by Hughes (2005) for Scotland, it will also be necessary to involve the manufacturers of these goods if EPR is to be successful. In addition, as pointed out by Lu *et al.* (2006) for Taiwan, a modified EPR system where MIS are not directly involved in recycling, but rather pay disposal fees to the governmental agency responsible for recycling, may work out best for SSA cities
- promoting biowaste treatment. Given that most of the waste generated is organic, this presents opportunities for biowaste to be treated using methods such as composting and anaerobic digestion to generate fertiliser

and biogas, as is being done in countries such as Germany, Sweden, Denmark *etc.* Although the performance of large-scale compost and anaerobic digestion plants treating MSW in SSA cities has not been very successful, this scenario was also common in high-income countries when these technologies were initially being promoted. However the failures were overcome through having proper designs, adequate operator training and favourable economic incentives. It is highly likely that SSA cities will be able to solve the problem of high failure rates if they follow what has been done in high-income countries. SSA cities need to ensure in particular that there is an assured market for the fertiliser and energy produced. In addition, according to Hoornweg and Bhada-Tata (2012), it is important that SSA cities encourage source sorting of the waste so that the waste available for treatment is less contaminated.

The largest waste stream generated in SSA is organic waste. Presently some of it is collected and dumped in landfills, which in most cases operate like open dumps. However, most of it is dumped in illegal places such as open land and drainage channels, creating environmental and public health hazards for the inhabitants of SSA cities. On the other hand, this organic waste stream is a resource whose management, if moved from disposal to higher up the waste management hierarchy, could have a beneficial impact on inhabitants' livelihoods.

The experiences of animal waste management initiatives in Uganda in the past and present have highlighted that unless farmers can expect an economic return equal to their level of investment, there will be little incentive for them to adopt sustainable waste management practices. This Ph.D. study proposes vermicomposting as an alternative incentive for farmers.

Another lesson learnt has been that participatory approaches to waste management that involve stakeholders greatly contribute to sustainable productivity and conservation of the environment. It is prudent to support the greater involvement of farmers and other stakeholders in the participatory development of simple and cheap technologies and procedures to utilise manure and waste in a sustainable manner. In conclusion, the success of some of the best practices in dealing with the problem of municipal and animal waste in cities has been rooted in their contribution to household incomes, energy needs, the development of partnerships among farmers, an analysis of waste treatment methods via LCA, collaboration, synergies dialogue and institutionalisation of key breakthroughs, the availability of markets for products, the cost effectiveness of operations and the bottom-up participatory process. Using Kampala city as a case study, the following chapter describes the methods that were used to investigate the benefits of moving the organic waste stream up the waste management hierarchy.

3. Materials and methods

Generally the methodology that was followed during the study consisted of determining the amount of organic waste in municipal waste, as well as its nutrient and energy content. This was done primarily to establish the value of organic waste. Animal farms were then mapped so as to establish the quantity of animal manure generated. In addition, the feeding regime of the animals and use of the manure generated was also established. This was done mainly to determine the prominence of organic waste recycling. The performance of vermicomposting in the degradation of organic waste and the production of biomass were then established by setting up and testing vermicompost reactors over a period of six months. The aim was to test the performance of a novel waste value chain. Finally the different waste value chains suitable for SSA cities were compared using LCA methodology.

The studies in Papers 1 – 3 were carried out in and around Kampala city as a case study of a SSA city. Kampala, the capital city of Uganda, is located 0°15′N and 32°30′E. It has a total area of 190km^2 (Matagi, 2002). The city is experiencing rapid population growth due to immigration and natural increase (Howard *et al.*, 2003) and its population is estimated to be 1.5 million (KCCA, 2012). Kampala city has five divisions, with Kawempe division being the poorest and the Central division, which includes the Central Business District (CBD), being the wealthiest of them all (Golooba, 2003). Makindye division is mainly a residential area with a mix of very low-income and medium-to-high income areas in addition to being generally peri-urban in nature (Mugagga, 2006). Kampala's other divisions are Rubaga and Nakawa which are also peri-urban in nature.

The specific methodologies followed for the studies are explained in more detail in the section below.

3.1 Characterisation of municipal waste in Kampala (Paper I)

This study was carried out at Kiteezi landfill, located about 12km north of Kampala city centre. The landfill is 20 acres in size and, at the time of the study, was being operated by the private company Otada Construction Company. Upon arrival the waste was weighed and upon dumping it was processed by ‘scavengers’ (also known as waste pickers) for the removal of material with a market value, *e.g.* paper, metals and plastics. Truck crawlers were used to spread and scatter the waste in an effort to stimulate decomposition. Sometimes the waste was sprayed with insecticide to kill off flies before it was covered with soil (Mugagga, 2006). The landfill has a leachate treatment plant which uses mechanical aeration to reduce the biological oxygen demand of the leachate before it is released into the environment. Kiteezi landfill receives waste from Kampala city and surrounding areas, but for this study the focus was on the waste received from Kampala city.

3.1.1 Field measurements

Five garbage trucks entering Kiteezi landfill, one from each of the five different divisions of Kampala, were randomly selected each day of the analysis using a random number table. The selected truck emptied its contents for analysis in a pre-selected area. Waste pickers already working at the site were employed for analysis and assisted in manually sorting the waste into organics, hard plastics, metals, papers, soft plastics (polythene), glass, textiles and leather and others, according to Zurbrügg (2003). The weights of the different fractions were recorded. The organic fraction was then thoroughly mixed and spread out by hand on a 5 by 2 m grid, from which 10 samples of one kilogram each were randomly picked per grid. These samples were then thoroughly mixed before a final one kilogram sample was drawn for nutrient and energy content analysis. The procedure was then repeated for one truck per division per day for thirty consecutive days, and thereafter for two consecutive days every two months. The total mass of material entering the landfill both during the days of study and for the full year was copied from the landfill’s log book.

3.1.2 Laboratory analyses

Moisture content was determined from samples dried at 105 °C for about three hours. Total nitrogen (N), total phosphorous (P) and total potassium (K) were determined from the samples following the procedure as specified in (Okalebo *et al.*, 2002). The energy content of the sample was determined by placing it in the sample pan of the bomb calorimeter (GallenKamp autobomb, United

Kingdom, CAB001.ABC.C) and following the procedure of (Jessup, 1960) that is still being used today.

3.1.3 Data analysis

The data collected were analysed using R statistical software's two-way ANOVA and Tukey test to check whether there was any difference in waste composition between the different divisions and months. The procedure used was as specified in Venables *et al.* (2012). The box plots were also generated using the R statistical software following the procedure specified in Venables *et al.* (2012)

3.2 Quantification of animal waste generated in Kampala (Paper II)

This study was conducted between March and August 2011, mainly among households involved in animal production in and around Kampala city. These households were identified and contacted with the help of their respective veterinary assistants. A total of 1,300 animal farmers from Kampala city were interviewed.

Data collected from the different farming households included the farm's global positioning system (GPS) coordinates (obtained using a Magellan Triton 500 hand-held GPS instrument), the type and number of animals kept, the type and origin of the animal feed used and the current usage of manure generated by the animals.

The data was analysed using R software for statistical ANOVA, Tukey test and logistic regression (Venables *et al.*, 2012). The location of the farms was mapped using the geographic information system (GIS) ArcMap 10 software, following the procedure specified by Hillier (2011).

3.3 Vermicompost treatment efficiency (Paper III)

The vermicompost reactor (VCR) was built and placed at the Makerere University Agricultural Research Institute Kabanyoro (MUARIK) on the outskirts of Kampala, Uganda. The reactor consisted of custom-made hardwood pallet frames stacked on top of one other (see Fig. 2). The base pallet with netting on the bottom was filled with bedding material in the form of matured compost. The bedding material acted as a refuge for the worms when the conditions in the compost became unfavourable (*e.g.* high temperature or ammonia concentration). Damp newspaper balls were placed at the edges of the pallet to encourage cocoon formation. As the compost filled up, additional support pallets were added. A top pallet, covered with netting, was placed on top, onto which banana leaves were placed to prevent light from entering the VCR.

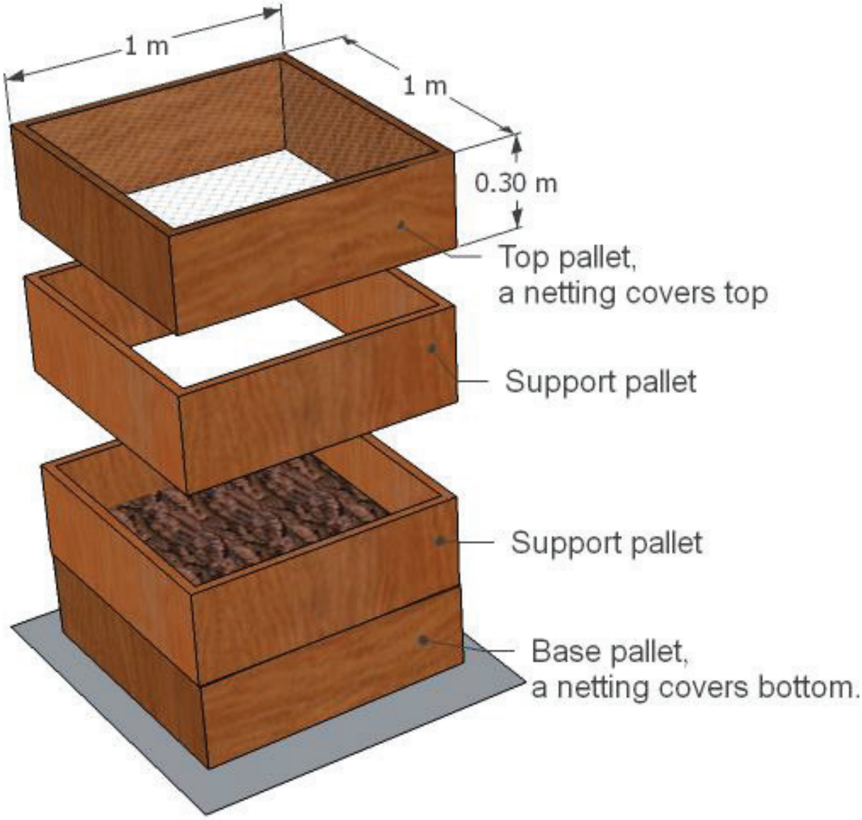

Figure 2: Vermicompost reactor

3.3.1 Addition of earthworms and waste to the VCR

Earthworms of the indigenous species *Eudrilus eugeniae* were used in the treatment unit. They were added to the VCR and their numbers noted down. In total 5,300 worms were added to the unit. The unit was mainly fed three-day-old manure (around 80 % of total feed added), but also fresh food waste (around 20 % of total feed added). The amount of waste added to the unit was adjusted in accordance with the amount consumed by the earthworms. At the end of the experiment (six months), samples of both the worms and the compost were taken.

3.3.2 Sampling

Samples were collected from two layers: the top layer and the centre-bottom layer. From each layer, five random grab samples of around 300 g each were collected in 500 mL plastic beakers.

3.3.3 Physicochemical analysis

Samples were sent to the Soil and Plant Analytical Laboratories at the National Agricultural Research Laboratories (NARL) in Kampala for analysis of total nitrogen (N), total phosphorous (P) and total potassium (K). The material was dried at 105 °C for 14 h for determination of total solids (TS) and at 550 °C for 6 h for volatile solids (VS).

3.3.4 Microbial analysis

Salmonella spp. was detected by growth on plates of xylose lysine desoxycholate agar (XLD) (Oxoid AB, Sweden) containing 0.15 % sodium-novobiocin which was incubated at 37 °C for 12 h. All salmonella-specific colonies were counted, with a detection limit of 10 CFU g^{-1}. *Enterococcus spp.* was grown on plates of Slanetz-Bartley agar (Oxoid AB, Sweden) incubated at 40-41 °C for 48 h and counted with a detection limit of 100 CFU g^{-1}. Total coliforms (TC) were enumerated in double layer agar using violet red bile agar (VRB) (Oxoid AB, Sweden) and counted with a detection limit of 10 CFU g^{-1}.

3.3.5 Worm analysis

The worms were counted manually. For microbial and physicochemical analysis, the washed worms were weighed and crushed using a mortar and pestle. For microbial analysis, predominantly adult worms were used.

3.3.6 Mass balance

The material in the vermicompost was assumed to be mainly polysaccharides (cellulose and starch), thus the chemical formula $C_6H_{10}O_5$ was used when calculating the amount of oxygen needed for respiration. For each polysaccharide, six oxygen molecules were required for full degradation into six carbon dioxide and five water molecules. For the mass balance, it was assumed that the total mass of material reduced on a VS basis had been completely respired into carbon dioxide and water.

3.4 LCA of organic waste treatment technologies (Paper IV)

LCA (life cycle assessment) methodology was used to perform the environmental comparison between the different technologies proposed for treating biodegradable waste to produce a quality organic fertiliser. According to ISO 14040, the main phases of the LCA procedure are goal and scope definition, inventory analysis and impact assessment (Baumann & Tillman, 2004). These are described below.

3.4.1 Goal and scope

The goal of the study was to evaluate and compare different biological waste treatment technologies for producing a soil improver or fertiliser from biodegradable waste in SSA in terms of their environmental impacts (energy use, global warming potential (GWP) and eutrophication potential). The LCA performed also sought to identify processes contributing most to the environmental impacts associated with a particular waste treatment technology, so that possible improvements in the life cycle of the different technologies could be suggested. The functional unit used was one tonne of impurity-free biodegradable waste treated to produce a quality soil improver/ fertiliser.

3.4.2 System boundaries

The generic system boundary on which the different biodegradable waste treatment system was based is shown in Figure 3. The system analysis began when the biodegradable waste treatment system received the waste at the gate of its pre-treatment section and ended after a soil improver or fertiliser had been applied in the field. Waste generation, collection and sorting processes were not considered because they were the same for the different treatment technologies. Product substitution was employed for those systems producing more than one end product.

3.4.3 Sensitivity analysis

Three sensitivity analyses were performed as follows:

1. investigation of the effect of including the wheel-loader and truck transport in the composting system (current practice in Ugandan compost plants) and wheel-loader in the AD system (Scenario I).
2. investigation of the effect caused by carbon bound in the soil (Cbind) with an assumed value of 3 % (Scenario II).
3. investigation of the effect of having a poorly managed AD system with methane leakage values of 20 % (Scenario III).

These were compared with the current conditions (baseline).

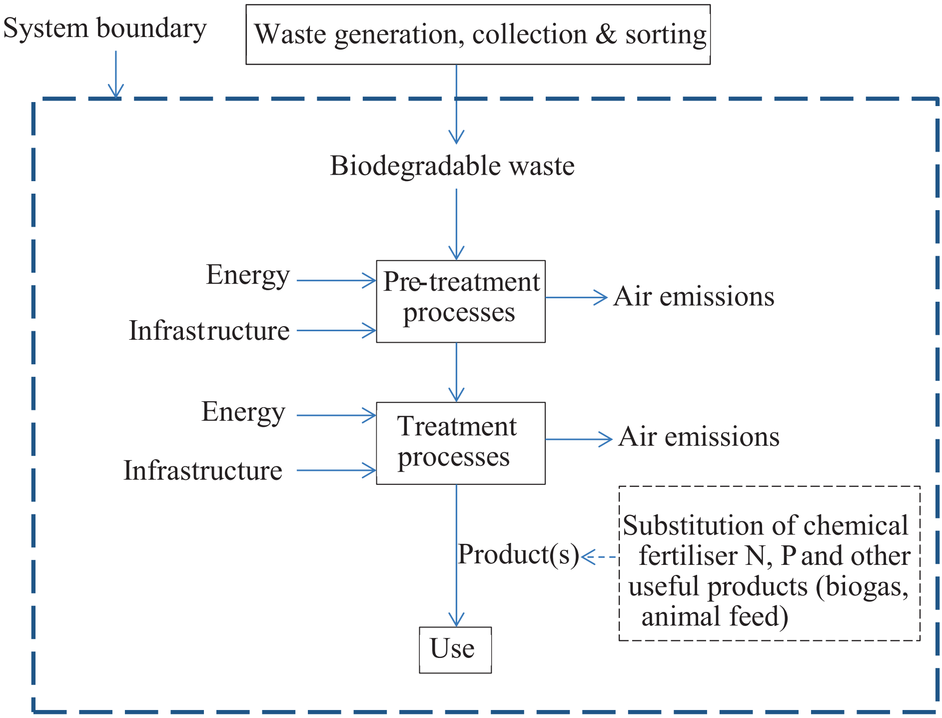

Figure 3: Generic system boundary of biodegradable waste treatment system

3.4.4 Impact categories

The impact categories considered in this study were emissions causing potential global warming and potential eutrophication and use of energy. These factors were chosen on the basis of environmental relevance. The characterisation factors used were taken from (Solomon *et al.*, 2007) for global warming (1, 25 and 298 CO2-equivalents for CO2, CH4 and nitrous oxide (N2O), respectively) and from (CML, 2002) for eutrophication (0.13, 0.35 and 0.10 phosphate-equivalents for nitrogen oxides (NOx), ammonia (NH3) and nitrate (NO3), respectively.

4. Results and discussions

This chapter reports and discusses the results of the studies undertaken to quantify the organic waste in municipal wastes collected and disposed at Kampala's landfill, as well as that generated on animal farms in Kampala. The chapter then reports on the results of and related discussions concerning the vermicompost studies performed to treat the organic waste generated in Kampala. Finally the results of the LCA study to compare the vermicompost treatment method with other organic waste treatment methods are reported and discussed.

4.1 Characterisation of Kampala's municipal waste – (Paper I)

4.1.1 Amount of waste delivered to landfill

Table 2 shows the amount of municipal waste collected from Kampala city's different divisions and delivered to the landfill by both KCCA and private trucks over a one-year period. Waste delivered by the private trucks is not location-specific unlike that of KCCA trucks. Statistical tests were therefore restricted to waste delivered by the latter.

ANOVA tests corresponding to a 95 % confidence interval showed that the quantity of waste delivered to the landfill from the Central division was significantly greater ($p<0.05$) than that of the other divisions. However there was no significant difference in waste quantities delivered to the landfill during the different months.

Table 2: Waste quantities (Gg) delivered to the landfill by KCCA and private trucks during the study period

Year	**Mon**	**KCCA trucks**						**Private trucks**	**Total waste**
		Kaw	Cent	Nak	Rub	Mak	Tot		
2011	**July**	3.1	5.4	3.7	3.2	3.0	18.4	9.5	27.9
2011	**Aug**	3.6	5.3	3.5	3.0	3.5	18.9	8.7	27.6
2011	**Sept**	3.1	5.8	3.6	3.4	1.9	17.8	9.0	26.8
2011	**Octr**	2.8	5.6	3.2	3.2	2.8	17.6	9.5	27.1
2011	**Nov**	3.0	5.4	3.2	3.4	2.9	17.9	10.0	27.9
2011	**Dec**	3.2	5.7	3.3	3.4	2.8	18.4	8.6	27.0
2012	**Jan**	3.0	5.8	4.2	3.2	2.7	18.9	9.1	28.0
2012	**Feb**	3.2	5.6	4.0	3.4	2.1	18.3	8.7	27.0
2012	**Mar**	3.6	6.2	4.1	3.5	2.7	20.1	9.2	29.3
2012	**Apr**	3.7	7.0	4.6	3.2	2.2	20.7	9.0	29.7
2012	**May**	3.2	5.5	4.0	3.8	3.0	19.5	10.0	29.5
2012	**Jun**	3.5	6.1	4.1	3.6	3.0	20.3	9.2	29.5
Average		3.3	5.6	3.8	3.4	2.7	18.8	9.2	28.0

More waste is collected from the Central division because of its political sensitivity. As such, it receives more resources for waste management. For example it is allocated about twice the number of waste collection trucks compared to the other divisions and waste collection is performed 24 hours a day while in the other divisions it is carried out for 12 hours a day. A similar trend was reported for Nairobi city (Henry *et al.*, 2006). Both Henry *et al.* (2006) and Parrot *et al.* (2009) reported a reduction in the amount of waste delivered to landfill in Nairobi and Yaoundé respectively during the wet season compared with the dry season. However, in the present study there was no significant difference in the total quantities of waste delivered to landfill in the dry and wet months. Both Henry *et al.* (2006) and Parrot *et al.* (2009) cite impassable roads during the wet season as the major reason for the reduction in total waste quantity delivered to landfill. Although Kampala also has several impassable roads during the wet months, the results of this study indicate that this factor has a minimal effect on the total waste collection. It appears that areas with poor roads are avoided during the wet months, with waste collectors concentrating their services on areas with better roads. In most cases, such areas are more affluent and most likely to generate less organic waste than less affluent areas. This could explain the difference observed in waste composition between the different months, with more plastics and paper and less organics in the wet months (Table 4). It also indicates that the limiting factor in collection is actually transport capacity and not waste generation. Furthermore, the collection of waste in selected areas during the wet months could be responsible for the practice of dumping waste into drainage channels during rain/storm events, which can lead to a blockage of the channels and subsequent flooding in low-lying areas.

4.1.2 Physical composition of Kampala's MSW

In Kampala, the most dominant waste streams obtained in the waste generated were organics (92 %), soft plastics (3 %), hard plastics (2 %) and papers (1 %) (Tables 3 and 4).

The two-way ANOVA test showed no significant differences ($P > 0.05$) in the percentage of metal, glass, textile and leather and other waste fractions between the different divisions and months. However the same test showed a significant difference ($P < 0.05$) in the percentage of paper waste between the different divisions and months. Further analysis by Tukey tests revealed that Central division had a significantly higher ($P < 0.05$) percentage of paper waste than other divisions. This is expected since the Central Business District is located in the Central division.

Table 3: Mean composition of municipal waste from Kampala by percentage weight and total waste collected from the five different divisions of Kampala city (mean ± CV)

Division	Organic	Hard plastics	Metals	Papers	Soft plastics	Glass	Textiles & leather	Other
Nakawa	91.0 ± 0.0	2.0 ± 0.9	0.1 ± 0.7	1.2 ± 1.2	3.9 ± 0.4	0.5 ± 0.9	0.6 ± 0.9	0.6 ± 0.8
Makindye	95.0 ± 0.0	1.1 ± 0.6	0.1 ± 0.9	0.7 ± 0.9	2.0 ± 0.5	0.3 ± 0.6	0.3 ± 0.9	0.6 ± 0.8
Kawempe	92.9 ± 0.0	1.6 ± 0.8	0.1 ± 0.9	0.7 ± 0.9	3.2 ± 0.5	0.7 ± 1.1	0.3 ± 0.8	0.5 ± 0.8
Central	91.9 ± 0.0	1.7 ± 0.7	0.2 ± 0.7	2.1± 0.9	2.4 ± 0.5	0.7 ± 0.7	0.4 ± 0.9	0.7 ± 0.9
Rubaga	89.8 ± 0.0	2.4 ± 0.8	0.2 ± 0.7	1.9 ± 0.8	3.6 ± 0.6	0.6 ± 0.9	0.7 ± 1.0	0.7 ± 1.0

Table 4: Mean composition of municipal waste from Kampala by percentage weight in seven sampling months (mean ± CV)

Month	Organics	Soft plastics	Hard plastics	Papers	Glass	Textiles & leather	Metals	Others
February*	93.6 ± 0.0	4.0 ± 0.5	1.0 ± 0.4	1.1 ± 1.0	0.5 ± 0.5	0.4 ± 1.3	0.1 ± 0.5	0.4 ± 0.5
April†	92.5 ± 0.0	3.3 ± 0.5	1.3 ± 0.5	1.5 ± 0.8	0.4 ± 0.2	0.5 ± 0.6	0.1 ± 0.7	0.5 ± 0.7
June†	87.2 ± 0.0	4.0 ± 0.3	3.7 ± 0.4	2.2 ± 0.5	0.9 ± 0.5	0.7 ± 0.5	0.3 ± 0.3	1.1 ± 0.5
July*	96.0 ± 0.0	1.9 ± 0.5	0.9 ± 0.5	0.3 ± 1.1	0.4 ± 0.7	0.2 ± 1.1	0.1 ± 1.0	0.3 ± 0.8
August*	94.8 ± 0.0	2.4 ± 0.6	0.9 ± 0.4	0.8 ± 1.1	0.3 ± 0.7	0.4 ± 1.2	0.1 ± 0.7	0.4 ± 0.7
October†	85.8 ± 0.1	4.1 ± 0.4	3.3 ± 0.3	2.8 ± 0.8	1.4 ± 0.5	0.8 ± 0.6	0.3 ± 0.4	1.4 ± 0.3
December*	94.6 ± 0.0	2.5 ± 0.5	1.2 ± 0.6	0.6 ± 1.0	0.2 ± 0.5	0.3 ± 0.8	0.1 ± 0.7	0.3 ± 0.4
Average wet months	88.5 ± 0.0	3.8 ± 0.1	2.8 ± 0.5	2.2 ± 0.3	0.9 ± 0.5	0.7 ± 0.2	0.2 ± 0.4	1.0 ± 0.5
Average dry months	94.8 ± 0.0	2.4 ± 0.1	1.0 ± 0.2	0.7 ± 0.4	0.3 ± 0.3	0.3 ± 0.3	0.1 ± 0.2	0.3 ± 0.3
Annually	92.1 ± 0.0	3.0 ± 0.3	1.8 ± 0.7	1.3 ± 0.7	0.6 ± 0.7	0.5 ± 0.5	0.1 ± 0.6	0.6± 0.8
Total/yr (Gg)	310.0	10.0	6.1	4.4	2.0	1.7	0.3	2.0

† Wet months (total rainfall >150 mm per month)

*Dry months (total rainfall <100 mm per month)

Waste from Makindye division had the highest content of organics, but the lowest content of plastics, while that from Nakawa and Rubaga divisions had the lowest organic content, but the highest plastic content (Table 3). The two-way ANOVA test showed a significant difference ($P<0.05$) in the percentage of organic waste fraction between the different divisions. Further analysis by Tukey tests revealed that Makindye had a significantly higher ($P<0.05$) percentage of organic waste than either Nakawa or Rubaga. It is likely that the good road network in Makindye facilitated better waste collection in lower income areas that mainly generate organic waste. A similar finding was reported for Nairobi and other Kenyan cities (Henry *et al.*, 2006).

The highest content of organic waste was obtained during July, August, December and February and the lowest during October, June and April (Table 7). The highest content of plastic waste (both hard and soft) was obtained during October, June and April. Two-way ANOVA showed a significant difference ($P<0.05$) in the percentage of organic and plastic waste delivered to landfill between the different months. The Tukey test confirmed that the percentage of organic waste was significantly lower ($P<0.05$) in June and October compared with the other months. The organic waste fraction delivered in April was also significantly lower ($P<0.05$) than that delivered in July and August. In addition to waste collectors collecting waste from mainly affluent areas with a better road network during wet months, another explanation for the higher content of organic waste in the waste stream is that the dry months normally coincide with the harvest season for many food crops in the city's hinterland and peri-urban areas. As such the city markets are flooded with an abundance of various food crops at cheaper prices (Haggblade & Dewina, 2010). This process of increased availability and consumption of these food crops by the city's inhabitants could also be responsible for the higher prevalence of organic waste during the dry months than during the wet months.

4.1.3 Chemical composition of the organic fraction in Kampala's MSW

The mean moisture, nutrient and energy contents of samples taken from the organic waste delivered in the different months are summarised in Table 5.

Table 5: Nutrient, energy (mean ±CV), total waste weight (dry matter) and moisture content of organic waste delivered to landfill in Kampala during different months of the year

Month	**M_C (%)**	**Nitrogen (g/Kg DM)**	**Phosphorus (g/Kg DM)**	**Potassium (g/Kg DM)**	**Gross_EC (MJ/kg DM)**	**Tot waste in DM (Gg)**
February*	66.8 ± 0.0	18.5 ± 0.3	3.0 ± 0.3	31.4 ± 0.3	16.3 ± 0.2	8.4
April†	76.6 ± 0.0	13.5 ± 0.2	2.4 ± 0.2	6.9 ± 0.2	18.5 ± 0.3	6.4
June†	71.7 ± 0.1	18.6 ± 0.4	2.4 ± 0.3	9.5 ± 0.7	17.7 ± 0.3	7.3
July*	68.5 ± 0.1	21.8 ±0.2	3.0 ± 0.2	29.2 ± 0.3	15.6 ± 0.1	8.4
August*	69.2 ± 0.1	21.4± 0.2	2.7 ± 0.4	23.5 ± 0.4	17.0 ± 0.3	8.1
October†	74.8 ± 0.1	14.0± 0.3	2.4 ± 0.2	6.1 ± 0.3	16.7 ± 0.2	5.9
December*	70.0 ± 0.1	24.7 ± 0.2	3.3 ± 0.4	30.0 ± 0.4	19.2 ± 0.2	7.7
Average wet months	74.4 ± 0.0	15.4 ± 0.2	2.4 ± 0.0	7.5 ± 0.2	17.6 ± 0.1	6.5
Average dry months	68.6 ± 0.0	21.6 ± 0.1	3.0 ± 0.1	28.5 ± 0.1	17.0 ± 0.1	8.2
Average overall	71.1 ± 0.0	18.9 ± 0.2	2.7 ± 0.1	19.5 ± 0.1	17.3 ± 0.1	7.5

† Wet months (total rainfall >150 mm per month)

*Dry months (total rainfall <100 mm per month)

The average nutrient composition of the organic fraction in Kampala municipal waste during the dry months was 2.16 % nitrogen, 0.30 % phosphorus and 2.85 % potassium (Table 5). During the wet months, the average composition was 1.54 % nitrogen, 0.24 % phosphorus and 0.75 % potassium. This translates into an average of 1800, 260 and 1900 Mg of nitrogen, phosphorus and potassium respectively in the organic fraction of the waste delivered to landfill annually in Kampala. The two-way ANOVA test showed a significant difference ($P<0.05$) in moisture and potassium content of the organic waste delivered to the landfill in wet and dry months. The same test also showed a significant difference ($P<0.05$) in the nitrogen content of the organic waste in different months. According to Tukey tests, in April and October the nitrogen content of organic waste was significantly lower than in July, August and December ($P<0.05$). However the two-way ANOVA showed no significant differences in any of the measured chemical composition parameters of the organic waste for the different divisions of Kampala.

An explanation for the larger amount of nutrients during the dry months is that, as discussed in the previous section, it normally coincides with the harvest period for many crops (Haggblade & Dewina, 2010). Therefore, it is possible that crop wastes (and their constituent nutrients) could be present in significantly higher amounts in organic waste during the dry months than in the wet months. One of the most widely eaten foods in Kampala is bananas, locally known as matooke, and their harvest time coincides with the dry months (Haggblade & Dewina, 2010). This would also explain the unusually high amount of potassium in organic waste during the dry months as opposed to the wet months. Furthermore, according to Table 5, the nitrogen concentration in the organic fraction was highest in December. This could probably be explained by a wider variety of foodstuffs being consumed during the festive season, including food with a high protein content such as meat.

Amoding (2007) established that market waste in Kampala city contains on average 1.57 % nitrogen, 0.21 % phosphorus and 2.95 % potassium. Comparing the present results with these figures, it can be seen that the results of this study for the dry months were fairly similar, confirming the assumption that crop waste dominated the organic waste fraction generated in the dry months. Cofie *et al.* (2009) reported the quality of co-compost from a pilot plant using faecal sludge and organic waste in Kumasi, Ghana to be 1.19 % nitrogen, 1.6 % phosphorus and 1.7 % potassium. Comparing the results of Kampala with those from Kumasi, it can be concluded that it is possible to obtain a superior quality of co-compost from a combination of municipal waste and faecal sludge in Kampala.

The average gross energy content of the organic factions was 17.3 MJ/kg DM (Table 5). This figure is quite similar to the 18.0 MJ/kg DM reported by Bingh (2004), showing that organic waste has a potential for energy recovery through incineration. However, its high average moisture content of 71 % is likely to make incineration an uneconomical option (Kathirvale *et al.*, 2004).

The annual landfilling of plant nutrients from organic waste in Kampala corresponded to 92, 110 and 680 % respectively of the amounts of mineral nitrogen, phosphorus and potassium fertiliser imported to Uganda annually (FAO, 2010.). The plant availability of nitrogen in organic material is lower than that in mineral fertiliser, but anaerobic treatment would increase the availability of nitrogen in the organic material. The availability of phosphorus and potassium is more similar to that in mineral fertiliser. In addition, the organic material contains other micronutrients required by plants, as well as organic material that improves the soil structure considerably. This indicates the high potential of re-using this fraction, which could even have a significant impact on the national economy, as it would considerably increase self-sufficiency.

The energy content in the material collected annually corresponded to 1.6×10^9 MJ. If this material were processed in a biogas plant and 50 % were converted into biogas, it could be expected that 8.0×10^8 MJ of biogas would be produced, which could be used for electricity production or as vehicle fuel. Diverting organic waste from landfill into the recycling of energy and plant nutrients could therefore provide great opportunities for the future.

4.2 Quantification of animal waste generated in Kampala – (Paper II)

Animal agriculture is widely practised in Kampala. Some of the possible reasons for this include the provision of a source of income to the urban poor in particular, given the high demand for livestock products in the city (Katongole *et al.*, 2012), improvement of household nutrition through the provision of animal protein and stabilisation of household food security (Zezza & Tasciotti, 2010). Also, according to Ishagi *et al.* (2002), many livestock keepers find animal agriculture a more viable enterprise than crop production given the limitation of space. The number of animals and animal farms in the different divisions of Kampala is shown in Table 6.

The animal waste generated mainly consisted of animal faeces (poultry droppings) and urine. This waste is used in a variety of ways, as shown in Table 7.

Table 6: Number of animals (A) and farms (F) in the five divisions of Kampala City, Uganda

Name of Division	No. of Farms	No. of Sheep		No. of Goats		No. of Cattle		No. of Pigs		No. of Poultry		Animal Units*
		A	F	A	F	A	F	A	F	A	F	
Central	22	19	4	53	9	62	14	51	3	299	6	63
Kawempe	450	96	24	960	128	1630	296	1200	107	75400	176	1900
Makindye	120	19	8	500	50	610	97	740	33	11900	57	590
Nakawa	200	21	6	480	71	620	86	5800	48	113000	45	2100
Rubaga	510	57	21	1100	199	930	185	1200	150	47300	57	1300
Total	1300	212		3080		3850		9000		250000		
Animal units*		21		310		2200		900		2500		5950

*One animal unit is equal to one dairy cow or three other cattle or 10 sheep, goats and fattening pigs, or 100 poultry.

Table 7: Animal manure handling methods practised in the five divisions of Kampala City

Division	Waste usage (%)										
	Disd	Dntd	Hpd	Sold	Village	Dmp_KS	Biogas	Pigs	Burnt	Fert	Const.
Central	50	5	5	9	32						
Kawempe	42	5		2		4	1		1	44	
Makindye	22	10	3	11			3	1	9	41	1
Nakawa	53									47	
Rubaga	85									15	
Total	59	3	0	2	1	1	1	0	1	32	0

Disd = discarded, Dntd = donated, Hpd = heaped, Village = transported to the village, Dmp_KS = dumped in the municipality's waste skips, Pigs = fed to pigs, Fert = fertiliser in garden, Const = construction

About 60 % of the animal manure generated in the city is discarded in some way, while 32 % is used as fertiliser on crop fields (Figure 4). Other ways in which the manure generated is utilised include a donation free of charge to those who need it (3 %), especially peri-urban farm owners, selling it (2 %), taking it to the village to be used as fertiliser in the gardens there (1 %), generation of biogas (1 %) and incineration for insect control reasons (1%). Other insignificant uses include construction, feed for pigs and just heaping it up and letting the rain wash it away. Many farmers discard the manure as there is no comprehensive national urban policy and institutional framework to regulate the use of solid waste in the country (WaterAid, 2011). The animal manure usage in this study is similar to that reported by Prain *et al.* (2010) for Nakuru City, Kenya, where 54.5 % of the manure generated was discarded, 30.3 % was used as fertiliser in crop fields, 1.3 % was sold and 13.9 % had different uses. In Yaoundé City, Cameroon, on the other hand, most of the manure generated is used as fertiliser on crop fields within the city, while about 10 % is sold as fertiliser to other provinces. This has been attributed to the higher level awareness among urban farmers in Yaoundé of the contribution of manure to soil fertility (Prain *et al.*, 2010).

Most of the manure in Kampala City, especially in Central, Rubaga, Kawempe and Nakawa divisions, is discarded. According to Zake *et al.* (2010), this is because the smallholder farmers attach little importance to manure management. The urban crop-producing farms are also unaware of the resources in the manure, resulting in soil degradation and reduced crop yields (Mubiru *et al.*, 2007). Most of the discarded manure is dumped into drainage channels where it is carried off by running water. In the few areas that have KCCA skips nearby, some manure is dumped in them and eventually disposed of in the city landfill. Some manure is heaped and left uncovered, which not only leads to contamination of the atmosphere with greenhouse gases, but also leaves the manure exposed to disease vectors such as flies and to runoff by rain events. Through the running water, the manure eventually finds its way to Lake Victoria, contributing to its eutrophication (Banadda *et al.*, 2009). In the past, the numerous natural wetlands around Kampala acted as filters for the polluted water, but most of these have been destroyed as a result of human activities. Eutrophication has not only resulted in a loss in biodiversity of Lake Victoria, but has also led to a significant increase in water treatment costs for the National Water and Sewage Corporation, the body charged with treating and supplying clean water to Kampala City (Banadda *et al*. 2009).

On the other hand, most of the crop urban agricultural waste produced is re-used, especially in animal feed. In this study animals in Kampala City were found to be fed a variety of crop agricultural waste, including 62 % on peel (banana, potatoes and cassava), food waste (22 %), market waste (9 %) and crop residues (11 %). This is in agreement with previous studies (Maxwell 1995; Ishagi *et al*. 2002; Katongole *et al*. 2011), which highlighted the importance of different animal feeds complementing each other. A similar finding for Kampala City was reported by Prain *et al*. (2010). Likewise in Nakuru, Kenya, a variety of animal feeds are used, including pasture (53 %), concentrates (30 %) and organic refuse (17 %) (Prain *et al*. 2010).

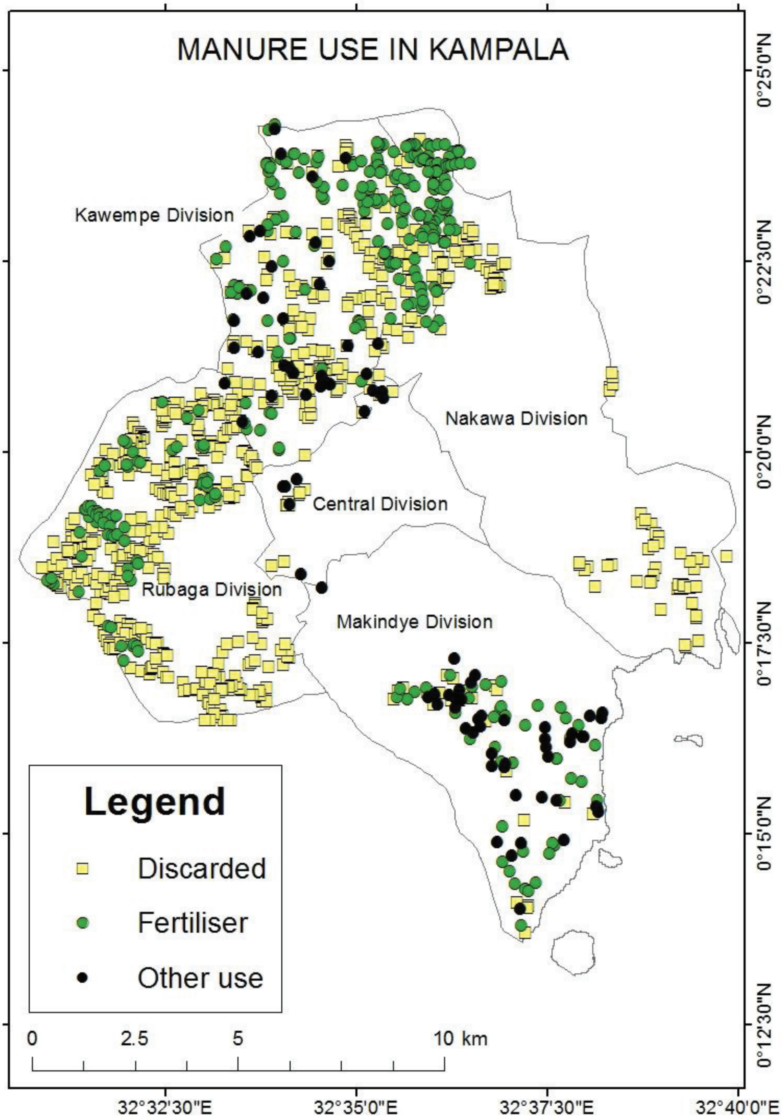

Figure 4: Manure management in the five divisions of Kampala

4.3 Vermicompost treatment efficiency – (Paper III)

Some of the results obtained from the assessment of the performance efficiency of the vermicompost reactor in treatment of organic waste in Kampala city are shown below.

4.3.1 Physicochemical parameters of the vermicompost

Table 8 shows the results of the physicochemical analysis performed on the vermicompost reactor. It shows that the percentage TS increased while the percentage VS decreased during the vermicomposting process. The N content in the vermicomposted material decreased significantly ($p < 0.05$), while the K content increased significantly. The change in P was small and only significant between the fresh material and VC-L2. The percentage concentration of nutrients decreased as they were incorporated into worm biomass. The K concentration was quite high while the concentration of P was rather low, probably because the cows were fed banana leaves which are high in K and low in P (Katongole *et al.*, 2008).

4.3.2 Microbial parameters of the vermicompost

Table 9 shows the results of the microbial analysis performed on the vermicompost reactor. There was no significant difference ($p > 0.05$) in the concentration of *Enterococcus spp.* and total coliforms (TC) between the fresh material and the vermicompost, nor was there any difference in the concentration of the two between VC-L1and VC-L2. *Salmonella spp.* was found in the fresh material, but not in the vermicomposted material or the worms.

Table 8: TS, VS, N, P and K content (%) of fresh material and VC-L1 and VC-L2 layers of the vermicompost reactor, mean ± SD

	TS (%)	VS (%)	N (%)	P (%)	K (%)
Fresh material	18.8 ± 1.1	78.2 ± 0.3	3.07 ± 0.001	0.046 ± 0.000	0.76 ± 0.12
VC-L1	$25.5 \pm 0.8^{a,b}$	62.2 ± 2.4^{a}	2.55 ± 0.049^{a}	0.052 ± 0.003	1.02 ± 0.00^{a}
VC-L2	$28.2 \pm 1.3^{a,b}$	59.6 ± 3.2^{a}	2.54 ± 0.028^{a}	0.054 ± 0.002^{a}	1.02 ± 0.00^{a}

[a]Significantly different ($p < 0.05$) from fresh material [b]Significantly different ($p < 0.05$) from VC-L1/VC-L2

Table 9: Microbial parameters of fresh material, VC-L1 and VC-L2 layers of the vermicompost reactor and the worms, mean ± SD

	Enterococcus spp. **(CFU g^{-1})**	***Salmonella spp.*** **(CFU g^{-1})**	**TC (CFU g^{-1})**
Fresh material	$7.75 \times 10^{3} \pm 1.66 \times 10^{3}$	158 ± 223	$1.37 \times 10^{5} \pm 1.25 \times 10^{5}$
VC-L1	$7.67 \times 10^{3} \pm 3.43 \times 10^{3}$	*	$3.87 \times 10^{5} \pm 1.76 \times 10^{5}$
VC-L2	$1.13 \times 10^{3} \pm 6.51 \times 10^{3}$	*	$1.14 \times 10^{5} \pm 9.83 \times 10^{4}$
Worms	$3.09 \times 10^{3} \pm 1.98 \times 10^{3}$	*	$2.79 \times 10^{5} \pm 2.76 \times 10^{4}$

Although vermicomposting has been reported as being effective in reducing pathogenic microorganisms (Kumar & Shweta, 2011; Contreras-Ramos *et al.*, 2005; Eastman *et al.*, 2001), in this study, however, the indicators *E. faecalis* and TC were found in the same concentrations in the processed material and worms as in the inflow material, despite the fact that the material had been well degraded. *Salmonella spp.,* on the other hand, though present in the inflow material, was not found in the processed material or in the worms. In studies reporting good pathogen reductions, batch systems with retention times between 60 days and six months were used. In a vertical flow continuous feeding system, such as that used here, it is likely that pathogens are spread through leaching from fresh layers down to the more processed layers (Aira *et al.*, 2011). Monroy *et al.* (2009) demonstrate a high reduction in TC on applying a low dosage of pig slurry, but not when applying a large dose. The high volume and constant feeding of this VCR system could have contributed to the low reduction shown in this system. Leaching from the fresh material to the lower layers, along with the movement of worms, could have transported microorganisms around the VCR.

A noteworthy finding was that no *Salmonella spp.* was found in the vermicompost, although fresh material had been fed into the VCR on the day before sampling, demonstrating the robustness of the vermicomposting system for inactivation of certain bacteria in the Enterobacteriaceae family. Allowing for a post-stabilisation step, in which no fresh material is added could improve the hygiene quality of the vermicompost considerably (Lalander *et al.*, 2013). However, by removing animal manure from the streets and containing it, the risk of disease transmission from the manure is already significantly lowered. Additional management strategies, such as crop selection and spreading techniques, can reduce the risk of using the vermicompost as fertiliser. If the crop to be fertilised is consumed raw or grows close to the ground, it is advisable to post-treat the vermicompost. A possible post-treatment is ammonia sanitisation, which not only sanitises the material but also increases its fertiliser value (Vinnerås, 2007).

In using worms as an animal feed, for a more closed-loop system, or in cases where the animals share common pathogens, it is advisable to treat the worms (drying or boiling) to reduce the risk of disease transmission. However, in a large-scale feed production system based on worms, post-processing occurs as an natural step, as the feed needs to be preserved and rendered storable, but also mixed with other feedstuffs in order to produce an optimised feed mixture.

4.3.3 Mass balance and efficiency of the vermicomposting process

The material reduction of the VCR was calculated as 45.9 %, while the VS loss in the material was 58.4 %. The waste-to-biomass conversion ratio (BCR) was 3.6 % on a TS basis (Table 10). Of the 90.4 kg TS of waste added to the system, 44 kg were converted into vermicompost and 3.2 kg into worm biomass (Figure 5). In total, 45.4 kg of oxygen was required for the degradation of the material. In the process, 62.4 kg of carbon dioxide and 21.3 kg of water were released (Figure 5).

Table 10: Efficiency of the VCR

Process parameters	Percentage (%)
Waste-to-biomass conversion rate (BCR)	3.6
Material reduction (TS basis)	45.9
Material respired	42.4
Total VS loss material	58.4

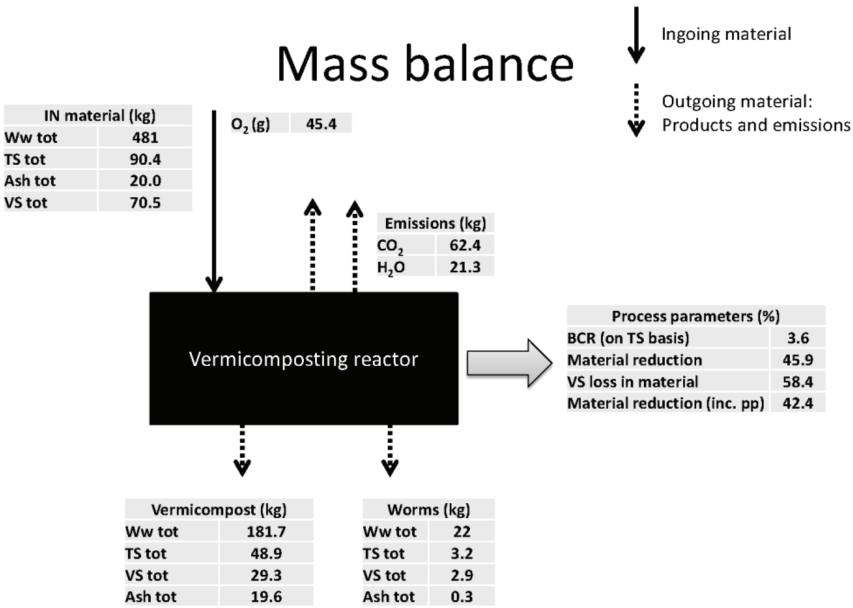

Figure 5: Mass balance of the vermicompost reactor (VCR)

Although in the present study a BCR of 3.6 % was achieved, higher BCR values have been reported in Edwards (1985) and (Mitchell, 1997; Edwards, 1985). This is mainly because many factors influence the BCR value obtained. According to Yadav *et al.* (2011), initial worm stocking density dictates which of the two products (vermicompost and biomass) is optimised. In their study, a higher stocking density (3 kg m^{-3}) increased vermicompost production while a lower stocking density (0.5 kg m^{-3}) increased biomass production. Ndegwa *et al.* (2000) on the other hand determined that a higher feeding rate of 1.25 kg feed kg^{-1} worm day^{-1} generated greater biomass production and BCR. However, with this feeding rate, the material processing was lacking and a larger quantity of material was found unprocessed at the end of the experiment. For better vermicompost production, a lower feeding rate of 0.75 kg feed kg^{-1} worm day^{-1} was necessary. In the present study the exact feeding rate per worm was not determined as the number of worms in the unit was not known at all times, but in the end a feeding rate of around 0.4 kg feed kg^{-1} worm day^{-1} was used. In the present study, the VCR was fed with a mixture of three-day-old manure and food waste. An increase in the quantity of the latter led to an increase in temperature of over 40 °C in the VCR. A similar observation was made when the VCR was fed with excess cow dung than was capable of being consumed by the worms. At the first harvest, the worms were large (because of excess available feed during this time), while at the second harvest the worms were smaller (due to adjustment in the feeding to provide the worms only with the quantity of feed they could consume). This finding was in agreement with what was reported by Yadav *et al.* (2011). Vorsters *et al.* (1997) found that the average individual worm mass decreased with increased worm density. With more frequent harvesting, the worm density could be kept lower and a higher BCR could be expected.

4.4 Lifecycle assessment of organic waste treatment technologies – (Paper III)

The results obtained for the LCA study performed to compare the environmental performance of the different organic waste treatment technologies are presented in Figures 6, 7 and 8.

As can be seen from Figure 6, the dry AD system performed best by far in terms of energy use, followed by composting, BSF and vermicomposting. The good performance of the dry AD system was mainly because of its energy production capability.

According to Mshandete and Parawira (2009), only 10 % of the population in SSA countries has access to electricity. The rest of the population mainly depends on biomass in the form firewood and charcoal to meet energy needs, resulting in significant environmental issues (Parawira, 2009) and health problems (Nzila *et al.*, 2012). The AD system can play a role in addressing the energy needs of the population, as well as in reducing the environmental and health problems associated with current practices. Construction of the digester, which included infrastructure and transport, had an impact on energy use in all the technologies (Figure 5). The vermicomposting system performed poorly in terms of energy use, partly because of the greater amount of energy used during its construction. According to Munroe (2007), the vermicomposting system requires more space because worms are surface feeders and do not operate in material more than one metre deep. Thus the construction of a large surface area is of paramount importance if the vermicomposting system is to be successful.

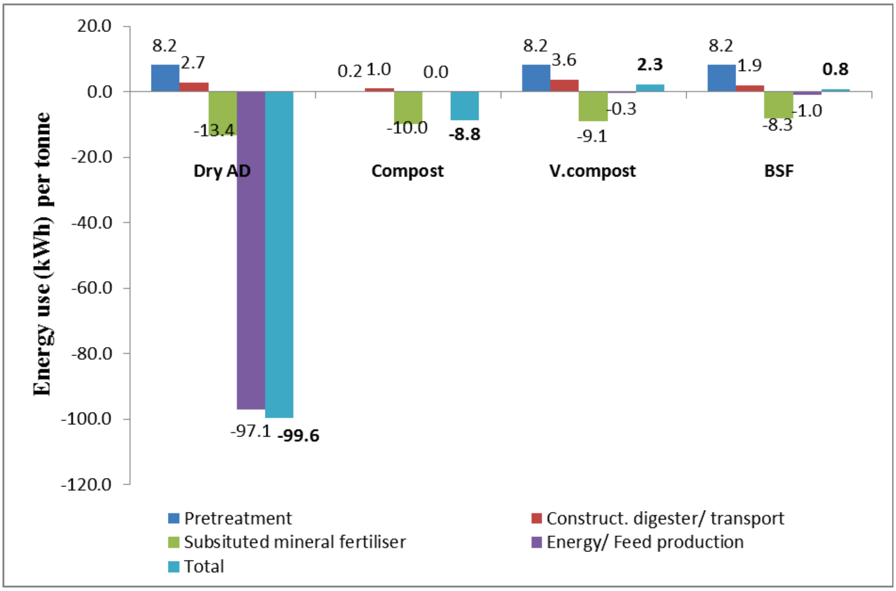

Figure 6: Energy use in the different biodegradable waste treatment technologies. AD = anaerobic digestion treatment, BSF = black soldier fly treatment

Although Nzila *et al.* (2012) performed an LCA for different AD systems used locally to produce biogas in SSA countries, it is difficult to compare their findings with those obtained in this study since the boundary conditions and functional unit chosen were different. The net energy value of 40.4 kWh per tonne which they reported for the worst AD system is quite high compared with the findings in this study, and originated mainly because electricity production from biogas was not considered by (Nzila *et al.*, 2012).

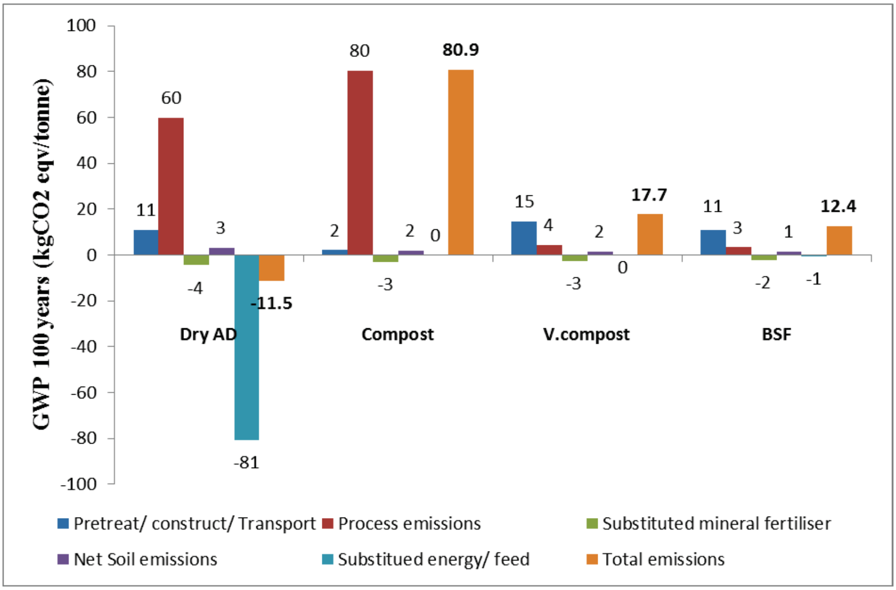

Figure 7. Global warming potential (GWP) of the different biodegradable waste treatment technologies. AD = anaerobic digestion treatment, BSF = black soldier fly treatment.

In terms of global warming, the dry AD system was again the best treatment, followed by BSF, vermicomposting and composting in that order (Figure 7).

The good performance of the AD system as regards global warming was mainly because of the electricity it produces replaces electricity produced by fossil fuel. The process emissions, especially in the AD and composting treatment technologies, contributed significantly to the GWP. The worst performing technology was the composting system (Figure 6). However according to Couth and Trois (2012), GWP associated with the composting of municipal waste is far less than that generated when the same waste is dumped in landfill. The poor performance of the composting system was mainly due to the greenhouse gases (GHG) released during the composting process. According to Boldrin *et al.* (2009), GHG emissions due to degradation of organic matter during the composting process (direct) are dependent on both the management and type of technology. Proper blending of input feedstock and optimised forced aeration can minimise the production of GHG, while treatment for removal of CH_4 and N_2O could result in large improvements in the system compared with open systems where gaseous emissions are not treated. Boldrin *et al.* (2009) and Ermolaev *et al.* (2014) also showed that home composting has lower direct GHG emissions and thus could be preferable to large-scale composting systems in terms of GWP. Although the fugitive emissions represented significant GHG emissions in the AD system, their effect was nevertheless cancelled out by the electricity produced, which replaced electricity produced by fossil fuel. In addition, in well-performing AD systems, the fugitive emissions are less than the 10 % assumed here, thus presenting a way in which the performance of the AD system can be increased further. However, it is a challenge to achieve low emissions from dry phase systems such as those studied here. Furthermore, if the digestate needs to be stored before use, this can cause a high level of emissions. Couth and Trois (2012) report that SSA countries are experiencing a massive increase in their GHG emissions, with GHG from waste being greater than the global average. AD technology could play an important role in reversing this trend. Barton *et al.* (2008) compared a number of options for managing urban waste and also established that AD performed best in terms of GWP. They determined that the AD system provided a net benefit in terms of GHG of -0.21 tCO2-eq/t waste, while composting was essentially carbon neutral. Nzila *et al.* (2012), on the other hand, established that the best-performing AD system had net emissions of 0.074tCO2-eq/t waste. These findings are quite different from those in this study, mainly because Barton *et al.* (2008)) did not consider the use phase of the digestate/compost produced and Nzila *et al.* (2012) used different system boundaries.

A graphical representation of the eutrophication potential of the different biodegradable waste treatment technologies analysed in the present study revealed a similar pattern to the other indicators (Figure 8).

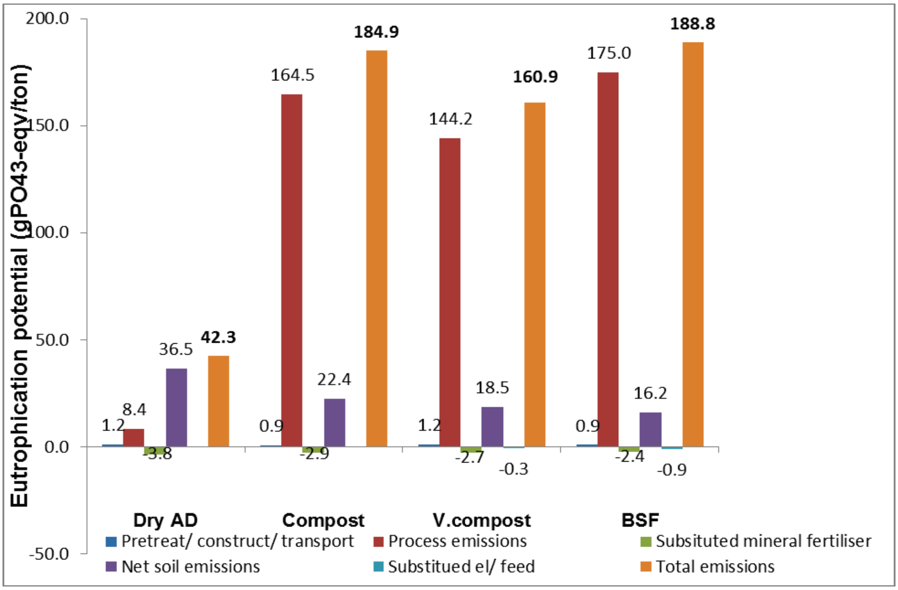

Figure 8. Eutrophication potential of the different biodegradable waste treatment technologies. AD = anaerobic digestion treatment, BSF = black soldier fly treatment.

Figure 8 shows that the AD system performed best in eutrophication, while the compost, BSF and also the vermicompost systems performed poorly. This is mainly because of the ammonia volatilisation in these systems. According to Boldrin *et al.* (2009), in the compost system this can be improved by modifying the waste type composted and introducing more garden waste. However it is not certain whether this will be successful when undertaken for the BSF and vermicompost systems. Further research is therefore needed to establish the effect of modification of the waste type on ammonia volatilisation in the BSF and vermicompost systems.

Table 11: Sensitivity analysis on potential energy use, global warming potential (GWP) and eutrophication in Scenarios I-IV (see text for explanation). BSF = black soldier fly treatment.

	Baseline values and increases from baseline values (per tonne of waste)			
Scenario	System	Energy (kWh)	GWP (kg CO2 eqv.)	Eutrophication (g PO4-3 eqv)
Baseline	Anaerobic digestion	-99.6	-11.5	42.3
	Compost	-8.8	80.9	184.9
	Vermicompost	2.3	17.7	160.9
	BSF	0.8	12.4	188.8
I: Wheel-loader	Anaerobic digestion	-97.0	-8.0	46.1
	Compost	-6.5	82.8	187.8
II: C_{bind} = 3 %,	Anaerobic digestion	-	-16.7	-
	Compost	-	77.5	-
	Vermicompost	-	14.3	-
	BSF	-	9.3	-
III: Methane leakage 20 %	Anaerobic digestion	-	44.5	-

Sensitivity analysis showed that, including the wheeloader (Scenario II) had a small impact on the energy and GWP of the AD system (Table 11). However, it had a significant impact on GWP of the composting system, making its performance even worse. Raising the Cbind value to 3 % (Scenario III) significantly improved GWP of the different systems, while a poorly performing AD system with methane losses of 20 % (Scenario IV) changed its status as the best performing system (Table 11), thus highlighting the importance of this factor in AD's global warming performance. Sensitivity analysis also showed that the different changes had a negligible effect on eutrophication potential.

5. General discussions

This chapter contains a general discussion on the products of the various organic waste management technologies and their markets in particular, as well as on the waste treatment technology that can be recommended, considering technological challenges, scales of operation, required investments, operation and maintenance, marketable products and environmental impacts.

5.1 Farms and their use of fertilisers

Paper II established that animal farms were predominantly located on the periphery of Kampala city, which is more peri-urban in nature and has a lower population density. This finding was in agreement with what was reported by Prain *et al.* (2010) and is shown in Table 12.

Table 12: Urban agriculture classification system in Kampala city (adapted from Prain *et al.* (2010))

	Urban, old	**Urban, new (dense slum)**	**Peri-urban in transition**	**Peri-urban (peripheral)**
Population density	Very high	High	Medium	Low
Prevalence of crop production	Low	Low	Medium	High
Prevalence of local livestock	Low	Low	Low	High
Prevalence of improved livestock	Medium	High	High	Low
Land availability	Limited	Limited	Moderate	Very good

Table 12 shows the high prevalence of crop and livestock production in peri-urban areas of Kampala city. From this, it was expected that there would have been numerous opportunities for nutrient recycling through the re-use of animal manure generated as fertiliser on crop farms in close proximity to animal farms. However, this was not the case as Paper II determined that only

32 % of the manure generated on animal farms in Kampala as used as fertiliser, while about 60 % of this manure was discarded in one way or another. This is happening in spite of the fact that there is a major decline in soil fertility all over Uganda (Pender *et al.*, 2001), with Uganda reportedly having one of the highest rates of soil nutrient depletion in SSA (Henao & Baanante, 2006; Stoorvogel & Smaling, 1990). The low usage of animal manure in Kampala established in Paper II is in agreement with what was reported by UBOS (2007), as shown in Table 13.

Table 13: Percentage of farm households using fertilisers in Uganda (adapted from (UBOS, 2007)).

Region	Chemical fertiliser	Manure
Central	1.3	8.7
Eastern	1.1	4.1
Northern	0.7	0.5
Western	0.6	9.6
National	1.0	6.8

The low usage of fertiliser in Uganda mirrors that of the SSA region (excluding South Africa), as shown in Table 14, where the fertiliser usage in this region is generally far below that of other regions in the developing world.

Table 14: Fertiliser use intensity and growth by developing region in 1962, 1982 and 2002 (Morris, 2007).

Region	Total nutrients (kilograms / hectare)			Annual growth (%)	
Year	1962	1982	2002	1962 - 1982	1982 - 2002
South Asia	3	38	101	13.2	5.0
East and South-east Asia	12	53	96	7.6	3.4
Latin America	10	43	78	7.8	3.1
SSA	1	7	8	8.7	0.9
Average for Developing Regions	7	35	71	9.3	3.1

In addition, Henao and Baanante (2006) reported that for the period 2002-2004, 85 % of African arable land experienced nutrient depletion rates of over 30 kg per hectare of nutrients per year, while 40 % experienced nutrient depletion rates of over 60 kg per hectare per year. For Uganda, the figure was 66 kg per hectare per year.

Table 13 shows that the majority of farm households in Uganda do not maximise their crop yields, thus leading to low productivity. An example of low productivity in SSA countries is shown by cereal yield statistics for the year 2000 derived from FAOSTAT and cited by Morris (2007) as follows: one hectare of land yielded an average of 1.0 metric tonnes of cereals compared to 3.4, 2.9 and 2.4 metric tonnes for East and South-east Asia, Latin America and South Asia respectively. According to Bayite-Kasule (2009), one reason for low fertiliser use in Uganda is inadequate research and policy analysis on fertiliser promotion and use. For instance, farm households are not motivated to use fertilisers because of an absence of information on crop-fertiliser profitability across the country, meaning that farmers cannot tell exactly how much they stand to gain or lose when they apply a particular fertiliser on a particular crop. Having this information (value-cost ratio for each fertiliser) can stimulate farmers' interest in the use of fertilisers (Bayite-Kasule, 2009). Other impediments to fertiliser usage by farmers in SSA, according to Morris (2007), include a lack of market information about the availability and cost of fertilizer, an inability to purchase fertilisers due to poverty among farmers and a lack of knowledge on how to use fertilisers efficiently. It should be noted however that it is difficult to restore organic matter, a key ingredient in the fertility of SSA's tropical soils, so that without nutrient replenishment, African farmers risk degrading their soils to the point of no return. Thus organic fertilisers, where available, should form an integral part of the soil fertility management strategy (Morris, 2007). This Ph.D. study was therefore an attempt to generate organic fertiliser from urban municipal waste that can be of use in addressing the problem of soil degradation of African soils.

Some of the practical interventions that can be used by authorities to promote fertiliser usage among farmers include strengthening agricultural research through the provision of adequate funding to various agricultural organisations to enable them carry out on-farm fertiliser trials and demonstrations, improving the financial viability of crop enterprises by providing market information, and protecting farmers against fluctuating crop prices, which in turn will improve farmers' ability to purchase fertilisers.

Although experts acknowledge the desirability of organic fertilisers in improving soil fertility levels, they also agree that exclusive dependence on them to maintain soil fertility levels in this age of intensive production may not be possible and recommend that they complement inorganic fertilisers (Morris, 2007). Nevertheless, as established in this study (Papers I and II), their quantities from municipal waste are considerable, as has been reported for other SSA cities (Hoornweg & Bhada-Tata, 2012; Kofoworola, 2007; Bolaane & Ali, 2004). In addition, adding value to the large quantity of organic waste in municipal waste can tackle two issues at the same time: getting rid of organic waste and providing a soil improver/ fertiliser.

In Paper III, it was also established that vermicomposting of waste is a viable venture for supporting UA in SSA cities. According to Singh *et al.* (2011), vermicompost is beneficial to agricultural soil in terms of increased moisture retention ability, better nutrient holding capacity, superior soil structure and higher levels of microbial activity. Atiyeh *et al.* (2000) report that vermicompost has a higher concentration of nitrates, which is the more plant-available form of nitrogen. Vermicompost's popularity has increased greatly due to its high economic value compared to traditional compost (Tripathi & Bhardwaj, 2004). The nutrients in it, which are in a higher concentration than in the waste from which it was derived, are readily available for plant growth (Tripathi & Bhardwaj, 2004). Thus use of vermicompost also has considerable potential for addressing the declining yields in SSA cities such as Kampala.

In Paper I, it was established that the quantity of organic waste dumped at Kampala's landfill constituted an average value of 92.1 % of the 28,000 tonnes or so of waste brought to the landfill every month. Average nutrient content of the organic waste was 1.89 % nitrogen, 0.27 % phosphorous and 1.95 % potassium (Table 5). This translates into 1800, 260 and 1900 Mg of nitrogen, phosphorus and potassium respectively in the organic fraction of waste delivered to landfill annually in Kampala following the procedures specified in in Paper IV. When the quantity of nutrients in non-utilised animal manure are added, the total quantity of plant nutrients lost in Kampala's organic waste is determined to be 1410 Mg nitrogen, 653 Mg phosphorus and 4800 Mg potassium – nutrients which, if utilised, could go a long way towards improving urban crop agriculture in Kampala.

According to Bayite-Kasule (2009), the production of maize in the central region of Uganda (where Kampala is located) requires 90 kg of nitrogen and 20 kg of phosphorus per hectare. Kampala city has about 1000 ha of its area under crop cultivation according to personal communication from Ahimbisibwe (2014). If all this area was to be cultivated with maize, the nutrients required would be 180 Mg of nitrogen and 40 Mg of phosphorous for the two cropping seasons. Applying nutrients lost in animal manure to crop fields in Kampala, it can be seen that 33% and 7.5% of Kampala's maize requirement of nitrogen and phosphorus respectively could be met. When including, the unutilised nutrients from the total organic waste collected (organic waste at landfill and unutilised animal waste) are able to meet 330% and 660% of the requirements of Kampala's maize requirement of nitrogen and phosphorus respectively. Given that the districts surrounding Kampala are peri-urban/ rural in nature (Muhanguzi *et al.*, 2012) with lots of crop farming activities taking place in them (Kaye, 2006), the excess nutrients produced in Kampala would require short transports only for appropriate distribution of the nutrients

Having the knowledge that a large quantity of vital plant nutrients remains unexploited in municipal waste may encourage municipal authorities to promote the waste management hierarchy, especially as regards material recovery. Doing this would have many benefits, some of which may include lengthening the life span of landfills, reducing greenhouse gases emitted from poorly disposed organic waste and improving food security through a stimulation of urban agriculture, to name just a few.

In Kampala, there is no widespread use of fertiliser from organic waste (Mugagga, 2006). Although KCCA policy encourages waste composting in Kampala (WMW, 2013), no noticeable practical step has been taken to implement this policy. For instance, there is no large-scale compost plant set up to compost waste in the city (Mugagga, 2006) nor has awareness been raised to encourage small-scale composting and other waste management activities such as sorting of waste (OAG, 2010). It is likely that this is due to a lack of funds to support this activity.

Urban farmers in some SSA cities have adopted the use of organic waste as a fertiliser on their crop farms. For example in Jos, Nigeria, Olowolafe (2008) reported that farmers apply municipal waste in combination with mineral fertilisers, and sometimes with poultry droppings and/or cow dung to address the challenge of low soil fertility. In the research to determine the effect of municipal waste on soil properties, Olowolafe (2008) established that soil fertility variables were greatly enhanced by this practice. Asomani-Boateng (2007) explored the feasibility of recycling organic solid waste into urban cultivation as a sustainable waste management strategy in low-income neighbourhoods of Accra, Ghana, using low-cost composting of household organic solid waste by poor urban farmers. Although the study revealed that waste-based urban cultivation could significantly reduce quantities of organic solid waste for disposal, it also noted some major challenges associated with this process. Some of these included 80 % of land used by the farmers for cultivation were developed by landowners into residences, resulting in the displacement of farmers and hence a discontinuation of the composting process. Farmers demanded financial incentives to continue their participation in the composting process. This shows the difficulty of implementing small-scale low-cost organic waste composting using poor urban farmers.

Paper II established that 32 % of animal manure generated in Kampala is used as fertiliser, showing that there are a number of farmers that appreciate the value animal manure as an important source of crop nutrients. Although Paper II also established that most of the animal farmers whose animal manure is re-used as fertiliser have their own crop gardens (farms), so there is a possibility that some make use of it as a disposal method. This is due to the extremely poor manure management witnessed on some crop farms and yet, according to

Zake *et al.* (2010), proper manure management is a very important factor in conserving the nutrient value of the manure. Thus there is a likelihood of even fewer animal farms appreciating the value of animal manure as a fertiliser. In Yaoundé city, Cameroon, on the other hand, most of the manure generated is used as fertiliser on crop fields. However not all animal manure produced is utilised on crop farms within the city environs. Some of it is sold off to other provinces given that trade in animal manure is highly developed and manure is packaged in 40 kg bags and sold to farmers. This has been attributed to the higher level of awareness among urban farmers in Yaoundé of manure's contribution to soil fertility (Prain *et al.*, 2010). Thus with increased awareness among farmers in Uganda, there is a possibility of increasing the re-use of manure as a fertiliser in Kampala, as is the case in Yaoundé. However, given that farmers in rural areas suffer from high poverty levels, the sale of manure from Kampala may not be feasible at the moment. The recognition of fertilising ability of manure is very pronounced globally, especially in Europe and North America, where the use of animal manure on crop fields is widespread, a practice that also addresses concerns associated with the disposal of manure. This practice also increases the efficiency of vital plant nutrients such as nitrogen and phosphorus.

5.2 Animal feed as a product of waste management

As has already been mentioned in Paper II, about 60 % of the manure generated in Kampala is discarded. However animal manure can also be used to support the aquaculture industry by fertilising fish ponds (Rutaisire, 2007). This is important as most farmers in SSA cannot afford the expensive industrial aqua-feeds in addition to the local fishmeal and soybean or oilseed cake to feed their fish stock. Consequently, it is estimated that by 2020, animal manure requirements in SSA by this industry will be between 260 and 760 Gg per annum (Hecht, 2007), showing how valuable animal manure is to the aquaculture industry in SSA. It is therefore important that animal manure is collected, bagged and transported to those who need it (Hecht, 2007).

Furthermore, as already mentioned in chapter 4, although a high waste-to-biomass conversion ratio (BCR) is possible, in the low maintenance and non-optimised vermicompost system established for this study, a BCR value of 3.6 % was obtained. This implies that if the vermicompost system is adopted to treat both municipal waste dumped at the landfill (Paper I) and wasted animal manure (Paper II) in Kampala, 1Gg of biomass would be generated monthly. This figure is rather conservative as, according to Paper III, with more frequent worm harvesting it is possible to attain a higher BCR. Worms can be used as a protein source for the poultry and pig industry. This is very important in Kampala as although farmers normally use commercial feeds for poultry (Paper II), its high cost significantly affects the profitability of this enterprise (Katongole *et al.*, 2012).

Furthermore, most of the commercial chicken feeds (over 80 %) on the Ugandan market are adulterated. Chicken feeds, especially the silver cyprinid *Rastrineobola argentea* locally known as “mukene”, are deliberately mixed with sand, ash and sawdust by unscrupulous traders to increase their weights and maximise profits. The practice is so widespread and serious that a 100 kg bag of “mukene” may contain between 40 to 60 kg of contaminants. Such adulterated feeds either kill poultry or stunt their growth, leading to low productivity and an increased disease burden (Kagolo, 2012). Although there is a National Animal Feeds Policy in place whose aim is to ensure that quality animal feeds are on the market (MAAIF, 2005), this policy has never been implemented. According to (Katongole *et al.*, 2012), this is because the Animal Feeds Bill which was supposed to operationalise this policy has never been passed. As a result, fake animal feeds are quite ubiquitous on the Ugandan market. This has had a significant effect on farmers’ productivity and profits, causing many to abandon poultry farming altogether. In the case of pig farming, food waste is a popular feed source, as highlighted in Paper II. However, according to Katongole *et al.* (2012) food waste contains zoonotic pathogens such as *Salmonella* spp and so the feeding of food waste to pigs has been banned in some countries (Myer *et al.*, 1999).

The promotion of vermiculture could address the problem associated with fake feeds on the Ugandan market, as well as that of the presence of zoonotic pathogens in food waste. This is because vermiculture, as demonstrated by this study (Paper III), is easy to practise and does not require sophisticated technology to achieve success. It therefore has the potential to be readily taken up by livestock farmers as a way of producing their own feeds themselves. In this case, the worms produced could replace the silver cyprind, a good pathway for the rampant adulteration in animal feed currently being witnessed. In addition, given that zoonotic pathogens like *Salmonella* spp are inactivated during vermicomposting (Paper III), the food waste produced could be vermicomposted and the worms produced fed to pigs, chicken or fish. Hence the concern about pathogens being spread through food waste can be addressed. Although the study also found that not all pathogens can be inactivated, in a large-scale feed production system based on worms, post-processing occurs naturally as feeds need to be preserved and rendered storable or to be mixed with other feeds. The pathogens present can be inactivated by simple heat treatment during the drying process. Vermiculture also has the potential to address the problem of the high cost of feeds since worms are cheaply produced from waste. The only cost incurred is the labour cost of gathering the waste and feeding it to the worms. However this is not a problem in many SSA countries such as Uganda, where the cost of human labour is fairly low.

5.3 Biogas in relation to energy system in Uganda

According to Paper I, the waste generated in Kampala has a high energy potential and could therefore be exploited to meet the energy needs of Kampala. For instance, the energy content in the material collected annually corresponded to 1.6×10^9 MJ. If this material were processed in a biogas plant and 50 % converted into biogas, 8.0×10^8 MJ of biogas could be expected to be produced. When converted into electricity in a generator with 35 % efficiency, this energy could produce 2.8×10^8 MJ of electricity annually for use mainly in lighting. This is would be extremely important as Uganda's current electricity demand is far greater than its meagre supply and this has forced the country to resort to the installation of expensive thermal generation (Buchholz & Da Silva, 2010). As a result, the country suffers from high energy prices and uneven distribution (Buchholz & Da Silva, 2010), a factor that explains the fact that only 5 % of Ugandan households have access to the electricity grid (NEMA, 2007). In an attempt to alleviate this, the Ugandan government has come up with a policy on renewable energy. Among other things this policy emphasises the development of renewable energy sources through the use of various technologies such as biogas technology (MEMD, 2006).

Biogas technology is not a new technology in Uganda. According to Walekhwa *et al.* (2009), biogas technology was introduced to Uganda in the 1950s and since then it has been promoted by mainly non-governmental organisations (NGOs), including Heifer Project International (HPI), Adventist Relief Agencies (ADRA), AMREF and Africa 2000 Network among others. At present, it is estimated that there are about 500 functioning biogas plants in the country (MEMD, 2006). In spite of this, the contribution of biogas technology to meeting the country's energy needs is negligible, with biomass mainly in the form of fuel wood and charcoal contributing over 90 % of the total energy needs of the country and almost all the energy used to meet basic energy needs for cooking and water heating in rural areas, most urban households, institutions and commercial buildings (MEMD, 2006). The heavy reliance on fuel wood and charcoal, with the consumption of the latter increasing at a rate close to the urban growth rate of 6 % per annum, has greatly contributed to the degradation of the country's forests (MEMD, 2006). Other countries in the region also rely heavily on biomass, as shown in Table 15.

Table 15. Energy consumption and electrification patterns (% of households) in East African countries

Country	Energy consumption		Electrification	
	Biomass	Other	Urban	Rural
Kenya	70	30	46	4
Rwanda	90	10	48	1
Tanzania	90	10	38	2
Uganda	93	7	8	1

UNDP/GTZ (2005), as cited in (NEMA, 2007)

Owing to the significant disadvantages associated with the commonly used energy sources in Uganda, there is an urgent need to seek new sources of energy. Biogas energy is one such source of energy. However, as already mentioned, although it was introduced several decades ago, its contribution to the energy needs of the country is still negligible. According to Parawira (2009), this is due to the following: poor quality plants and material choice due to inexperienced contractors and consultants, users lacking in ownership responsibility, poorly trained operators and a lack of technical knowledge on maintenance and repair, and poorly informed policy makers/authorities who have failed to pass enabling policies that can stimulate government support for biogas technology. It should be noted that similar challenges were met when the biogas technology were introduced in high-income countries. However, according to Wilkinson (2011), the challenges associated with biogas technology have been overcome through operator training, the employment of better designs and the introduction of economic incentives. If SSA municipal authorities such KCCA adopt measures employed by high-income countries to attain success in their AD plants, AD technology will probably be successful in supplying energy to SSA cities such as Kampala.

5.4 Waste management and treatment technologies

Technologies available to treat organic waste include AD, fly larvae processing, vermicompost and compost. Paper IV showed that the AD system was best performing in terms of energy use, GWP and eutrophication. In addition, AD's digestate had the highest concentration of vital plant nutrients (Paper IV) and was therefore best suited to support agriculture. Compost was best suited to treating large quantities of organic waste, and windrow composting is especially easy to manage, a trait that makes it extremely useful for SSA conditions (Paper IV). Fly larvae composting is novel to SSA conditions and more research is needed to investigate its suitability for SSA conditions.

Large-scale anaerobic digesters have been employed to treat the large quantities of biodegradable waste contained in municipal waste in many countries (Parawira, 2009), therefore SSA countries should not be an exception. However AD technology has a fundamental disadvantage. According to Couth and Trois (2012), AD technology is technologically more complex to manage and requires significant financial investment compared to other biodegradable waste treatment technologies. Challenges associated with methane leakages could also represent a significant risk factor (Paper IV). Therefore subsidies and intensive training programmes are needed to increase the viability of AD technology in SSA cities (Parawira, 2009). The challenges with AD technology notwithstanding, its promotion could go a long way towards, among other things, addressing the acute energy crisis being experienced in SSA (Parawira, 2009). It would also be better if AD plants that combine the digestion of animal manure with municipal waste are employed as they are not only associated with high biogas yields (Raven & Gregersen, 2007) but will also treat wasted animal manure (in the case of Kampala, for instance).

Compost plants have also been set up in many SSA cities, such as Accra. However their performance has not been satisfactory for various reasons. For instance, large-scale compost plants set up to treat Accra's organic waste failed due to inadequate managerial skills (Oteng-Ababio *et al.*, 2013). Other factors contributing to the failure of large-scale compost plants in LMI countries include high operational and maintenance costs and a lack of a readily available market for the compost (Ngoc & Schnitzer, 2009). It is therefore important for municipal authorities to have a plan in place on how such challenges will be overcome before even thinking of setting up the compost plants. As NGOs are active participants in composting activities in cities such as Kawasaki, Japan (Geng *et al.*, 2010) and Dhaka, Bangladesh (Zurbrügg *et al.*, 2005), composting has been a tremendous success in these cities. It is likely that if NGOs are also encouraged and motivated to participate in composting activities in SSA cities such as Kampala, waste composting would probably encounter a similar success. Furthermore, according to Hoornweg and Bhada-Tata (2012), another challenge associated with composting in low-income countries is the lack of markets for the compost and awareness of the compost process.

Furthermore, AD plants and composting plants for treating municipal waste will only be successful if enabling laws are passed and enforced by municipal authorities. In Japan, for example, suitable legislation, such as the food recycling law, which made it mandatory to recycle food waste into compost or biogas or animal feed, was passed and enforced. This law greatly stimulated biodegradable waste recycling (Takata *et al.*, 2012). In Korea, on the other hand, the introduction of a volume-based waste fee system through suitable legislation is credited with the increase in recycling (Lee & Paik, 2011). The adoption and enforcement of similar legislation in Kampala has the potential to create an enabling environment for any proposed projects on AD or composting to achieve success.

6. Conclusions and perspectives

6.1 Lessons from the waste management hierarchy for SSA cities

The waste management hierarchy is a tool that can greatly aid the management of waste in the SSA cities. However, in order for it to be effective, deliberate policies that implement it should be enforced, for example a policy on the compulsory sorting of municipal waste. Currently most of the waste generated in SSA cities is disposed of in landfill, leading to social, environmental and health problems. However, elsewhere the waste quantities being disposed of in landfill have been reduced through the introduction of the landfill tax (in the EU) and the volume-based waste fee system (in Korea and Taiwan). It is possible that by adopting these practices, SSA cities could reduce the volume of waste available for disposal.

Results from this study revealed that the largest fraction of waste generated in Uganda and most SSA cities is organic, and hence that there is huge potential for resource recovery through the introduction of AD and compost systems. Although there have been some attempts at introducing large-scale AD and compost systems in cities in LMI countries, in some instances this has not been successful due to challenges related to poor design, maintenance mechanisms and skills. However, challenges with the AD system have been overcome through better reactor design, better operator training and favourable economic conditions. As regards the latter, in Germany a generous feed-in tariff for renewable energy greatly stimulated the growth of AD technology there. Meanwhile, for the compost system, the challenge of a lack of market for the compost generated due to strong competition from chemical fertilisers has been overcome by government policy favouring the purchase of food products from farms that used the compost generated. It is highly likely that if SSA cities were to do the same, it could stimulate growth in AD and compost technology.

Re-use and recycling activities in SSA countries are not as effective as they are in high-income countries mainly because municipal authorities do not give them the attention they deserve and leave them in the hands of informal groups, such as scavenger organisations. In addition, with the exception of scrap metal, there is a lack of the affordable technology needed to undertake the recycling. Direct involvement of municipal authorities in re-use and recycling activities, with NGOs and other groups complementing their efforts, can greatly stimulate these activities. Furthermore, as has happened in high-income countries, if introduced and enforced through legislation, EPR can greatly stimulate recycling activities. Additionally, the local use of mineral fertiliser is low and several studies show a higher yield from crops fertilised with organic fertilisers or combined organic and mineral fertilisers due to low soil carbon levels (Adamtey *et al.*, 2009).

6.2 Waste quantities generated in Kampala

About 28,000 tonnes of municipal waste from Kampala city is delivered to landfill every month. KCCA records show that this is about 40 % of the total waste generated in Kampala. Analysis of the physical composition of the municipal waste revealed that it consisted mainly of organic material (92.1 %), soft plastic (3.0 %), hard plastic (1.8 %), and paper (1.1 %). The average chemical composition of its organic fraction was 71 % moisture, 1.89 % nitrogen, 0.27 % phosphorus, and 1.73 % potassium. The plant nutrients in landfilled organic waste from Kampala corresponded to 92, 110, and 680 % of imported fertiliser nitrogen, phosphorus and potassium respectively. The waste also had a gross energy content of 17.3 MJ/kg. Both the physical composition and the chemical composition of the waste varied depending on whether the month was dry or wet, while the physical composition also varied depending on the city division generating the waste. Recycling of some fractions of the waste is being successfully carried out in some divisions already. The organic waste, although suitable for production of compost, is not suitable for energy recovery through incineration due to its high moisture content.

Animal farms are predominantly located around the periphery of Kampala, mainly in Kawempe and Rubaga divisions. Nakawa division has the largest number of animal units (2,100), followed by Kawempe (1,900 units), Rubaga (1,300 units), Makindye (590 units) and Central (63 units). A variety of feeds are used for animals in Kampala City, with the predominant feedstuffs being food peel and pasture. There is quite high potential for the use of manure as a fertiliser, since >60 % is currently wasted, mainly owing to a lack of awareness among urban farmers and a lack of sufficient regulation of manure disposal by the city authorities. However, the nutrient content of the major feeds used and the manure generated must be quantified and the hygiene quality of the manure determined in order to assess correctly the quality of the resource currently available in Kampala. Larger farms often combine animal and crop production and tend to re-use manure more than small farms.

6.3 Organic waste treatment method suitable for SSA cities

A simple field vermicompost reactor established in Kampala was found to operate well even with a low level of maintenance. The unoptimised system proved highly efficient in transforming cattle manure and food waste into odourless, porous and homogenised vermicompost, demonstrating a 45.9 % reduction in the waste material on a TS basis. The BCR was estimated to be 3.6 % on a TS basis, which is comparable to that in other more regulated systems. Increasing the maintenance level slightly, with more frequent worm harvesting, could increase the BCR further. The hygiene quality of the vermicompost was low, but it could be improved by introducing a post-stabilisation step in which no fresh feed is added. The vermicomposting system was found to be a viable manure management strategy for small-scale urban animal agriculture.

6.4 Environmental systems analysis of waste treatment methods for SSA cities

The study showed that the AD system was best performing in terms of energy use, GWP and eutrophication. However a poorly managed AD system with large methane leakages performs poorly in terms of GWP. The compost system performed poorly with regard to GWP mainly because of the direct emissions in the composting process. Composting is in many respects the easiest system to implement, however, and in terms of GWP is far better than the landfilling of biodegradable waste (Couth & Trois, 2012). Improved management of the composting process could reduce these emissions and improve performance of the composting system with regard to GWP. Overall, in terms of environmental performance, this study concludes that the AD system is most suitable for SSA cities and it would probably be beneficial for the authorities to take steps to promote it. In areas near water bodies where eutrophication is a challenge, the vermicompost system would appear preferable. However more studies are needed to verify this before implementation.

6.5 Future perspectives

Even though this study determined the best waste treatment technology from an environmental point of view, it needs to be accompanied by other studies on social and economic acceptance to obtain the best technology for waste treatment in SSA cities.

An acute shortage of data from SSA cities reduces the accuracy of LCA. Studies are urgently needed on:

- the measurement of direct emissions from the different subsystems of waste treatment technologies
- the viability of BSF technology in SSA.

There is a requirement to map the location of crop farms in Kampala and attempt to model a relationship between them and the animal farms. In addition, the effect of dumped animal manure on water quality in Kampala needs to be ascertained through further studies.

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